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25th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting

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Richard L. Sydnor
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California Institute of Technology
Pasadena, California

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TWENTY–FIVE YEARS OF PTTI

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Abstract

The availability of reliable, industrially produced atomic clocks in the mid–1960s brought about a great increase in the use of Precise Time and Time Interval (PTTI) in electronic systems, particularly in communications, electronic navigation, and space systems. By 1968, the need for better planning of timing operations, and also the need to inform systems managers and systems engineers of the capabilities of this new specialization became so great that a special Strategic Planning Meeting was organized at the U.S. Naval Observatory. The original purpose of the meeting, to plan, to exchange practical information, and to bring future requirements into the open, is still with us. The first meeting, in April 1969, demonstrated the need to make it into an annual affair. The talk will summarize the major developments that took place in the last 25 years and we will look back at the contributors and events that are now documented in the Proceedings. The discussion will also include some thoughts about suggested future directions in the organization of these PTTI Strategic Planning Conferences as they have now become a major feature in our timing community.

INTRODUCTION

The story of the 25 years of the PTTI conference can be told from different angles. First, I could review the achievements of the conference, and of its contributors. Then I should include a brief review of the main advances reported at this conference and acknowledge the work of those who made these advances possible; these people don't always show up at our meeting. We can also look with a more general perspective: Technical meetings such as this one are a major engine of scientific–technical progress. Without the pressure of deadlines, the great majority of the papers would not be published (that is my estimate, based upon my own experience). It is, therefore, of some importance whether and how these conferences are organized, who is the sponsor and organizer, and which goals will be pursued. And in the particular case of this PTTI Strategic Planning Meeting, these questions are probably even more critical than elsewhere if, as we hope, the information exchanged will influence decisions of often far–reaching importance. Therefore, questions of the management of conferences, particularly technical conferences, cannot be ignored because they are far more important than it may appear to the unsuspecting attendee. I want to take this opportunity to help clarify the peculiar aims of this conference, because knowing the goals should assist every participant to maximize the benefits arising from being here.

In this talk I will attempt to look at all of these aspects and my main motivation will be to do that in a way that will open up a vista of the future, as it can be seen today, of the conference as well as of the area of PTTI. We know, of course, that attempts to look into the future are notoriously deceptive. The expectation that things will continue in their present direction will almost always be disappointed because change is the most fundamental aspect of everything (and we should know because time is the abstract measure of change!). Indeed, the unforeseen is the most likely to happen. But by reflecting upon the driving forces of meetings and technology, and keeping in mind the general principles that govern all things, we could gain some idea of the potentialities of future developments.

BACKGROUND AND ORGANIZATION OF THE CONFERENCE

Looking back can indeed be salutary and humbling. When, in 1969, we decided to follow a recommendation made by Nick Acrivos[1] and Clark Wardrip (National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC)) to call a meeting as a forum to discuss what was really needed in the way of precise time and frequency, nobody dreamed about making this a regular conference, and it didn't appear at all likely that we would end up in splendid settings such as this one.

Unfortunately, Nick is not with us anymore. But Mr. Wardrip is here and we may question him as to what exactly they had in mind when they proposed a requirements and operations meeting at a time, when other people, such as myself, believed they knew exactly what the requirements for PTTI were. At any rate, the U.S. Naval Observatory (USNO) took up the suggestion, and the meeting turned out to be such a success that making it a regular event was one of the recommendations of that first meeting. The first meeting made it also clear that it was necessary to bring in more support by the way of additional sponsoring agencies concerned with applications of PTTI.

The reason for the success is, I believe, primarily due to two factors: There is a real need for a regular technical information exchange of this kind, and second, the conference management has kept the original goals and principles firmly in mind. Management! It has been often said, first by Lao–Tzu around 600 BC in the famous Tao–te–king, that the best government is the one that one does not see or feel. Because then, the people will say "We did it all ourselves!" However, a conference does not run by itself and definite visible actions are necessary; moreover, they must be planned far in advance. This is the function of an executive committee which is established by the sponsors. From the two original sponsors, NASA/GSFC and the USNO, the number has increased to seven. These sponsors, listed on the first page of the program[2], are those agencies that are most concerned with applications of PTTI, in operational systems and in R&D. Over the last 25 years, the interest and concern of various sponsors have changed and we have lost some of them, such as the National Institutes of Standards and Technology. This is regrettable, but we must understand the need everywhere to concentrate according to the local priorities.

The members of the executive committee, listed on page *ix*, are appointed by their respective sponsor agency. They, in turn, elect a chairman. Most of the administrative functions are the responsibility of this chairman (Mrs. Sheila Faulkner, during the last 8 years), who must propose actions and get them approved by the committee. The overall policy for the conduct of the conference, therefore, comes from the sponsoring agencies through their respective representatives, and the committee meetings serve to coordinate these basic goals and to develop the details for the coming conference.

It is interesting to note that, in contrast to meetings organized by the various professional societies, the organization and the sponsors of this conference predominantly reflect management concerns. This is still a planning meeting and the objectives as listed on page *iii* reflect this very clearly. Our main concern is not in technical details but in making capabilities known, doing our best to avoid needless proliferation of efforts, revealing future requirements, and facilitating lines of technical communication. It is this fundamental difference in outlook and goals that sets this conference apart from other meetings. This difference is also reflected in the format of the Proceedings. Every effort is made to convey as much practical information as possible (names, telephone numbers, questions and answers, etc.)

It is only logical that in the light of this orientation, the whole organization of the conference has to be handled quite differently from what is the norm for purely scientific or engineering conferences. Ideally, we want to have the best compromise between technical expertise and presentation skills for our speakers, who are supposed to present overviews and ideas that will lead to discussion and further communication.

The experience of the last 25 conferences has shown that this lofty ideal is very hard to implement. Not only is it very difficult to find an acceptable compromise between the profound but incomprehensible expert on the one hand, and a showman who is only capable of producing platitudes peppered with an endless number of buzzwords, on the other, but in addition, there are the pressures coming from the "contributed" papers which we cannot, and should not, completely ignore. And there is an even deeper problem. It has to do with the art of maximizing useful information exchange in a very limited amount of time. As I see it, the presentations, in contrast to the more detailed papers, should only introduce a subject, delineate its scope, and give an idea of potential problems, but refrain from sticking with details. Now, please tell this to our esteemed colleagues! The real problem, in other words, is what Bohr called the unavoidable conflict between understandability and accuracy. But we must try! This is one of the heavy responsibilities of the program committee chairman. Again, a situation somewhat different from the usual situation where the major problem is usually to avoid getting papers which have been given already several times before. For us, if it is an excellent communication, that ought not to be a problem.

The second, and possibly an even more serious problem, is in attracting those people who can profit from the conference. We believe, with Socrates, that if one would only know what is best (in totality, i.e., in the long run), he could not avoid doing it! Hence, our most serious efforts to induce busy systems engineers and project managers to come here. I know that we have achieved an excellent features–to–price ratio, thanks to our executive committee chairman whose efforts are most appreciated. And, I believe, our efforts are paying off. In contrast to the general trend, the PTTI conference has increased its attendance, however slightly.

TECHNICAL PROGRESS AS SEEN AT THE PTTI MEETINGS

During these 25 years, we have seen the precision of timing go from about 0.1 microsecond to fractions of a nanosecond, and frequency control from parts in ten to the twelfth to parts in ten to the fifteenth. In the dissemination techniques we have seen our reliance go from VLF and Omega to LORAN C, and now to the GPS and two–way time transfers. Clock technology has seen an even more impressive change, largely due to the fantastic advance in electronics. There are three particular observations that I can make: the evolution of the hydrogen maser into the best available clock, albeit at a premium price and support effort; the perfection of the cesium standard into a most reliable, high accuracy, industrial product; and the very great effort that has gone into the GPS which has been the main driver for clock technology during the last 20 years. These are the most outstanding items, in my opinion. However, one must also mention a host of other developments. There is the impact of lower cost solid state electronics that has also achieved a previously impossible increase in reliability. And then we have the applications of PTTI in the most advanced research, in VLBI, in pulsar research and others.

During the first ten years of the conference, a tendency developed to focus very narrowly on particular systems during each year. One year we would see most presentations on LORAN C timing, in another it was VLF/Omega. Then it was hydrogen masers. This narrow selection was later abandoned in favor of a more general approach in the way this year's conference has stated its particular objectives on page *iii.*

In looking over the programs of the 25 years, it seems that the whole field has widened considerably. Two decades ago, no one was interested in timing of power systems, for example, or of timing via the Internet. We were much more narrow also in regard to the general technological approach. I believe this to be a sign of growing maturity of our specialty.

In looking back, I can also say that the meetings have been a major help for the USNO in its function under the DoD PTTI Directive. I also know that the Proceedings have been most useful to those who took the time to look through them.

OUTLOOK INTO THE FUTURE

With the caveats expressed at the beginnings of this talk, we can speculate about what is going to happen to this conference in the future. One thing is absolutely certain: It is not going to continue as it is today. And the change will come in a way that is hard to foresee now when the problems of today obscure our vision. I believe, however, that one can suspect a few tendencies. I expect a further increase in applications in mass electronics. In other words, while the main driving force of the past has been the desire for greater performance by way of accuracy, the future will demand lower price and smaller size as the main goals. Of course, this will depend very much on the general world political situation, no doubt. If a major economic crisis develops, then all technical activities will suffer. If, on the other hand, another major threat would appear, then we would see a resurgence of the hectic activities that will be necessary to defend us. At any rate, however, there will be no decrease of new ideas, of inventions, of improvements of all kinds. It is only the rate of progress that is hard to gauge, not progress itself. And if the conference continues to be useful, then it will continue to report on these developments.

NOTES, AND LITERATURE REFERENCES

[1] Nick Acrivos, a retired Army major, had come to USNO from the Army Map Service as our first PTTI operations officer. His amazing energy and resourcefulness were major factors in the Observatory's quick implementation of the DoD PTTI Instruction. He coined the phrase Precise Time and Time Interval (PTTI).

[2] Program PTTI'93

QUESTIONS AND ANSWERS

M. Van Melle (Rockwell): I was wondering what the status of rubidium is. You didn't mention that too much.

Dr. Winkler: I have mentioned that as one of the technologies. If you look through the papers, the main emphasis during the last 20 years has been in the reduction of the drift of rubidium standards: a simplification in the manufacturing and reduction of the drift. In fact, the specifications very much emphasize a drift of less than, let's say, one part in ten to the eleventh per month.

I feel that this will not continue; that I can see the main applications of rubidium standards in the future where you don't care what the long-term drift is. But you want to have a reliable, small, cheap standard which can be within a few parts in ten to the twelfth, out to a thousand, two thousand seconds. Because, the main application will be in avionics, there's no question about that. And whether and how soon these applications will be translated into massive orders of tens of thousands of units depends entirely on the price. It is again this vicious circle that if things are too expensive, then no orders will come in; and if the price goes down then, of course, many, many more people will enter the market for it. Because, today the main application I can see for timing for the next two or three years will be in support of integrity monitoring, the range where you want to have an inertial and timing fly wheel which will carry you through 500 to 1000 seconds and allow you to reduce the dynamic problem to a stationary problem with integration, and so on. And then this, of course, requires that you have less expensive standards. So to come back to your question, yes there has been much emphasis. But I think for the future the emphasis will be different from what it has been in the past. It will be to reduce the price drastically and to relax the long-term stability requirements for rubidium standards.

Phillip Talley: I think it is important for this group to fully realize that rubidium has made significant advances in terms of stability and in terms of aging. And it will be the clock of the future for GPS on the II–R program. A lot of people may have been concerned that rubidium wouldn't have been as good as they had hoped for. But our demonstration is that it is as good and it is approaching certainly the performance of the cesiums and the predictability of aging is in there. I think that is an important thing for this group to understand.

Dr. Winkler: There is no question about that. On the basis of what we know today, I have to agree with you, even though I have expressed reservations about the II–R clock program in the past. In fact there are some rubidium standards in space now and have been all the time; except they have not been of the latest design or the latest type going in the GPS II–R program. Yes, I agree; but I consider that as a special, relatively small–scale application compared to the masses of rubidium standards which I can see in the future to be used in avionics – and in other applications as well such as communications – where you do not need the long-term stability. In GPS, of course, that has been an absolutely indispensable requirement, that the drift be very small and that it be predictable. I would add to what you said, for short-term applications, its noise level is slightly better than the cesium standards. This is certainly true. But given the numbers – you are talking about 25, 30 satellites (or possibly a few more), compared to the tens of thousands of applications which I see coming. I wanted to make that point clear.

David Allan, Allan's Time: I would like to have your comments on two items if I may. First of all, it seems to me that as we look over the last 25 years, we see the development of techniques for characterizing the stochastic behavior of clocks. More recently, because of the larger number of applications, we have seen the need to be more careful about environmental characterization; there seems to be a trend. The IEEE specifically has issued a standard on the stochastic measures, and now we are working very hard to get a new standard which deals with environmental questions, I think because of the very important aspects of vibration and application-sensitive things. So that is item one.

The second item is that it seems to me that the large number of applications are coming in avionics, but I see a tremendous marriage occurring between telecommunication and time and frequency, which is going to be very important for the future for rubidium, quartz, cesium, hydrogen – perhaps not hydrogen in telecom; but I would like to have your feelings on that.

Dr. Winkler: I completely agree with both of your points, except that I did not spend time mentioning the standards which you have implied that exist and the effort on the part of the IEEE to come out with standards and recommendations in these areas. Because, I think this really has not been a major focus in this conference. The driving forces for these standards came more from the Frequency Control Symposium and most of it from the IEEE. That is the standards committee; and the international commission, CCIR, those are the drivers in that area. And the CCDS also, and the International Committee for Weight and Measures. So here, again, the emphasis is not in the development so much of technology as in the applications and, as you say education; bridging that gap of communication between two different cultures. That is what we are dealing with in this area. There are two different cultures: technology is on one side and managers, systems engineers on the other side. And that is a serious problem. And if we don't succeed in having some regular communication between them and mutual education, I think we will pay a dear price for that in the form of duplication of efforts, of wasted efforts of all kinds.

But I completely agree with your comment also that the communications area will see a massive application of atomic standards and of precise time and frequency technology in general. That is a sign of maturing technology, that suddenly a large-scale application comes up. And that will further cause a feedback loop, that by reducing the price of individual units, it will promote further increases.

John Vig, U.S. Army Research Labs: I think you mentioned that there is already a GPS receiver for $400; and it possibly can give you 100 ns of accuracy. I have two questions. How low can it go in the future? And, what will be its impact on PTTI as far as the business aspects and as far as the research aspects are concerned?

Dr. Winkler: How low it can go – well, I think you have to start with the parts count, the necessary elements which have to go in. And I think $300 for a six–channel receiver OEM price is very low. I don't think you will see the price dropping much below that. I cannot see that.

But the second part of the question, what is the impact for science and technological applications, the answer is "vast." The fact that you can so inexpensively, anywhere on earth, have a common time and frequency reference has vast implications. Just yesterday I talked with John Klobuchar from Cambridge. He said that we have possibly hundreds of applications where we can time–tag remote measurements. We cannot do that now with sufficient accuracy. And economics come in very strongly too. So my answer to you very quickly is that the impact will be vast.

John Vig: That wasn't my question. The impact on the applications is going to be vast, no question about it. My question was, "What will it do to business by the manufacturers of PTTI products, people who make frequency standards for example?" Why do people need a two–thousand dollar oscillator if they can buy a four hundred dollar GPS receiver that can give them 100 ns? And why should the DoD, for example, sponsor research in this area on precision oscillators if people can buy a four hundred dollar GPS receiver?

Dr. Winkler: Your question goes to the very core of why do we use precision time and frequency standards in systems. We use them in order to provide a local independence for a certain period of time. I think that will continue to exist, that requirement. If you have an application which absolutey requires *at all times* to be within, let's say, one part in ten to the twelfth, I would not design a system without having a good cesium standard at that location.

So this will require very subtle judgments. And I think your question is a good one. It is certainly something which we have to discuss. And I am indeed aware of several problems which have cropped up in systems design where suddenly the budget people raised exactly that question: "If you have your time and frequency available, why do we need that?" That is a similar question of why do we spend money for insurance; it is exactly the same thing. It requires a risk analysis of putting numbers down, costs on it. My gut feeling is that you will always have to have some precision frequency standard. And certainly you will need good local oscillators.

Let's take the example, for instance, of GPS, the application. Why do we want to have a better standard in your receiver than what we use now? In order to facilitate a quick access, facilitate access during jamming, and all these questions. So the problem is much larger than just to say since I have time by buying a three hundred dollar receiver, I don't need anything else. Oh yes, you do if you are putting all these considerations into play. So my answer is that you still need it, but not in such massive numbers for such high precision standards as we do now.

Claudine Thomas, BIPM: You mentioned progress, in particularly hydrogen masers. Do you imagine that the definition of the SI unit for time, the second, could change in the near future?

Dr. Winkler: It is not, in my view, something which will happen during the next five years. Because, there is no unanimity in regard to a possible practical replacement for the cesium definition. It is also certainly true – and I am sure our colleague, Don Sullivan and the gentlemen from NIST will agree with that – that we have not completely exploited the capabilities of the cesium standards for the provision of an absolute standard of time. I think there is still work to be done and is being done. And the advance work being done at the standard laboratories and research laboratories for an eventual replacement have not yielded a clear advantage in making a change here. It will take time. I think over the next five years, I do not see that any agreement can be reached to replace that and nor do I see that need for taht. But when it comes to ten years *and beyond,* based on what I said before, we cannot be certain that things will not be changed. But we have not yet any good candidate for that. Maybe Dr. Sullivan from NIST will want to make a comment to that regard.

Donald B. Sullivan, NIST: I agree, of course, with your conclusion. I would stretch that time frame out to 20 years even. The difficulty here is that you really have to demonstrate an overwhelming advantage before you change something like this. And the process of international standards agreement is a very cumbersome and time-consuming thing. We really don't want to see change occur too quickly because it can have a negative impact. I believe that the potential for cesium with not only the optical pump but also the fountains goes well beyond a part in ten to the fourteen, certainly to a part in ten to the fifteen; and I can't imagine right now the applications that will need that. So I don't really see a driving force for such a change.

Albert Kirk, JPL: I see this trend that we take the GPS system and steer primary and secondary house standards. To what are we steering to? Would you make some comments, please, on this chain of the GPS system? What exactly is NIST, USNO, BIPM steering to? Whose time are we synchronizing to? And what are the areas of uncertainty along this chain?

Dr. Winkler: There are two parts to the question. Number one, in respect to frequency, we steer in the long–run to the frequency as given by the BIPM, based on an average of laboratory standards. Whichever are available, these provide a long–term reference in frequency for the time scale. For GPS, that is being done via the reference which is steered very closely to the BIPM. And we will hear more about that later in the conference.

In respect to timing, you must have a generally accepted standard, which is UTC/BIPM. That is what they are steering on. If you look at the last year, the GPS has been kept within UTC very closely, usually within 100 ns RMS. And I think that will improve. So there is no ambiguity, we must have a general standard. Of course it is ambiguous to define originally UTC. What is UTC? UTC goes back to UT-2 on January 1, 1958. That is how the principal epoch was fixed. But from then on, we just kept time more and more accurately as we could in order to satisfy the divergent requirements coming from a common frequency reference to the divergent requirements coming from a time reference. The steering philosophy, all kinds of details enter here. We don't want to make epoch changes; we don't want to step unnecessary. It is enough to have the leap seconds, which will probably carry for a while with us, but we don't want to make unnecessary frequency changes. The long–term reference is UTC/BIPM, and that is what is being followed. And I think we are making increasing progress in doing that better and better as time goes on. Again we will hear more about that from Dr. Thomas later today.

DoD and Navy PTTI Report

Richard E. Blumberg
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Abstract

In addition to its national responsibilities in astronomy and time, the U.S. Naval Observatory (USNO) has also the responsibility for overall DoD PTTI management. This function, originally established by DoD Directive in 1965, has now become part of DoD Instruction 5000.2. This instruction emphasizes the need for a common time reference (the USNO Master Clock), in addition to the need for widest coordination "to ensure worldwide continuity of precision." It also directs the appointment of PTTI managers from DoD Components to assist the DoD manager in the development of the Annual PTTI Requirements Summary, and in coordination of PTTI techniques among the Components. While the PTTI segment of the various electronic systems that use precise time is usually but a small piece of the action, it nevertheless is frequently the most critical one for the precise accomplishment of the mission. This is now generally recognized as one of the lessons of the Gulf War: Accuracy Saves Lives! As a consequence, we see today the emergence of another round of developments that aim at greater accuracy capabilities in the kind of scenario envisioned under the doctrine "From the Sea." The PTTI technology is deeply involved in these developments and this paper gives some examples.

This morning I am going to report on some aspects about the Department of Defense (DoD) Precise Time and Time Interval (PTTI) program: a) the PTTI managers and representatives and who they are; b) some of the actions that came out of last year's PTTI conference; c) a little bit on timing research and development; and finally, d) the importance of the requirements process.

First of all, what are the PTTI managers supposed to do? They are concerned with requirements, inter–operability, and standards. The issue of inter–operability is absolutely vital to the DoD, and not only the DoD but the rest of the nation as well. Concern with this issue is the major role that I see for the PTTI representatives. We cannot have services going off and developing their own systems, i.e., duplication of effort, in today's arena of dwindling resources.

Everything we do, particularly today, as resources become tighter, is tied to the requirements process. Why do we need better clocks? Why do we need ensembles? Why do we need the coordination of time? All has to be tied to DoD operations. If we are going to spend DoD dollars and cents on this program, we have got to be able to bridge the gap about which Dr. Winkler was talking, i.e., of going from the technical and engineering language of the folks that understand the aspects of precise time to the language that the program managers, the people that control the dollars and cents within the DoD, understand and appreciate. They are the ones who can say "Yes, I am willing to spend dollars to get timing down to the hundred picosecond level, down to the one picosecond level because I need it for 'x'." This is absolutely vital. Finally, the Research and Development Program needs to be coordinated so that it does support the requirement process.

Who are the PTTI representatives and managers? We have two levels essentially. The representatives (Figure 1) are the policy folks. They are at the senior level within their services. They essentially set policy for the DoD. The managers (Figure 2) work the day–to–day issues and problems that come up. These listings of our representatives and managers are current. Commander Dave Markham from SPAWAR has replaced Jay Berkowitz from SPAWAR. These are your points of contact within the DoD. You should know them.

A few words about the workshop from last year. One of the action items that came out of it was to put together a glossary of terms. It is important for newcomers into the field. One of the things that we talked about a little earlier was Father Time. You can take a look around the room and you see that we have a number of folks that can match him in terms of number of years in the program; but there are a lot of folks that are brand new to the program. What is precise time? Many of us have never thought about timing before. All of a sudden they are becoming experts within their areas of responsibility. Certainly, we have a new generation coming on board at the USNO. As a matter of fact, yesterday was the first time I have heard the term "Grandfather Time" in referring to Dr. Winkler.

Environmental versus the stochastic effects in clock technology and also measurement noise versus the actual clock noise is another concern. When we have a problem at the nanosecond level, what are we measuring? Are we really measuring the impacts of the noise? Or are we limited by our measurement systems? What are the environmental impacts? These were areas specifically identified in last year's workshop for additional work.

Next in our list of concerns are the impact of the improved frequency standards, the smart clocks, the 5071 Cesiums which are all remote–steerable. We don't have to have a man in the loop at the site. It can all be done by computer. The impact on having the capability to be able to remotely steer a clock and not have to have a dedicated resource sitting at that site is tremendous. The implications are savings in terms of dollars and cents, and also in our ability to have accurate time at remote sites. On the requirements issue, I'll talk a little bit about that later.

As I mentioned, we have a lot of experienced folks in this room and a lot of new folks. For the new folks there are a number of training opportunities available to us today within the DoD for PTTI, as shown in Figure 3. The annual meetings are excellent grounds to learn what is going on in the community, meet the people who are the community and are the experts, and discuss both the applications as well as the technological advancements. With regard to the Automated Data Service, the bulletin board, if you aren't on that bulletin board, you should be for exchange of information. Service training schools: the one at Lowry will be moving to Kessler since Lowry Air Force Base is closing down; and Ft. Gordon is the Army School in Georgia. There are also many tutorials and seminars of which you need to take advantage. For such an important area within the DoD, it is a very limited training opportunity!

Let's talk a little bit about our Research and Development Program, the exploratory 6.2 and 6.3 work. In Figure 4, you can see the correlation between the exploratory work that we are doing to improve clock accuracy and stability as well as to improve the models. With regard to new prediction models for polar motion, we are taking a look at using GPS instead of the VLBI radiotelescopes that we are using today. GPS may be able to help us in some of the polar motion studies.

Time transfer improvement; especially, two–way satellite time transfer, you will hear a considerable amount about that later on today. The improvements that we can make in GPS will givén help the proliferation of GPS receivers that is coming on line today. The key question is just how accurate can we transfer time through GPS; how precise can we be? Similarly this leads to the advanced research and development that you see in Figure 4.

The preceding speaker talked a little bit about progress in PTTI. In Figure 5, we see that in about every ten years, there is an order of magnitude of increase in our capability to provide precise time. The devices we have used have really been tied to those order of magnitude increases. I have "ion storage device" up there for the year 2003, to get down to the hundred ps. That is a guess; I don't know what the next hardware piece is going to be; you folks are the experts in that. Can we use cesium? Will it continue throughout? It is largely driven by this question mark that you see right here and that is, "What is the requirement? Who is the user out there? What do they need? Why do they need it?" And then, "How can we provide it? Is 2003 good enough? Do we need to be at the hundred ps level in ten years or do we need to be there next year or the year after?" That is part of the requirements process. And that needs work.

Time distribution: LORAN–C is being phased out as a DoD navigation system; however it is very vital to time transfer. GPS and GPS common–view capabilities get us down to ten and five nanosecond range, with two–way satellite transfer, we are rapidly approaching a one nanosecond capability. I am not certain that we are there yet with reliability and universal applications, but we are rapidly getting there. Certainly, GPS is again critical to our ability to distribute time and ties right in to the requirements.

I would like to conclude with a discussion of the requirements. Our requirements in navigation, communications, time systems, and targeting systems within the DoD have been well defined for a number of years. But they have been well defined in terms that in the past have not been scrutinized as closely as they are going to be. As we approach the next budgeting, planning and programming process within the DoD, it is going to become absolutely critical that we articulate what our timing requirements are and how that translates into the operation of the master clock at the USNO, the time reference stations that we have throughout the DoD and throughout the world. How do we get that time information into the hands of the operator and to the operating systems that need that timing information?

I was very impressed yesterday when I got a chance to see some of the hardware demonstrations, particularly in the area of communications and navigation. For those of you who did not see the hardware yesterday, make sure you get a good look at some of the capabilities of the hardware, the dollar and cents involved in procuring that hardware. It runs a considerable range. If a ms is good enough, you can buy a three hundred dollar GPS receiver today. If you need ps capability, then you need a much more sophisticated piece of hardware. We also need to do the research and development to give us that capability. And as PTTI DoD manager, I have to be able to stand up in front of DoD and say I need this much money to conduct this kind of research and development to produce this sort of a master clock by this year in order to satisfy those DoD requirements. And that is really what the bottom line is in terms of the DoD: what is my operational requirement, when do we need to get there, and how do we get there?

When I talk about the DoD, it also reflects our national interest. Very quickly, our national interest in communications, particularly in high data rates, as we get into data exchange and data processing, is the future of the world. And I think that there is a lot of work that we do behind the scenes in precise time that is going to become much more visible to the world of telecommunications here in the near term.

That is a summary of where we are within the DoD and within the Navy. Thank you.

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USNO

Information and Training in PTTI

★ **Two Annual Meetings**

- ➡ PTTI Applications & Planning Meeting (Dec)
- ➡ Symposium on Frequency Control (June)

★ **Automated Data Service**

★ **Training**

- ➡ Service Training Schools (Lowry AFB, Ft. Gordon)
- ➡ Tutorials (USNO, ARL)
- ➡ Seminars (NIST and Commercial Sources)

USNO

PTTI Development Program

★ Exploratory (6.2)

- ➡ Improved Clock Accuracy & Stability
- ➡ Improved Algorithms & Statistical Models
- ➡ New Prediction Models for Polar Motion
- ➡ Time Transfer Improvement
  - Two-Way Sat. Time Transfer
  - Laser Techniques
  - Increased GPS Accuracy

★ Advanced (6.3)

- ➡ Master Clock Upgrade
- ➡ Time Transfer
- ➡ VLBI for Earth Orientation
  - Polar Motion Studies

USNO

Progress in PTTI

	1963	1973	1983	1993	2003
Capability	1 μs.	100 ns.	10 ns.	1 ns.	100 ps.
Devices	Cesium Clocks	Hi-Perf. Cesium	Hydrogen Masers	Ensembles	Ion Storage Devices
Users	Polaris	DSCS	GPS	Advanced GPS	?

QUESTIONS AND ANSWERS

Pat Romanowski, Allen Osborne Associates: I have one question for the last speaker. That is whether or not you tie your time back into UTC and the broadcast over – I believe it's WWV.

Howard Hopkins: As far as I understand it, the time that we get through the USNO is UTC time. I am not sure what they do, however, at the PMEL level. I know that they receive time off the GPS and I assume that they correct their cesium clocks for that. But beyond that I just can't tell you any more.

Christine Hackman, NIST: I have a question for the first speaker. You made some mention of a bulletin board that we all should be on. How do you access it?

Richard Blumberg: The bulletin board is at the USNO; it is called "Automated Data Services." I will ask for some help from Dr. Winkler as to the details of how you access it.

Dr. Winkler, USNO: In every *Series IV*, which comes out weekly, there are instructions to do that on Page Two. The telephone numbers are also there. The bulletin board is accessible on three telephone numbers with any modem speed up to 14.5 kilobytes per second. It is available also on Internet. That information is widely distributed. We have asked for a password to access it, simply because for a while we have been inundated with inquiries and tests coming from all kinds of people. That is why we had to restrict access to the bona fide PTTI user. But there is no problem for anybody here to get that.

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STATUS OF FREQUENCY AND TIME SUPPORT FOR NASA SYSTEMS

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Abstract

The National Aeronautics and Space Administration (NASA) has Frequency and Timing Systems at many Facilities and Centers. This paper covers timing systems with specifications tighter than several microseconds. These ground based systems support scientific experiments and spacecraft tracking for the following programs: NASA Satellite Laser Ranging (NSLR); Network Mission Operations Support (NMOS); Kennedy Space Center (KSC); Very Long Baseline Interferometry (VLBI); Tracking Data Relay Satellite System (TDRSS) Ground Terminal Network, and the Deep Space Network (DSN).

Major equipment assemblies, specifications, performance and requirements, both present and future, will be presented.

INTRODUCTION

This paper describes six NASA ground based timing systems currently in use, the purpose of each timing system, and the program supported. The major equipment; frequency standards, clocks, and time synchronization receivers are included. Related specifications and performance are listed. Some of these specifications and performance characteristics are presented in graphical form.

NASA SATELLITE LASER RANGING NETWORK

The NASA Satellite Laser Ranging Network (NLSR) is a global network of both fixed and mobile laser ranging systems that measures the range to many satellites. These satellites are TOPEX, ERS–1, STELLA, LAEGOS I and II, STRAELLE, AJISAI and ETALON I and II. Another important function of the NSLR provides precise orbit determination of the operational satellites.

The centimeter accuracy of modern satellite ranging systems allow better estimates of the Earth's internal mass distribution, and global geodesy with accuracys of a few centimeters over continental distances.

Satellite laser ranging stations are located globally in over twenty countries and on every continent except Antarctica. The NASA network consists of four fixed stations and four transportable vans. The vans are moved approximately every six months to another field site.

The accuracy of laser ranging is critically dependent on the proper operation of highly stable reference oscillators in each NSLR station. The timing system at each station is driven by a Hewlett Packard "Standard Tube" Cesium Beam Frequency Standard that provides the time base frequency for the Ranging Time Interval Counter. To correlate the ranging measurements performed at different stations, ranging data at each location is synchronized with reference to UTC (USNO) to within less than one microsecond using GPS timing receivers. Performance specifications for frequency are those of a "Standard Tube" Cesium Beam Frequency Standard. This performance for Allan Deviation and Phase Noise is shown in Figures 1 and 2. The typical Laser Ranging System timing block diagram is shown in Figure 3.

The station time position data, time steps and other pertinent timing information are transmitted daily to the AlliedSignal Technical Services Corporation (ATSC) VAX computer system through the NSLR communication network. The data is reviewed and analyzed using an automated time position program that performs a least squares analysis and subsequently produces time position information for the stations. The results of the timing data analysis are reported to the Data Operations Group for inclusion in laser data analysis and the data base. This post processing of the time synchronization data resolves the offset to $\approx$ 0.5 microseconds.

NETWORK MISSION OPERATIONS SUPPORT

The Network Mission Operations Support (NMOS) provides pre–launch, launch support, and range safety for the Space Shuttle and other NASA spacecraft. The network also provides tracking and collection of data from low orbiting satellites. These timing systems are located at the Merritt Island Launch Area (MILA), Bermuda Island, Wallops Island, and Dakar, Africa.

The frequency standards at these stations are two Hewlett Packard model 5061A "Standard Tube" Cesium Beam Frequency Standards. The NMOS Frequency stability specifications are the same as for the frequency standard. This performance for Allan Deviation and Phase Noise are shown in Figures 1 and 2. The clocks at MILA, Bermuda, and Wallops are TRAK Systems model 8407–3 triple redundant with majority voting capability. The block diagram of these triple redundant clocks are shown in Figure 4. The time offset specification is less than 5 microseconds versus UTC (USNO).

Time synchronization is accomplished by using GPS or LORAN–C; depending on the location. MILA, Bermuda, and Wallops use LORAN–C as the reference source.

KENNEDY SPACE CENTER

The NASA Kennedy Space Center (KSC) also provides the pre–launch and launch support for the Space Shuttle and other NASA missions. This launch center has a centralized timing system, which consists of two separate clock systems. One clock is dedicated for support of the launch pads and the second is for support to the KSC industrial users.

Both of these timing systems are quite similar. The launch pad support timing system is a triple redundant clock each driven by a separate frequency source. One frequency source is a Frequency and Time Systems model 4065 Cesium Beam Frequency Standard. The second source is an Austron model 2100 LORAN–C timing receiver steering an external Austron model 2010B Crystal Oscillator Disciplined Frequency Standard. The third source is an Odetics model 325–868 GPS receiver also steering an internal crystal oscillator disciplined frequency standard. The 1 PPS from the three clocks (Odetics model 300–601) are intercompared by monitoring equipment (Odetics model 450). The resultant best clock of the three in the triple redundant set is the centralized complex on-line clock. This timing is then distributed to the KSC launch pads and industrial users.

Eastern Test Range timing (ETR) is available to this timing system through an ETR receiver and time code generator. This Kennedy Space Center Central Timing System is shown in Figure 5.

The time codes available for distribution are the IRIG serial codes D through G and NASA 36 Bit. Reference frequencies available are 5 MHz and data clock frequencies of 1.544 and 2.048 MHz.

The requirements for time synchronization are one microsecond maximum offset versus UTC at the centralized triple redundant clock. There is no requirement for propagation delay correction for timing distribution to the launch pads. The maximum time offset (propagation delay) from the central clock to the launch pads is less than one millisecond.

The performance specifications for the Industrial Users are the same.

VERY LONG BASELINE INTERFEROMETRY

NASA in coordination with the National Oceanic and Atmospheric Administration (NOAA), USNO, and agencies of several foreign countries conduct Very Long Baseline Interferometry (VLBI) experiments to determine time – varying geodetic baseline vectors for a variety of uses in the earth sciences. These Space Geodesy Program measurements result in the measured location of Tectonic Plates and associated plate motion.

Space Geodesy Stations are currently located in: Maryland, Massachusetts, Alaska, Hawaii, Canada (two locations), Chile, Brazil, Tasmania, and Norway.

The local oscillator at each of these sites is a model NR Hydrogen Maser Frequency Standard which was engineered and manufactured by Goddard Space Flight Center and the Johns Hopkins University Applied Physics Laboratory. All of these hydrogen masers are maintained and serviced by AlliedSignal Technical Services based in Columbia, Maryland. The 1 PPS clock output of the NR Hydrogen Maser is used to synchronize the clock in the VLBI Formatter assembly.

The required Allan Deviation performance is 2 to 3×10^{-15} at sampling times of 1000 seconds. The 1000 second sampling time is considered a representative period for geodetic VLBI. The NR Hydrogen Maser meets this requirement. Time offset versus UTC is maintained at less than $\approx$ 13 microseconds versus UTC (USNO) to facilitate VLBI data correlation during post processing. Frequency offset of the Hydrogen Maser is specified and maintained to less than 5×10^{-13} versus UTC.

The Global Positioning System (GPS) is used for time synchronization at the VLBI sites.

TRACKING DATA RELAY SATELLITE GROUND TERMINAL NETWORK

At present, there is one NASA Ground Terminal (NGT) located at White Sands, New Mexico. This ground terminal supports the NASA Tracking Data Relay Satellite System (TDRSS). A Second Tracking Ground Terminal (STGT) is currently under construction and is planned to be operational during the Fall of 1994.

Goddard Space Flight Center (GSFC) supplied the NGT timing system in 1979. This consists of two Hewlett Packard model 5061A–004 High Performance Cesium Beam Frequency Standards. Automatic non–dropout frequency switch equipment is provided. The clock is a TRAK Systems model 8407-1 triple redundant unit with majority vote/fault sense circuitry and distribution of multiple serial and parallel time codes as shown in Figure 4. GPS time synchronization receivers are used to measure time offset versus UTC.

The TDRSS Ground Support Program is currently adding the Second Tracking Terminal (STGT) approximately 16 kilometers from the existing NASA Ground Terminal (NGT). The STGT is currently scheduled to be operational during late 1994. The STGT frequency standards will be two Hewlett Packard model 5061B Cesium Beam Frequency Standards with high performance Cesium tubes. One Disciplined Crystal Oscillator Frequency Standard will be connected to each of the Cesium Beam Frequency Standards to reduce the close to the carrier phase noise. The clock will be a dual redundant unit.

In 1995, the NGT is planned to be upgraded including a new timing system. This replacement system is to include a new dual redundant clock. The frequency standards are planned to be Hewlett Packard model 5071 High Performance Cesium Beam Frequency Standards each driving a disciplined crystal oscillator to improve the phase noise performance. The frequency stability performance (Allan Deviation) is to be the same as the frequency standard.

NGT and STGT clock time offset requirements and performance versus UTC are one microsecond maximum. This is determined by measuring the station clock versus UTC using GPS receivers.

DEEP SPACE NETWORK

The Jet Propulsion Laboratory (JPL) controls the Deep Space Network (DSN) for NASA. This includes management, engineering and operation. The three complexes are located at Goldstone, California; Robledo, Spain; and Canberra, Australia. The DSN has provided support for all the Deep Space probes to the other planets, (*e.g.*: Magellan mapping of Venus and Galileo en route to Jupiter). Recently the DSN has been assigned the additional responsibility for the earth orbiting station at each of the three complexes.

The Frequency and Timing Subsystem (FTS) at each complex provides support for all missions. Some of the specialized operations are VLBI, Radio Science, Planet Mapping and photographs for all deep space missions.

The Signal Processing Center (SPC) at each complex has two Hydrogen Masers and two Cesium Beam Frequency Standards. One of the Hydrogen Masers is the prime, or on line standard, with the other acting as an operating spare. The clock is a TRAK model 8407–2 triple redundant unit with majority voting circuitry. The basic block diagram of this clock has been shown in Figure 4. The timing distribution to the local and remote users is via coaxial cables within the SPC and fiber optic cables between the SPC and each antenna. Each user is issued a Time Code Translator (TCT) which is really a Synchronized Time Code Generator that is driven by 5 MHz and synchronized by the master clock distribution equipment. Adjustable circuitry in each TCT reduces the propagation delay at the users interface to less than 50 nanoseconds offset versus the complex master clock. The block diagram of this complex frequency and timing system is shown in Figure 6.

Some reference frequency and timing users are located at the antennas which are remotely located from the SPC by 300 meters to 20 kilometers. For most of these antennas, it is necessary to meet the required Allan Deviation and Phase Noise specifications of the Hydrogen Maser. The requirements and actual measured performance is shown in Figures 7 and 8. The timing offset between Goldstone, the National Institute of Standards and Technology (NIST), and the two complexes in Spain and Australia is 3 microseconds (3 sigma) maximum. Knowledge of this offset, or measurement error, must be less than 50 nanoseconds. Frequency offset (syntonization) must be less than 6×10^{-13} (3 sigma) between complexes. Knowledge of this offset must be less than 3×10^{-13}. In order to guarantee this performance, the measurement must be considerably better.

To guarantee the time synchronization requirement, GPS receivers are utilized. This is accomplished by using the Common View technique and the current BIPM schedule. Data is collected twice weekly from the site receivers, reduced and published. It is estimated that the worst case frequency and timing measurement error is approximately 1×10^{-14} and 30 nanoseconds between Goldstone and Australia. Two Way Time Transfer is not in use by the DSN today because there is no Ku band commercial satellite link between the United States and Australia.

The Deep Space Network (DSN) has plans in progress to both expand and improve the Frequency and Timing Subsystem (FTS). This includes the addition of three 34 Meter Beam Wave Guide (BWG) antennas at Goldstone and one in Canberra. In addition there will be one 11 meter antenna installed at each of the three international complex sites to support the Orbiting Very Long Baseline Interferometry (OVLBI) program.

Frequency and timing distribution is required for each of these new antennas at these remote locations which are mostly 16 to 25 kilometers from the frequency standards and master clock in the complex signal processing center. Two of the 34 meter BWG antennas at Goldstone and one at Canberra will be provided with 100 MHz reference frequency distribution that does not degrade the Hydrogen Maser Allan Deviation and phase noise performance. The timing offset will be less than 50 nanoseconds with respect to the complex master clock. This distribution will be via single mode fiber optic cables buried five feet underground in order to greatly attenuate the diurnal temperature deviations and the resultant 100 MHz phase shift fluctuations[1].

For the DSN, JPL is currently developing new frequency standards for use in the future. These are the Linear Trapped Mercury Ion Frequency Standard (TIS) and the Superconducting Cavity Maser Oscillator (SCMO) currently being developed under the NASA Advanced Systems Program at JPL. The performance of the two Trapped Ion research and development units is approaching the short and medium term performance of the existing Hydrogen Masers and the long term performance (Tau greater than 10,000 seconds) is better than the Hydrogen Maser[2]. FTS engineering is currently discussing building four of these for implementation in the DSN over the next five years. The SCMO short term Allan Deviation and Phase Noise performance have been measured and are much better than anything available today[3]. A combined frequency standard combination of TIS and SCMO would produce short term and long term Allan Deviation and Phase Noise performance better than the Hydrogen Maser[4]. The TIS will reduce the clock drift with respect to UTC, thereby reducing the number of frequency adjustments per year from 2–3 to less than one. The Cassini mission to Saturn ground support FTS performance requirements today are barely met using Hydrogen Masers. We expect these to become tighter in the future and expect to need the combined TIS and SCMO frequency sources.

SUMMARY

Four of the above timing systems use Cesium Beam Frequency Standards and two use Hydrogen Maser Frequency Standards. Both meet the requirements for the particular project. Three of the six systems use triple redundant clocks, all with majority voting capability. GPS and LORAN–C are the two time synchronization methods. LORAN–C is utilized at three locations, which are within ground wave range of a local LORAN–C station. The GPS common view method is required for one global long baseline system with a 50 nanosecond timing and 3×10^{-13} frequency knowledge specification. The balance use GPS satellite time thus meeting the performance requirements.

ACKNOWLEDGEMENTS

The work described in this paper was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors appreciate the information and help contributed by Robert Price of AlliedSignal Technical Services on VLBI and Richard Flamm of Lockheed Communications Design and Development on the Kennedy Space Center Timing System.

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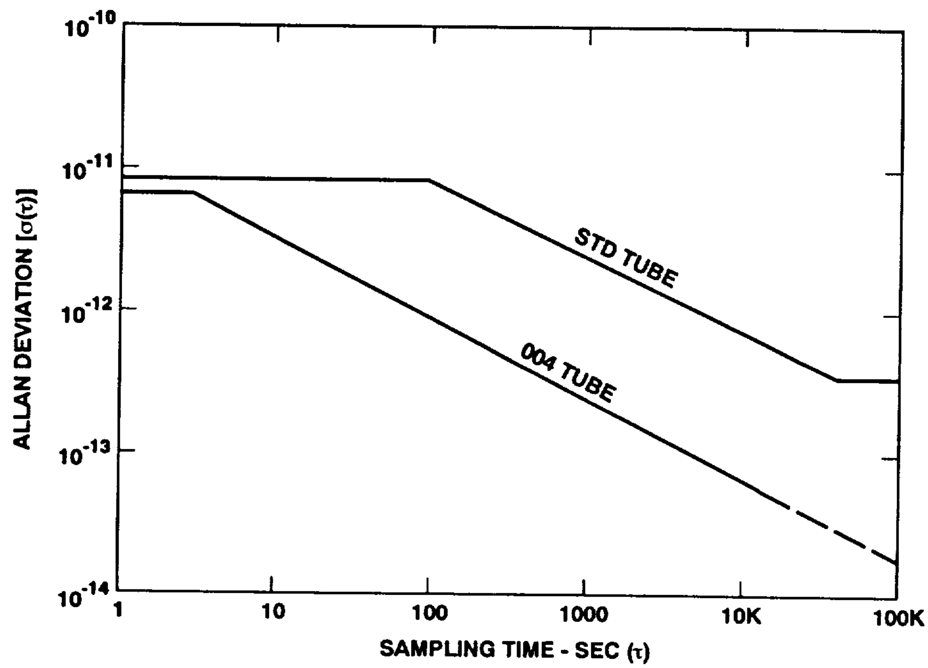

Figure 1. Allan Deviation HP 5061 Cesium Beam Frequency Standard

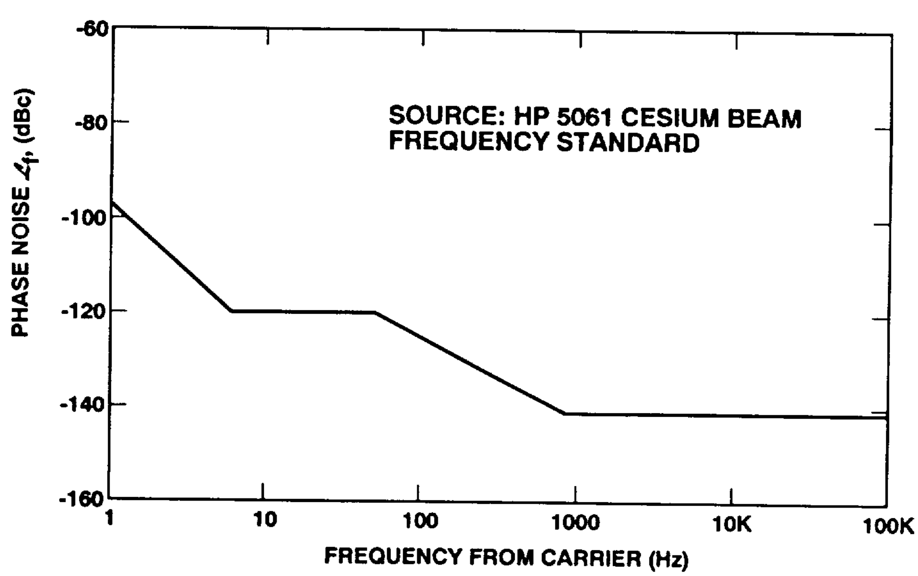

Figure 2. Single Sideband Phase Noise in a 1 Hz Bandwidth at 5 MHz

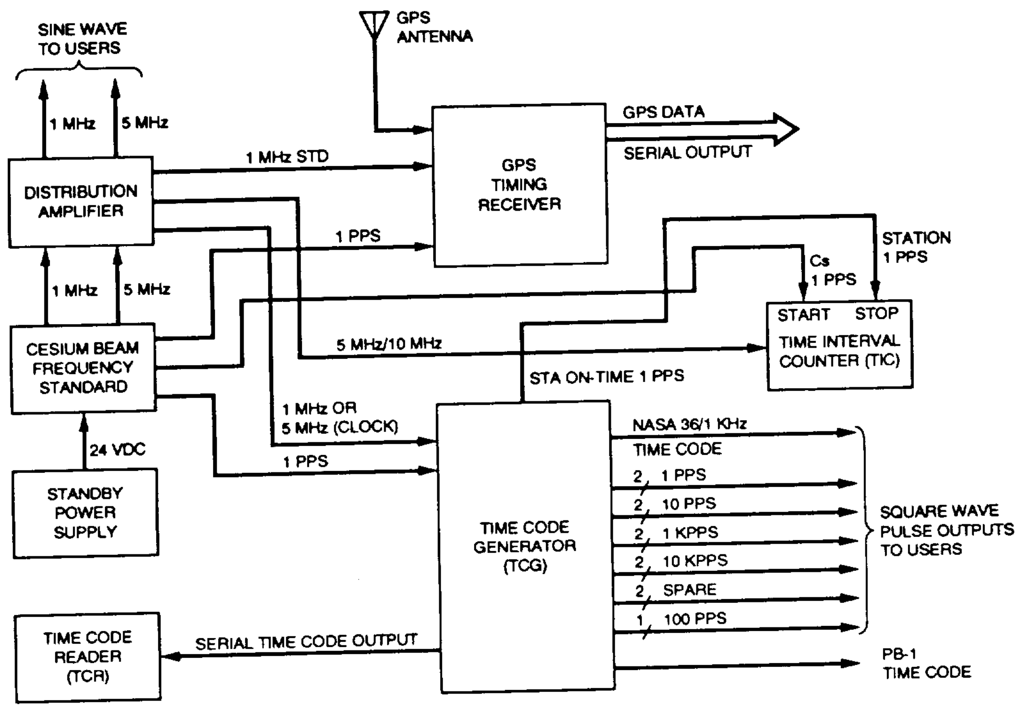

Figure 3. NSLR Timing Equipment

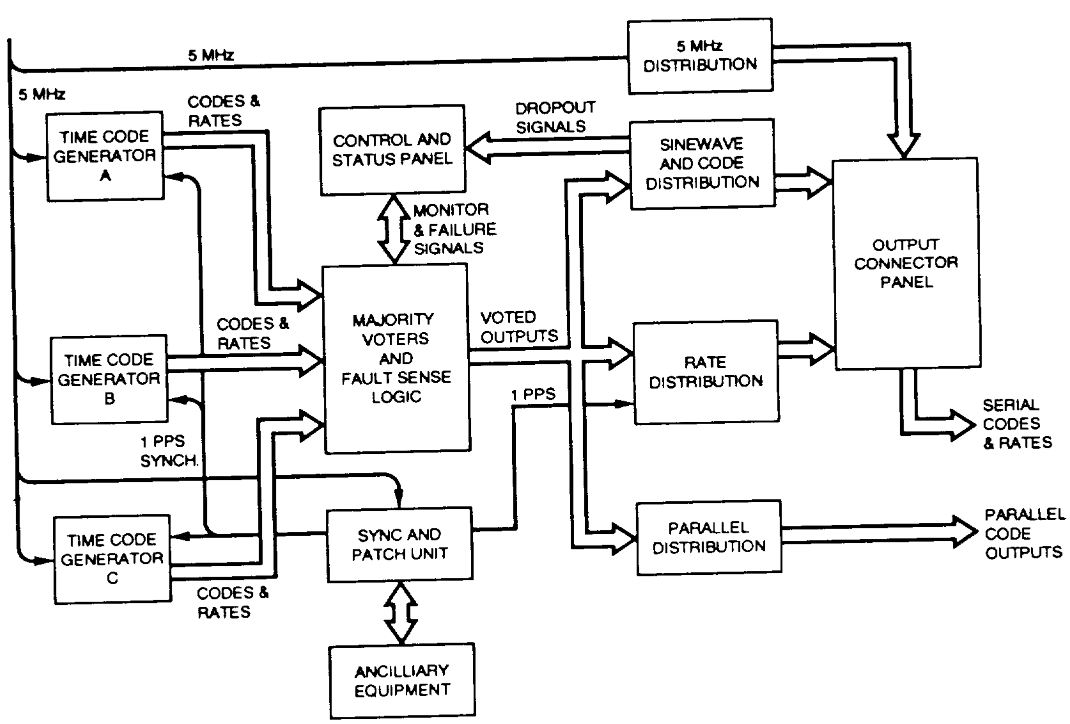

Figure 4. TRAK 8407 Triple Redundant Clock

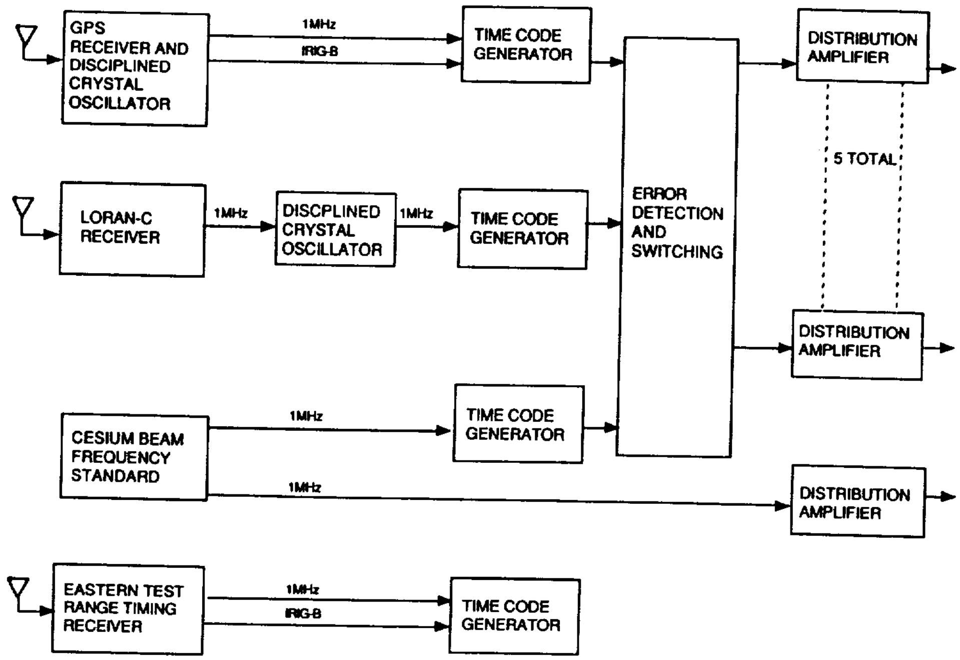

Figure 5. Kennedy Space Center Central Timing System

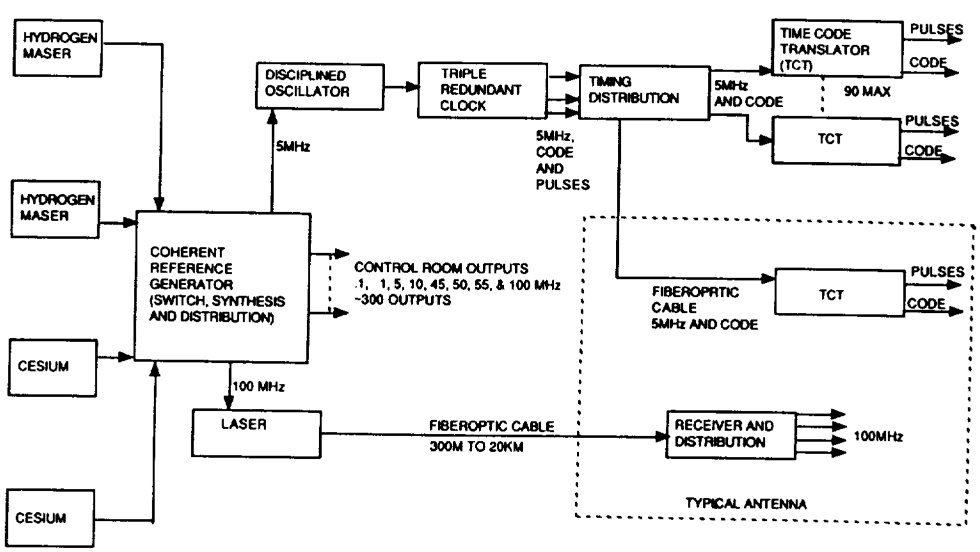

Figure 6. Deep Space Network Complex Frequency and Timing

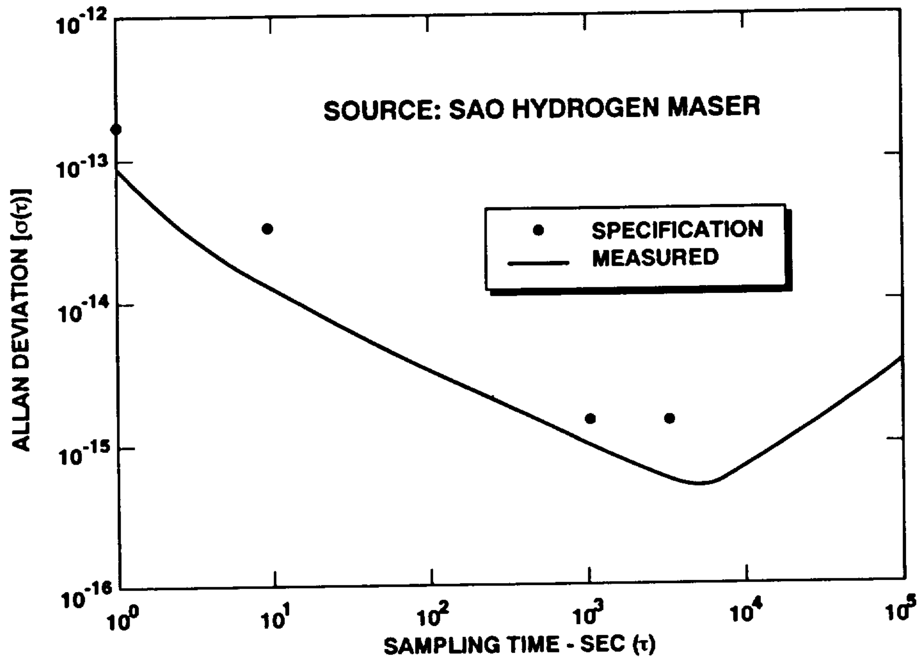

Figure 7. Allan Deviation at the Antenna

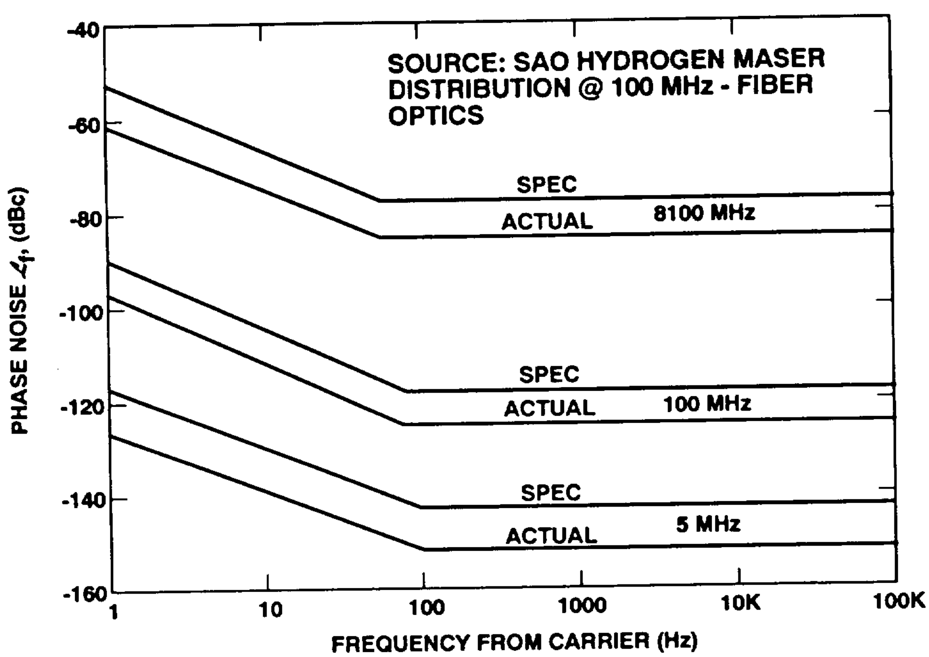

Figure 8. Single Sideband Phase Noise at the Antenna

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Time and Frequency Technology at NIST

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Abstract

The state of development of advanced timing systems at NIST is described. The paper presents work on cesium and rubidium frequency standards, stored-ion frequency standards, diode lasers used to pump such standards, time transfer, and methods for characterizing clocks, oscillators and time distribution systems. The emphasis is on NIST-developed technology rather than the general state of the art in this field.

1. Introduction

At an earlier meeting in this series I presented a paper which provides a concise outline of the activities of the NIST Time and Frequency Division[1]. See that paper for details of these programs. This paper focusses on subsequent developments and special issues which, in my judgement, might be of interest to this meeting. I divide the paper into sections on frequency standards (atomic clocks), time transfer, and characterization of components and systems.

2. Frequency Standards

2.1 Cesium Frequency Standards

The most substantial advance made by NIST in this area is the development of NIST–7, an optically pumped, cesium–beam frequency standard[2]. The design goal for this standard was an accuracy of 1×10^{-14}. At this date it has been evaluated to an accuracy of 2×10^{-14}, and all indications are that the full design accuracy will be achieved shortly. With very low beam flux (low oven temperature) the short–term stability has been demonstrated to be 6×10^{-13} at 1 second, a short–term stability better than that of any previous cesium–beam standard. The standard achieves its short–term stability through the more–efficient use of beam atoms afforded by the process of optical state preparation. The excellent short–term performance simplifies the evaluation of systematic uncertainties, since the standard's output averages down to well below 1×10^{-14} in a few hours. This standard will contribute significantly to the rate of coordinated Universal Time (UTC) as maintained by the Bureau International des Poids et Mesures.

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2.2 Stored–Ion Frequency Standards

Looking further to the future, NIST is developing a mercury–ion frequency standard using a linear trap design[3]. The trap design is related to that used by the Jet Propulsion Laboratory (JPL) in their successful development of a standard with exceptional short–term stability[4]. However, the NIST work differs from the JPL work in that NIST uses a smaller number of ions (50 to 100) located along the axis of the trap. With laser cooling to the millikelvin region, these ions experience exceedingly small perturbations, so that systematic errors should be controllable at a level well less than 1×10^{-16}. Trapping, cooling, and optical detection of the 40.5 GHz clock transition have been demonstrated, and we are now initiating study of the accuracy of the prototype standard. Earlier studies on a beryllium–ion standard indicated an unexpected shift arising from collisions between the stored ions and background gases in the trap[5]. To minimize such effects, the linear–trap experiments will use cryogenic cooling to reduce the background pressure to much lower levels.

2.3 Rubidium Frequency Standards

NIST[6] and others have been studying methods for improving the performance of rubidium frequency standards. Theory suggests[7] that replacing the spectrally broad, discharge lamp with a line–narrowed diode laser should substantially improve rubidium performance.

2.4 Quartz Oscillators

NIST does not have a major program on quartz oscillators but, in a small cooperative project, is looking at the question of flicker–floor noise limits in quartz devices[8]. This involves modelling and experiments designed to test the models. Environmental sensitivities of quartz oscillators have also been studied[9].

2.5 Diode Lasers for Advanced Frequency Standards

Emerging methods for laser–controlling the motions and quantum states of atoms and ions will have a dramatic impact on future frequency standards. Cesium–beam standards are reaching accuracy limits imposed by the Doppler effect and short observation times. These fundamental limits are removed when atoms and ions are cooled to very low temperatures. Recognizing the importance of lasers to future standards, NIST has initiated a program[10] to develop lasers that are suitable for use in frequency standards. Fortunately, during the last decade, simple, reliable diode lasers have emerged to play a role in a variety of commercial products. These diodes fit most of the requirements for application to future freqnency standards, except that the spectral purity of their output radiation is poor. Key aspects of the NIST program include line–narrowing of the output of the diode lasers, accurate control of their frequency tuning, and extension of their frequency coverage to spectral regions of importance to specific standards. The hope is that this program will produce lasers that are both simple and reliable and thus useful in the construction of both primary frequency standards and practical field standards.

3. Time Transfer

3.1 Two–Way Time Transfer

Two–way, time–transfer experiments between the U.S. and Europe will be performed during the next year. NIST, USNO, and a number of laboratories in Europe are collaborating to demonstrate this concept which uses telecommunication satellites. Two–way time–transfer experiments are described in greater detail in a number of other papers at this meeting. The potential accuracy of this technique is substantially higher than that of GPS common–view time transfer, but this is obtained at the price of broadcasting a signal from each of the comparison sites. Such broadcasting requires additional equipment and special licensing. NIST is also completing development of a new spread–spectrum modem for use in two–way time transfer. The NIST modem differs from existing two–way modems in that bandwidth and chipping rate are adjustable over broad ranges. The objective is to vary operating conditions so as to achieve high performance at minimum cost (for use of the communication channel).

3.2 Digital Time Codes through Telephone

Following the development of a digital telephone time service in Canada[11], NIST developed a related but different service called the Automated Computer Time Service (ACTS)[12]. These telephone services can be used to set time in computers to an accuracy approaching 1 ms. To achieve this accuracy requires a two–way process which calibrates the delay in the telephone link. The NIST service differs from the Canadian service in that the correction is developed at the delivery end rather than at the user's end of the connection. A very large number of applications can be served inexpensively through such services.

3.3 Digital Time Codes through Computer Networks

The telephone connection can be handled in a very predictable fashion, since the delay for a given connection remains very stable over a long period. This is not the situation for package–switched computer networks, but the need for delivering reasonably accurate time through such networks is high. Levine, in a paper in these proceedings, describes a method for handling this problem and a new network time service offered by NIST.

4. Characterization of Components and Systems

4.1 Measurement of Spectral Purity

Specifications of spectral purity (phase and amplitude noise) have been rising in importance during the last decade. While commercial instrumentation has been developed to meet some of these needs, there have been no central standards available to certify the performance of such instrumentation. NIST has thus developed capability for making highly accurate measurements of both phase noise and amplitude noise over a broad dynamic range. Measurements can be made at carrier frequencies from 5 MHz to 75 GHz at Fourier frequencies up to 1 GHz or 10% of the carrier frequency (whichever is smaller) from the carrier. The NIST measurement system supports evaluation of all measurement errors. Transfer standards operating at carrier frequencies of 5, 10, and 100 MHz have also been developed to support round-robin testing among laboratories. Transfer standards for 10, 20, and 40 GHz are nearing completion.

4.2 A Measure for Time Transfer Performance

The Allan variance and the modified Allan variance have been with us for many years but, while they are very useful in characterizing clocks and oscillators, they fail to provide an adequate measure of the performance of time transfer systems. Thus, NIST has developed a third measure, the time variance, which fills this need[13]. This new variance, a simple modification of the Allan variance, has been accepted as a standard by the telecommunications industry and by both the Telecommunication Standardization and Radio-Communication Sectors of the International Telecommunications Union (ITU). The additional development of a digital-filter view of all of these two-sample variances[13] has substantially aided in their acceptance by a broader segment of the technical community.

5. Summary

Over the last decade, advances in time and frequency technology by NIST and a large number of other organizations in the United States and elsewhere have been substantial. This paper has presented only those contributions made by NIST. The reader must integrate these with the much larger body of advances made worldwide to complete the picture of progress made in this field. The work reported here is that performed by many different staff members of the NIST Time and Frequency Division.

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QUESTIONS AND ANSWERS

Nicholas R. Renzetti, JPL: Based on the physics of the trapped mercury ion, what do you believe is achievable in terms of stability over time periods of several thousand seconds?

Donald Sullivan: Understand that what we are looking for is real long-term stability because of our approach. I think the stability of 1000 seconds will look much better from a device that is developed at the JPL. We are looking at hopefully a part in ten to the fifteen, a part in ten to the sixteen long-term. But I don't believe that we will achieve that at 1000 seconds. I think that is something that you need to look at with devices that have may more ions than the ones we are looking at. So our focus is dramatically different from that of the JPL.

Nicholas Renzetti: Well one reason for the question is that a distinguished member of the faculty of Cambridge University said that the inherent accuracy or stability would be a part in ten to the twentieth. Does that ring any bell with you?

Donald Sullivan: It doesn't ring a bell with me. Actually I don't know of any fundamental physical reason that limits us at all. It is a practical thing. The mercury ion is limited by the fact that we probably have a line with the width of one hertz at 10 to the 15 hertz for the optical transition; and we sort of believe that we can take care of all the systematics at that level. But there is no reason to imagine that the physics at this stage is limiting us. There may be things that I don't know about that he's mentioning, but I haven't heard the part in ten to the twentieth.

Nicholas Renzetti: Well what is driving this question is, we are involved in the search for gravitational waves. And we want to have a fairly long time period for the radio signal to go to the spacecraft and return to earth to capture more of space, through which a gravitational wave will pass. And that is the reason for driving these requirements.

Donald Sullivan: At 1000 seconds, I would be more willing to believe that the cryogenic hydrogen maser has a better chance in the long term than anything I know of. But there are many competitors. I think that the JPL work is pushing the hydrogen maser, but the hydrogen maser has a chance to make a quantum leap forward with the cool devices. That may be, for that type of experiment, the most important standard.

N94-30642

EUROPEAN PTTI REPORT

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Abstract

Time and Frequency Metrology in Europe presents some peculiar features in its three main components: research on clocks, comparisons and dissemination methods, and dissemination services. Apart from the usual activities of the national metrological laboratories, and increasing number of cooperation between the European Countries are promoted inside some European Organizations, such as the ECC, EFTA, EUROMET, WECC, that will be dealt witH in what follows. The present, evolving situation will be further influenced by the recent political changes in Eastern Europe.

1 Introduction

Despite a continental wide period of depression, Time and Frequency activities are well and alive in Europe, in all its three components: research on clocks, comparisons and dissemination methods , and dissemination services. In other terms the European laboratories accepted the struggle with the ubiquitous GPS and are trying to explore new avenues. The scope of this paper is to present a report on these activities, pointing out the practices or solutions that are peculiar to a developed continent that must cope with changing political and economical realities. Also technical or organizational aspects that are not alike to the practices followed in the States will be pointed out.

In the second section, with charts and graphs the distribution of all these activities over Europe is considered, along the selection criteria adopted.

Research on atomic clocks and related devices is presented in the third section, following two guide lines, the type of institution involved and the kind of research performed.

Section 4 – dealing with research on dissemination systems – sees three major items: a relevant series of ONE-WAY and TWO-WAY experiments, the research on the so-called marginal effects on GPS time comparisons, such as ionospheric and tropospheric effects and a continuing effort of the laser or optically based experiments for time dissemination.

Dissemination activities are presented in section 5. Two are the items of interest, one is in the realm of the well known distribution services – frequency standard and time signal emissions, time codes, and so on – , the other consists in the certification of "external" or industrial Laboratories.

Section 6 brings some news about the activities on time scale formation.

Information too has to be disseminated in a number of ways, as it will be seen in section 7.

In the last section, an exercise in summarizing the situation and in forecasting the future will be attempted, also taking into account the political changes occurring in the Continent.

Since this paper is a general survey, relevant bibliography will not be appended . The reader interested in the various technical topics, is referred to some Transactions or Proceedings of a number of devoted Symposia[1,2,3] and reviews[4,5].

2 ORGANIZATIONAL ASPECTS

Presenting a report on the PTTI activities in Europe, the concept of Europe itself has to be defined. For the recent political and economical changes, also the organization aspects has changed dramatically or are in progress to be modified.

While for the Western Countries general information is available or can be guessed, for Eastern Europe the past and the present situation is known with a far lesser extent. This fact is obviously reflected in this report . Data presented here were mostly deduced by personal acquaintances, visits, or, as it will be seen, by inspection of the literature. Omissions, errors or faulting guesses, of which the authors only will be responsible, will be undoubtedly traced.

The acronyms used are spelled out in the Annex, but some, more important will be now introduced in Table I.

TABLE I

EEC	European Economical Commission, an organization with economical and political scopes; most of the Western Europe Countries are members of EEC. It is planned that the political implications of EEC will increase with the time.
EFTA	European Free Trade Association, an organization with economical scopes only.
EUROMET	European Metrological Organization assuring collaboration in measurements standards, secures a common metro- logical basis for all the activities of:
WECC	Western European Calibration Cooperation, is an structure assuring the mutual recognition of calibration certificates between both EEC and EFTA Members.

This somehow complicated structure is needed in order to assure the uniformity of calibration criteria and standards for the obvious economical consequences.

The running of all the EEC and EFTA machineries is not an easy task; to give an example: in the history–laden Europe, there are twelve principal languages and six others have a recognized status, also EEC has only four official working languages.

Time and Frequency research is performed in:

- National Metrological Laboratories,
- National Research Laboratories, devoted to one specific topic (this is specially the case of France),
- Universities,
- Laboratories inside industries.

As regards to the National Metrological Laboratories, Europe is well equipped, as depicted in Table II, in which the Countries active now in the PTTI realm are listed in three groups depending on the period of the institution of their Metrological Laboratories.

For National Metrological Laboratory it is meant a State–supported institution performing on regular basis at least some of the four following activities:

- research on frequency standards,
- construction of a time scale
- research or activity on comparison and dissemination methods and systems,
- dissemination or calibration services.

TABLE II

around or before 1935	1950 -1980	around or after 1990
FRANCE OP - LPTF	CZEKOSLOVAKIA URE	DENMARK
GERMANY PTR - PTB	NETHERLANDS VSL	FINLAND
ITALY IEN	SWEDEN FOA	IRELAND
U.K. NPL	SWITZERLAND ON	PORTUGAL
	USSR VNIIFTRI	SPAIN

Some Countries, in particular France, has set an array of State–supported Laboratories via the national research Councils, usually linked to an University and devoted to a specific topic. For instance, are the well known L.H.A. (Laboratoire de l'Horloge Atomique), linked to the University of Paris–Sud and the L.P.M.O. (Laboratoire Physique et Metrologie des Oscillateurs).

Similarly, a few astronomical Observatories are engaged in research on frequency standards or in timing experiments, such as ON, the Observatoire Cantonal de Neuchatel, in Switzerland or OCA, Observatoire Côte d'Azur in France.

A great deal of activity is performed inside Universities, mostly on frequency standards and in a few cases – Austria (TUG), Germany (Stuttgart), Italy (Politecnico Torino), U.K.(Bangor and Leeds) – also in dissemination and comparison methods.

Finally, the PTTI research in Industry, even if some remarkable examples are available, is less of what is observed in the United States. Nevertheless in Russia at least two industrial concerns are manufacturing in series Hydrogen Masers and Cæsium beam standards, but the specific research activities and the number of researchers involved can be speculated only.

A special case in Europe is that of BIPM, the Bureau International des Poids et Mesures with seat in Paris; belonging this Bureau to and international 0rganization based the international Treaty signed in 1875 during the "Conference Diplomatique du Metre", its researchers and activities, in what follows, are not considered or if taken into account, a mention is given. By the way, BIPM is very active, as can be derived also from the program of this 25th PTTI Meeting, in which it is involved in at least five papers in Time Scale formation and on comparison methods.

With this limitation regarding BIPM, an attempt was made in order to deduce, at least approximately, the "work–force" engaged in PTTI activities in Europe, with the additional exception of the researchers working in military institutions, in Industry and in the Russian Labs.

The total amount is of about 130 people. About 50 are active in France (LPTF, LHA, LPMO, OCA, CNET, CNES and Universities); about 30 are estimated to operate in Germany (PTB, FTZ, MAX–Plank Institute, and an host of Universities). About 20 in Italy (IEN, IMGC, ISPT, and some Universities) and about the same figure can be credited to U.K., taking into account NPL, RGO, NAMAS and some Universities.

To investigate about the "productivity" and types of interest a bibliographical research was performed, by examining all the papers that in the last seven years, from 1987 to 1993 inclusive, were presented at :

- EFTF – the European Forum on Time and Frequency,
- FCS – the Frequency Control Symposium -, and at
- PTTI – the Precision Time and Time Interval Meeting,

or that appeared on:

- Metrologia and the
- Transactions of the IEEE Society on Instrumentation and Measurement.

For the two reviews obviously the analysis was limited to the available printed material.

At attempt was made to search also on Istmeritelnaia Technica and Radiotecnika i Electronika but the information gathered was not homogenuous, as time span, with the other sources; consequently data concerning the former USSR is not included.

The temporal window starts with 1987, when the first EFTF was held in Besancon in 1997.

This approach sounds very "academic", but it was felt adequate to gain a global idea of the amount and of the type of activities; of course all the five sources have a scientific committee operating a selection of the papers presented.

The total amount of papers prepared in European Labs in the seven years considered, in the domain of Time and Frequency and following the abovementioned selection criteria, is of some 520 titles, 15 of which coming from BIPM; the trends about the number of papers and the meetings of presentation, are presented in Fig.1 and Table III.

3 RESEARCH OF FREQUENCY STANDARDS AND CLOCKS

Using the data base of the previous section, an inquiry was made about the subject of the research and the kind of Laboratory involved, following the four types previously illustrated, i.e. National Standards Laboratory, national research laboratory dedicated to one specific topic – Astronomical Observatories included – , Universities and Industries.

The results are gathered in Table IV and Fig.2.

Over about 160 papers, near half are devoted to cæsium devices, traditional, optically pumped, fountains, etc.

This figure reflects the strong European involvement in the standard that embodies the SI definition of the second. Nearly 25 papers are dealing with the Hydrogen masers and the frequency stabilization of lasers, not so much as frequency standards, but as length standards or references.

More in detail, in the national Laboratories, in England the cæsium fountain is studied, in France to the fountain research an evaluation of an optically pumped cæsium beam was recently performed. Future activities are planned toward atomic clocks to be operated on microgravity conditions. Germany has built two vertical cæsium beams and some ion traps. Finally, in Italy, the final evaluation of the Magnesium beam standard was recently presented and a research activity was initiated on non–conventional cæsium beam frequency standard.

Of some interest is an effort of support and coordination launched by the European Community in the field of the cæsium devices. The responsibility of this activity was given to Politecnico di Torino. The aim of this effort is a coordination of the European laboratories, also via a support of researches mobility. England, France, Germany, Italy and Switzerland Labs joined in this effort.

As regards the kind of Laboratory, out of 165 papers, about 55 were prepared at National Metrological Institutes, about 65 at National research laboratories or Observatories, 30 in Universities and the last 10 ones in the industrial laboratories.

4 RESEARCH ON COMPARISON AND DISSEMINATION METHODS

Using always the data base introduced at point 3 a survey was performed about the papers on comparison, dissemination and other topics. The results are given in Fig. 3. Over 350 papers, the interest is evenly divided between comparison, dissemination precise quartz standards and applications of time and frequency technology.

The differences between synchronization, comparison and dissemination are faint ones since the same basic methods or technology can be used for all the three operations.

For these latter operations, four are the main lines of activity.

For comparisons, the so-called "two-way method" via a communication satellite and laser time transfer via satellites, for time transfer, the GPS ultimate accuracy capabilities and the time distribution systems via telephone lines.

4.1 Satellite Time Transfer — "two-way method"

The two-way method is one of the basic tools of time and frequency metrology. This time proven method was rejuvenated about ten years ago, at the University of Stuttgart by Prof. F. Hartl with the use of pseudo-random noise codes. The equipment is called MITREX (Microwave Timing and Ranging EXperiment) and is commercially available.

Two kind of activities are performed.

From one side the accuracy capability of the method and of the equipment was investigated, in comparison with other methods such as GPS and, in one instance, with LASSO.

LASSO stands for LAser Synchronization from Stationary Orbit; this method will be dealt with during this Meeting.

In the case of a comparisons with GPS, an experiment performed for about one year gave evidence that the time transfer results differ for about 3 ns, but a seasonal variation of about 8 ns was discovered.

This variation is possibly due to temperature-dependent delays in the GPS receiving equipment used.

The second activity about the two-way method lies in a program of mutual time comparisons between European Metrological Laboratories in Austria, France, Germany, Italy, the Netherlands, and United Kingdom. In one experiment, performed in August 1993, for the first time up to six stations took measurements at the same time; insofar the method was been used in bilateral or trilateral time comparisons.

For the researchers interested in this topic, NPL (National Physical Laboratory, Teddington, U.K.), has organized a periodic Newsletter[1]

Another satellite-related activity was a series of experiments on the one-way time comparison method, using the direct TV emissions from satellites. This method seems not used in the States.

The first experiment, on ECS satellites, started in 1988 and was coordinated by the IEN-Italy in the frame of a EUROMET project with the participation of eight European laboratories.

It was followed in 1991 by another one led by the NPL-U.K., joined by three other British

[1]Two-Way Satellite Time Transfer Newsletter, c.o. Dr. J. Davis, NPL, Teddington, Middlesex, U.K. TW11 0LW, fax +44 81 943 6452.

Laboratories and using two DBS (Direct Broadcasting Satellite), ASTRA and BRITSAT.

The last experiment to date has taken place in France between four Labs – Observatoire de Besançon, Observatoire de Paris, CNES/Toulouse, CERGA/Grasse – using TDF2 satellite.

All these direct–TV experiments aimed to demonstrate the utmost capabilities of the method for time and frequency comparisons and distribution over short and long baselines; a major effort has been done in reducing the synchronization error related to the position variation of the geostationary satellites.

This has been achieved exploring different ways to collect the results of the effect of the longitudinal drift of the satellites. It has been demonstrated that a synchronization precision from 10 to 100 ns, correcting for the satellite positions, are achievable.

4.2 Time comparison with laser techniques via geostationary satellites

This method was proposed to be tested on board of the Italian satellite SIRIO2, but a launch failure prevented any measurement. Later the experiment was successfully tested with the ESA satellite METEOSAT–P2 both inside Europe, between Austria and France, and later across the Atlantic Ocean.

This specific topic will be covered extensively during this Meeting by Veillet and Others.

At any rate it is worth mentioning that the European Space Agency decided recently to start a feasibility study involving spaceborne timing via lasers.

4.3 Extracting the utmost accuracy from GPS

The error budget of a time comparison or time dissemination via GPS or GLONASS satellites has a large number of entries, that can be gathered in a number of classes. For a time–minded user's stand point, the most important classes are the way to collect and treat the data, the position of the antenna, the equipment delays and their variations with time and temperature, and the propagation effects.

Quite a trust in these researches come from the BIPM, the Bureau International Poids et Mesures, in Paris and a great deal of research and experiments was performed at the BIPM itself in the recent years; the developments of this research was well covered in the past PTTI Meetings, mostly about the treatment of data and the influences of poorly known antenna coordinates.

These problems having been solved or identified, the interest is now on the propagation phenomena, boot in ionosphere and in troposphere and on the study of the equipment delays.

First results on these new lines will be presented during this 25th PTTI Meeting.

A better knowledge of ionospheric delay variations, was promoted by the possible use of the GPS system for the "precise" navigation of scientific satellites.

While some spacecraft, such as Earth observation satellites, are well above the ionosphere, other missions, such as the ARISTOTELES satellite of ESA are planned to be inserted in orbits well below the bulk of the ionization of the atmosphere.

4.4 time dissemination via modems and telephone lines

Also in Europe, telephone services provide time and date information. These services find widespread use, and their characteristics, the services provided and their use inside the national calibration schemes are described in the next point of this report.

5 DISSEMINATION AND TRACEABILITY

5.1 Dissemination

A major difference between Europe and the USA lies in the fact that in Europe a large share of the dissemination services is performed via dedicated or broadcasting stations operating in the LF and MF bands, between 50 kHz and about 1600 kHz.

Stations performing Time and Frequency dissemination services only are listed in Table V.

TABLE V

STATION	CALL SIGN	NATION	FREQUENCY kHz
PODEBRADY	OMA	CZECH Rep.	50
RUGBY	MSF	U.K.	60
PRANGINS	HBG	SWITZERLAND	75
MAINFLINGEN	DCF77	GERMANY	77,5

These stations emitstandard frequencies, time signals and time codes.

In the same LF band are operating seven LORAN-C stations that are used in some cases as frequency and time references. On the same line are to be mentioned the six stations of the CHAIKA system operating in the former Soviet Union.

A number of broadcasting stations disseminate standard frequency, time signals and time codes providing a widespread coverage.

For example the French station FRANCE INTER, located in Allouis, radiates on LF a standard frequency with the carrier and a time code via a suitable slow rate phase modulation on the carrier itself.

In Italy, since 1979, also the FM emissions on VHF band are used to disseminate timing information. At the moment, about 1500 FM transmitters broadcast a time code, giving a complete date information (year, month. day of the month, day of the week, hour, minute and second, plus additional information about the legal time) 25 times per day. This particular service is used by a large amount of users, for a wide range of applications, from automatic clock setting to the electrical power plants dispatching. This time code is also used in automatic devices to discipline remote oscillators. Using standard FM emissions, it was demonstrated that a frequency traceability within a few units in 10^{-10} can be achieved.

On the other end, the time proved dissemination services operating on HF bands were in practice discontinued in the last years, with the exception of the Russian transmitters operating at 10 and 15 MHz and one station in Italy, IAM, active on 5 MHz.

A peculiar service is provided via telephone lines, with time codes giving a complete time and date information, mostly for the PC synchronization. This service, born from a cooperation of four metrological Laboratories of Austria, Sweden, the Netherlands and Italy, has been an attempt towards a standardization of the format for Europe. These services can be used also from the USA, via telephone modems.

These telephone services were first implemented at the Technical University of Graz – Austria – in 1988 and subsequently in Sweden (1990), in Italy (1991) and are planned, using the same code, to be in operation in the near future in Germany, the Netherlands and in the United Kingdom.

5.2 Traceability

In many European countries, the national metrological laboratories operate calibration services consisting of high level calibration laboratories, independent or included in large companies or educational institutions.

These laboratories are accredited for the dissemination of the SI units while the national primary laboratories operate a surveillance program to verify their traceability. This assures the confidence level of the calibration system and allows to recognize a technical equivalence between the calibration certificates issued by the primary laboratories and the accredited laboratories, apart from their different uncertainties levels.

As regards time and frequency, table VI lists the number of accredited centers in the different countries updated at 1993, while in table VII are reported the different links used for the traceability to the primary laboratories.

TABLE VI

NATION	CALIBRATION SERVICE	NUMBER OF ACCREDITED CENTERS FREQUENCY	TIME INTERVAL
DENMARK	DANAK	5	5
FINLAND	FINAS	7	2
FRANCE	FRETAC	32	4
GERMANY	DKD	13	6
IRELAND	ILAB	3	3
ITALY	SIT	12	-
NETHERLANDS	NKO	16	10
PORTUGAL	IPQ	4	-
SPAIN	SCI	4	2
SWEDEN	SWEDAC	5	5
SWITZERLAND	SCS	8	1
U.K.	NAMAS	32	7

Out of the 17 Accreditation Services of the European Economic Area, 12 are consequently operating Time and Frequency Calibration Centers; 141 Centers are accredited for Frequency measurements, with uncertainties ranging from 1×10^{-9} to 1×10^{-12}, and 45 for time interval measurements.

TABLE VII
SOME OF THE METROLOGICAL LINKS USED FOR TRACEABILITY IN SOME CALIBRATION SERVICES

SERVICE	TV METHOD	GPS	HBG	DCF	MSF	BROADCAST
DANAK				X		
DKD				X		
FINAS	X					X
FRETAC	X	X	X	X		X
NAMAS					X	
NKO	X	X		X		
SCS			X	X		
SIT	X	X				X

Information given in Tables VI and VII is believed to reflect the situation at the end of 1993.

To ensure that the criteria followed in one Country are accepted in another, the Commission of the European Communities has supported the mutual recognition of accreditation schemes between Community States Members and EFTA Members, an activity that is performed by the organization of the National Calibration Services in Western Europe, called "Western European Calibration Cooperation" (WECC). EUROMET, that is a European collaboration in measurements standards, secures a common metrological basis for the WECC activities.

At present, 17 Countries cooperate to build up and maintain mutual confidence between their calibrations services to reach a state of the mutual agreement on the equivalence of the Services and of the Certificates issued by the accredited laboratories.

In other words, a Calibration Certificate emitted by an accredited Laboratory in any Country is accepted in each Member State.

6 TIME SCALES

A meeting devoted to the algorithms to be used on Time Scale formation was held in Turin, Italy, in 1988; the relevant proceedings were printed by the NIST.

Research on this rather elusive topic gave, in the period considered, 22 papers, most of wich prepared at BIPM, since the formation of TAI is entrusted with this Bureau and at IEN. A book by Graveaud on this topic will be quoted in the next section.

7 INFORMATION DISSEMINATION

As regard the dissemination of information, France and Switzerland started seven years ago the organization of an European Frequency and Time Forum; about this succesfull annual conference a detailed report will be presented later during this 25th PTTI Meeting.

Italy is organizing periodically summer schools on Fundamental Constants and Metrology. The last one was held in 1989, with the participation of some fifty students, coming mostly from metrological laboratories. The courses are given in English and the teachers are leading experts in the various fields.

The relevant text are issued by North–Holland.

Four books, one of which prepared partially in Europe, appeared in the last years.

The first is the well known "The Quantum Physics of Atomic Frequency Standards" by J. Vanier and C. Audoin. The second – "La mesure de la Frequence des Oscillateurs" – by KRONOS; under this pen–name are some French colleagues (Audoin, Bernard, Besson, Gagnepain, Groslambert, Granveaud, Neau, Olivier and Rutman). Also in the French language is "Echelles de temps atomique" by M.Granveaud, on the algorithms and criteria of time scale formation. The last one, written in Italian by A. De Marchi and L. Lo Presti, – "Incertezze di misura"' – deals with the representation of noises both in frequency and in time domain and with the uncertainty in measurements; this topic is seen from the point of view of the theorist and from that of laboratory–minded researcher.

Finally are worth of mention two efforts of my University – Politecnico di Torino – in organizing, since twenty years a course on Time and Frequency Metrology and in establishing postgraduate courses in Metrology in general and on Time and Frequency in particular. These courses lead to a Ph.D. degree in Metrology, in a 3 to 4 years period. These courses are given in Italian, but also foreign students are admitted. At the moment completing their curricula, are one Chinese and two Mexicans.

The information above is limited to Italy because the authors are familiar with their national situation; possibly some other courses are held elsewhere in Europe.

8 FINAL REMARKS

A general remark is the fact that the European developed research finds no adequate industrial counterpart. Quite a deal of the research performed in the Universities remains at academic level.

The man–power and the allocated founds appear adequate to the size of the populations and industries to be served, but the necessity to respect national priorities involves sometimes a duplication of efforts.

One must be aware of the fact that in the past the "technical standards" were a "polite" form of protection for the factories of a Country. In other terms the "acceptable technical standards" played the role of customs.

Speaking of "duplication" a word of prudence is of order. While in calibration and applied Metrology services the amount of resources to be dedicated, at the end must be proportional to the market to be served, the situation is quite different as regards the fundamental Metrology. In this realm, where the accuracy of a device can be only estimated and not measured, "duplication" of efforts is needed for two reasons. The search of systematic unknown effects from one side and of new avenues to reach a specific goal from the other. These facts are not usually appreciated by the Administrators for wich a cæsium standard is always a cæsium standard.

The situation is dramatically improved in the last years with the adoption of common standards, procedures and with the mutual acknowledgment of the calibration certificates, as was considered in point 5.2.

In some circles the idea of an European Metrological Laboratory was ventilated, but it seemed a too bold step. The difficulties are psychological – the national pride –, technical – the different needs and levels of industries–, and economical – such as the different priorities given by one Country.

What can be done, and has been done, is a painstaking effort of coordination. In the realm of standards (not the devices, the calibration values and procedures) much was achieved.

In the sectors of comparisons and dissemination some results were obtained, as seen in point 5.

Also for the research on primary frequency standards, an initiative is under way, as mentioned in point 3.

But two mayor problems, one economical, the second political stand in front of the research on Time and Frequency in Europe, the first is in the limited amount of money that will be allocated in future, at least in some nations.

The second one, a major task indeed, awaits the European Laboratories in establishing cooperation plans with the metrological Laboratories of east Europe. Western European Labs were and are, to some extent, technology minded where in Eastern Labs, sometimes, the ingenuity was limited only by the available technology. A lot can be learned from both sides, in this cooperation and amalgamation process.

Another effort of organization to be attempted is a possible cohordination between the three annual Symposia : EFTF, FCS and PTTI. All three are very vital entreprises, but in a period of general shortage of resources, some considerations should be made about this topic, leading toward a sort of sharing in frequency or in time domain.

REFERENCES

[1] EFTF Forum Europeen Frequence et Temps - European Frequency and Time Forum

[2] FCS Frequency Control Symposium

[3] PTTI Precise Time and Time Interval Applications and Planning Meeting

[4] METROLOGIA Springer International, published under the Auspices of the International Committee of Weights and Measures

[5] IEEE Transactions on Instrumentation and Measurement, a publication of the IEEE Instrumentation and Measurement Society

ANNEX I	
ACRONYMS USED IN THE TEXT	
BEV	Bundesamt fur Eich–und Vermessungwesen, Wien, Austria
CNES	Centre National Etudes Spatiales, Toulouse, France
CNET	Centre National Etudes Télécommunication, Bagneux, France
DANAK	National Calibration service of Denmark
DKD	National Calibration service of Germany
FINAS	National Calibration service of Finland
FRETAC	National Calibration service of France
FTZ	Fernmeldetechnisches Zentralamt, Darmstadt, Germany
IEN	Istituto Elettrotecnico Nazionale, Torino, Italy
ILAB	National Calibration service of Ireland
IMGC	Istituto di Metrologia G. Colonnetti, Torino, Italy
INS	Istitute of Navigation, Stuttgart, Germany
IPQ	National Calibration service of Portugal
ISPT	Istituto Superiore Poste e Telecomunicazioni, Roma, Italy
LHA	Laboratoire de l'Horloge Atomique, Orsay, France
LPMO	Laboratoire Physique M‹sure Oscillateurs, Besancon, France
LPTF	Laboratoire Primaire Temps et Fr‹quence, Paris, France
NAMAS	National Calibration service of United Kingdom
NKO	National Calibration service of Netherlands
NPL	National Physical Laboratory, Teddington, U.K.
OCA	Observatoire Cote d'Azur, Grasse, France
ON	Osservatorie de Neuchatel, Neuchatel, Switzerland
OP	Observatoire de Paris, Paris, France
ORB	Observatoire Royal de Belgique, Brussels, Belgium
PKNM	Polski Komitet Normalizacji Miar i Jakosci, Warszawa, Poland
POLIMI	Politecnico di Milano, Milano, Italy
POLITO	Politecnico di Torino, Torino, Italy
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
RGO	Royal Greenwich Observatory, Herstmonceux, United Kingdom
ROA	Real Instituto y Observatorio de la Armada, San Fernando, Espana
SCI	National Calibration service of Spain
SCS	National Calibration service of Switzerland
SIT	National Calibration service of Italy
SNT	Swedish National time and Frequency Laboratory, Stockholm, Sweden
SWEDAC	National Calibration service of Sweden
TUG	Technische Universitat, Graz, Oesterreich
URE	Ustav Radiotechniky a Elektroniky CSAV, Praha, Ceskoslovensko
VNIIFTRI	National Metrological Laboratory, Mendelejevo, CIS
VSL	Van Swinden Laboratorium, Delft, Nederland

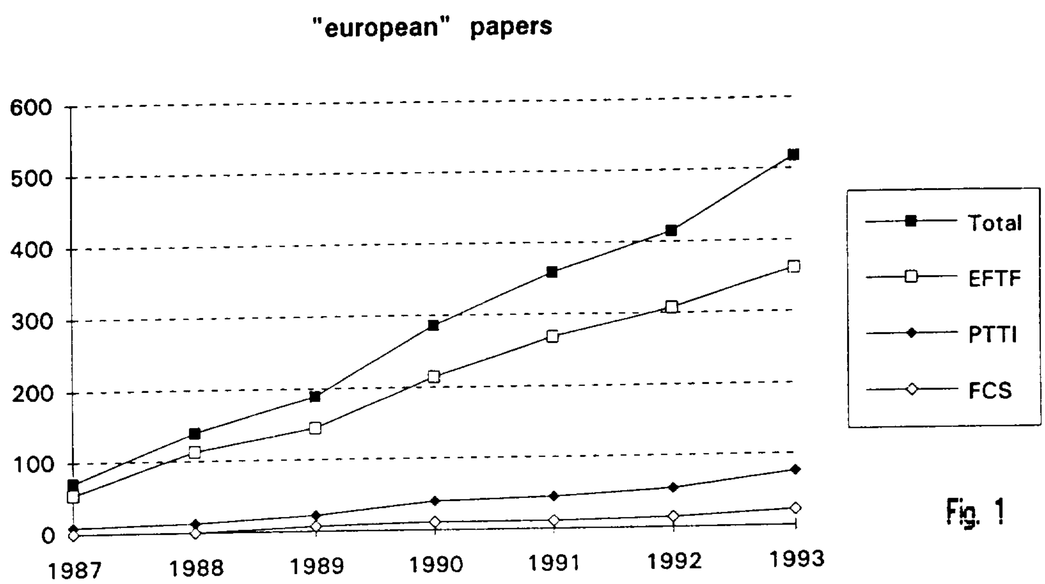

Fig. 1

PAPERS

TABLE III

Year	Total	EFTF	PTTI
1987	70	54	9
1988	138	113	13
1989	187	144	22
1990	284	214	40
1991	353	268	45
1992	409	307	54
1993	510	361	76

PAPERS ON ATOMIC FREQUENCY STANDARDS

TABLE IV

Year	Total	Caesium	Hydrogen	Rubidium	Ion trap	Laser	Magnesium
1987	17	8	4	0	1	2	1
1988	41	20	5	2	4	6	2
1989	52	27	5	2	4	9	2
1990	84	38	10	3	8	12	2
1991	117	52	18	6	8	20	4
1992	131	58	22	7	9	22	4
1993	165	74	28	8	10	28	6

papers on frequency standards

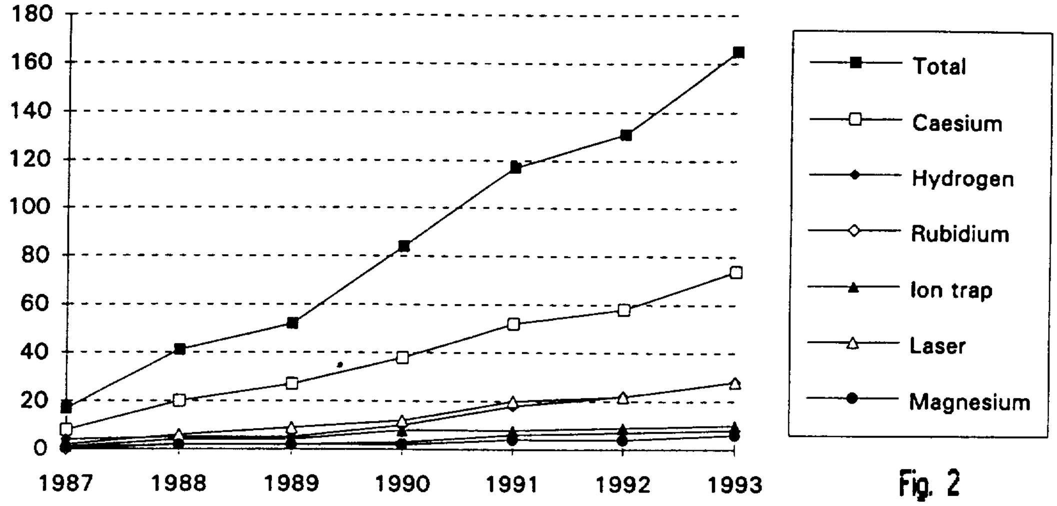

Fig. 2

PAPERS ON COMPARISONS AND DISSEMINATION						
Year	Total	applications	spectral purity	time scales	comparisons	dissemination
1987	36	6	2	4	6	3
1988	40	7	3	0	7	5
1989	41	6	7	1	3	12
1990	70	17	5	5	7	21
1991	41	0	3	1	12	12
1992	45	6	2	3	5	13
1993	73	4	1	5	24	15

papers on comparison and dissemination

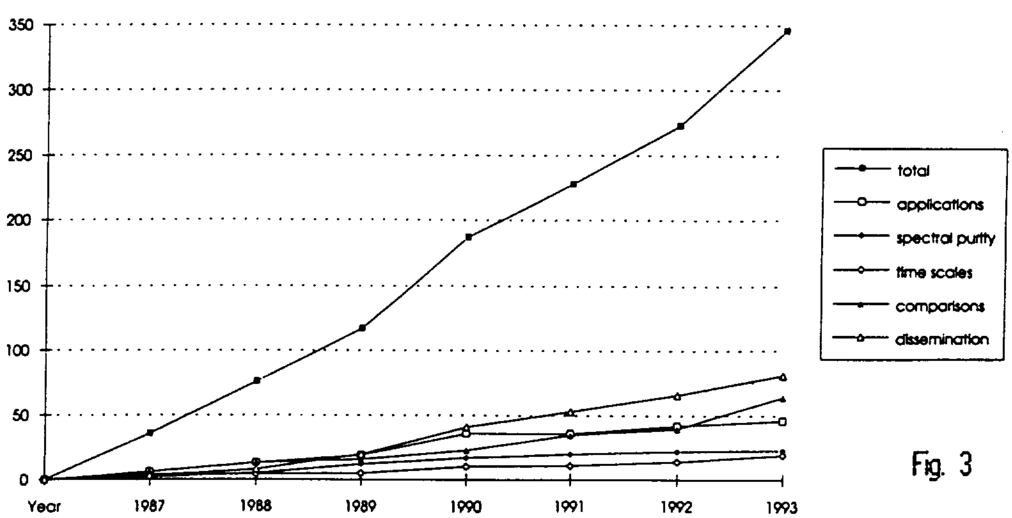

Fig. 3

QUESTIONS AND ANSWERS

Claudine Thomas, BIPM: I thank you, Professor Leschiutta, for mentioning the BIPM. But I think it is my duty to say again and to stress again here that the BIPM is an entirely environmental body and that we remain, as we have always been of course, at the service of all states that are members of the *Metre Convention*, or *Conservatoire de Metre* in French; and we have no particular relationship with Europe except with friendship because of the proximity, for instance, of the Paris Observatory. But that is all.

The other point is that you didn't mention a publication of the accuracy research of primary frequency standards which is operating at the Paris Observatory, the LPTF, the optical pumped primary frequency cesium standards which has been evaluated for one–second accuracy; and this accuracy has been published. It is not so good right now because it is only one part in ten to the 13 I think. But it has already been published in the BIPM security and maybe Metrology, I don't know. Thank you.

Professor Leschiutta: I thank you very much. But since I was rushing, I forgot to make some statement regarding this. All the papers prepared at the BIPM were not included in my calculations. As you will see in the text, I took account of the publication prepared at BIPM mostly on time–scale information and also recently on other topics. And you will find a precise order concerning that recognition. Obviously we are to some extent in Europe, stimulated heavily on the BIPM at home. But BIPM is an international laboratory in this situation.

WORKSHOP A: ENSEMBLE MANAGEMENT

Sam Stein
Timing Solutions, Incorporated

Goals:

- Deliver timing signals locally in real time
- Synchronization of remote sites
- Provide frequency and syntonization
- Maximize reliability and availability
- Deliver UTC

Performance Objectives

- Minimize the probability of doing harm
- Frequency stability improvement is of secondary importance
- Peak errors are more significant than RMS errors
- Outlier detection is critical
- Impact of frequency steering on users is not known

Operational Objectives

- 100% automation with operator oversight
- "guru" free operation
- Minimum probability of an out of tolerance event
- Facilities without gurus are not steering, but would like to

Needed improvements

- Ability to change phase with low noise
- Highly deterministic steering
- Independent intelligence in steering mechanism that returns to nominal on other failures
- Real time access to UTC with smaller errors

WORKSHOP B: USER/SUPPLIER COMMUNICATION

Martin B. Bloch
Frequency Electronics, Inc.

The consensus of all the participants was the folowing:

A. Early communication between the system designer and the hardware supplier will have significant improvement in cost and cycle time.

B. The use of off–the–shelf designs whch meet the environmental requirements must be implemented in the 1990's to be cost competitive.

C. Minimize bureaucracy that clouds the system requirements and significantly increases product cost. In order to achieve this objective, the following recommendations came out from the panel discussion:

1. Initiate additionel educational program through technical confrences or industry lecture series to improve the dialog between system designer, supplier, end user, and all of the support services (quality control, material processes, documentation).
2. Establish a cooperative spirit between industry, government, and universtities to meet the future challenge of components and subsystems for military, aerospace, and commercial end use.
3. Obtain data from existing clocks in satellites and timing systems used by the military in order to establish a history of long term performance.
4. Improvements in testing and testing methods in order to eliminate non–value–added tasks that have significant impact on cost and cycle time.
5. The use of off–the–shelf products for significant advantage both in cost and delivery, however, it is imperative thata clear understanding must be achieved between the user and the manufacturer to ensure that the environmental requirements are met.
6. Communication: The following areas have continuously created cost and delivery problems.
   a) static vs dynamic phase noise
   b) stabilization time vs long term aging
   c) behavior of oscillator and clocks during transient conditions of shock, temperature changes, and random vibration.

A great deal of mystery exists in industry between the system designer, the responible engineer on the project, and what suppliers can provide. The education process is necessary and the possibility of "white paper"" generation for distribution though the industry would be helpful.

7. Over Specifying Requirements: The general consensus of all the participants is:
   a) It does not improve the reliability of the product. As a matter of fact, over testing and alignment difficulty might detract from the relibility of the product.
   b) There are significant cost drivers. 165 dB floor is readily achievable on quartz os SAW oscillators. 169 dB floor is twice as difficult.
   c) The added margin for safety and testing errors by each layer of people touching the specification makes some clocks impossible or very expensive to build.
   d) The bureaucracy in specifying the product has to be analyzed and reduced considerably with the objective of achieving system requirements without burdening the product with non–value–added requirements which, in many cases, triple the product cost.

The conclusion of the workshop is there are major misunderstandings between system designers, government imposed requirements, and product manufacturers which require communication, education, and constant dialog for better quality products at lower costs and with shorter cycle times.

WORKSHOP C: R&D/ SALES/ENGINEERING

Jack Kusters
Hewlett–Packard Co.

Overall Comments: significant difference in outlook and perceived problems in those providing services to the Military and in those providing similar product services to the commercial world.

General Workshop: Good opportunity to share viewpoints, opinions, experiences in the problem areas discussed.

Identified problem areas which impede communications between Sales, R&D, and Engineering:

1. **External Problems**
   - Customer uncertainty
   - Need for customer education
   - Cost problems
     - Timing on funding
2. **Internal Problems**
   - No control on specifications
     - Ownership not defined
     - No product champion
   - No common language
   - Cultural differences
3. **Product Problems**
   - "The Perfect Product" vs "Good Enough"
     - "Good Enough" defined as what the customer really wants/needs

1. **Possible solutions to external problems**

   a. Customer education
   - Seminars, technical articles, workshops
   - Anticipate the customer's need
     - Unsolicited proposals
   - Sharing data with customer, even some proprietary

- Make the customer part of the problem and solution
  - Provide input on specifications
  - Joint development when appropriate
- Customer visits to factory

b. **Staff Education**

- Direct contact with customer by R&D and Engineering
- Staff rotation into all Sales/R&D/Engineering functions
- QFD (Quality Function Deployment)
- Core Teams

2. Possible solutions to internal problems

a. Abolish silos

- Core Teams
- Combined Meetings
- Concurrent engineering – Design for Manufacturing
- Co–location
- Self–elected planning group
- Self–empowerment
- Interactive brainstorming
  - Combined Sales/R&D/Engineering group
  - Unstructured, but with defined goals

b. **Other areas that may impede communication**

- Use system engineering to tie project together
- Importance of testing
- Human engineering factors
- TQM – impact of ISO 9000
- Reaching the right person

3. Possible solutions for the "Perfect" vs "Good Enough"

- Communication with customers on options
- Knowing what the customer really wants
  - Verifying with customer
  - Communicating customer preferences to all
- Good specifications

- Consider customer costs
- Don't try to meet multiple customer needs with a single product
    - No killer general purpose solutions
    - Costs too much – Low customer value
- Design for manufacturing – manufacturing engineers on core team

AN OPERATIONAL CONTROL SEGMENT (OCS) UPDATE ON GPS CONSTELLATION STATUS AND FUTURE PROGRAM DIRECTIONS

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Editors Introduction

This paper is the edited transcript of Lt. Colonel Freer's presentation. The figures were the over head projection transparencies.

Lt. Colonel Freer's Paper

We run the GPS Master Control Station from the Second Space Operation Squadron out of Falcon Air Force Base, Colorado. This is our squadron symbol (Figure 1); the real story here is a big success story in terms of where GPS has gone and especially how PTTI applications have been so much a big part of GPS and how much a part of PTTI that GPS has become.

They asked me to speak this year and give you an update on what is going on with GPS. The message as far as GPS and PTTI are concerned is all a good one. I want to talk a few minutes this afternoon about the performance of GPS and then discuss the Federal Radionavigation Plan (Figure 2), which is a document outside the purview of the Department of Defense (DoD) and the Department of Transportation (DoT). One of the concerns with GPS, to not only the time users, but to a lot of other folks, is that the DoD has pretty much guarded GPS operations; and I want to talk a little bit about what the DoD and the DoT have signed up to in terms of assurances to this community and to aviation interests, as well as other modes of transportation in terms of GPS continuity and availability. Finally, I will bring up a couple of issues that hopefully will be of interest to many in this group.

The Federal Radionavigation Plan was the topic chosen because a person from the utility industry got up at last years PTTI and asked a question on how we can be assured that somebody is not going to turn GPS off tomorrow or the next day. I want to spend a little time on that logic because the military is very reliant on GPS and we're planning on operating it into the foreseeable future. So I will give you some of the real words in that regard straight from that plan. And, then I will discuss with you some of the issues that are current, including a blue ribbon panel between the DoT and the DoD that is looking at GPS management, operations, funding, etc.

Here is a slide in terms of GPS performance (Figure 3). Again, the performance charts are really a good news story. We talked about requirements, performance; you see that we don't even get on the requirements scale. We are looking at 100 ns as the specification that we are trying to meet; and it doesn't even make it onto the chart. So it is a good news story all around in terms of the UTC USNO time transfer that goes on with the GPS constellation.

We have 26 satellites on orbit. I will get into the status of the individual satellites, but it is a very successful program, time transfer being a by-product of the primary emphasis of navigation. For those who don't understand all of how GPS works, a nanosecond of time error equates to about a foot of navigation error in terms of the way we do business in looking at the navigation specifications. So, time is extremely important to getting all our error rates for the primary mission down into the requirements.

I will talk a little bit more about it later, but time transfer keeps finding better and better ways to do business, especially when it comes to secure telecommunications, cryptosynching, and into the next generation commercial telecommunication requirements. As we try to work at the margins in terms of better ways to do telecommunications; packet, burst, etc. GPS promises to be valuable.

I put this slide (Figure 4) up just to show you that again GPS is performing its primary mission extremely effectively. The reason I want to talk to you about this slide is this: the requirements for GPS, as I mentioned are in time 100 ns, the availability and the reliability requirements on GPS are far less than the actual performance of the system to date (Figure 5). So we get to the "chicken or the egg," what is the requirement? I think we need to start thinking about what is the expectation. In other words, I think the expectation is that we never get worse than what we have today, and that we look for ways to improve it. How we get that expectation into hard requirements that people can defend in the budget process is not a trivial task. But requirements, if you look at the hard definition of military requirements or specifications, the answer is that we are doing much better than we should be, so I cannot have any money to make any improvements. I think that logic does not follow. People expect GPS service at its current rate or better; then we need to figure out how we make those expectations and customer satisfaction indexes into requirements. Because unless we tackle that, we cannot do a very good job of defending the budget to make improvements to support PTTI capabilities.

I put this slide (Figure 5) up to show you that while some of you are focused strictly on PTTI, GPS is not. GPS has an important secondary payload of nuclear detonation detection. As we were saying at our workshop, the sensors and the sophistication of those secondary payloads actually takes up more time than the primary navigation clock payload activity on to meet our primary mission. A very important treaty monitoring capability, a very important national security capability, and clearly a political activity in terms of "civilianizing" what we currently know as "GPS." It is easy for people to say let's set up a civil organization to do GPS; but my input is that this secondary payload has a lot of heavy hitters that are going to be very hesitant to let that happen.

This slide (Figure 6) shows a look at time transfer. It goes from plus 60 to minus 60 ns. Over the course of up to three years, that is our daily performance. I am going to get into some more time transfer performance in a moment. But again, that is looking back. This peak is J–Day 355. Last Christmas season, we were doing some calibrations between USNO and we had a little miscommunication between a master control station. And we think we have those procedures ironed out. As a matter of fact, we did learn some lessons from that. Some more updated, a little bit less crunched data. Again, here is a look at a different way to format a quarter's worth of GPS data (Figure 7), the third quarter of '93. And we are now looking at RMS here as what we think is a better measurement of how we are doing in terms of steering to USNO. And you would expect that is okay only if your axis kind of goes around zero; I think this information points that, at least from a cursory look, that is the case.

Expanding a little bit more into the more current data, again it is a good news story (Figure 8). The margins there on the axis, plus or minus 20 ns, are five times better than specified. So GPS continues to perform with no regard with what the requirement is, in that we are looking for ways to do it better every day; and not provide any less service than people have come to expect to satisfy our customers. Again that is kind of not the schooled solution, but I think it is something that we on the government side of things need to be able to articulate on and then defend: that GPS is becoming a utility; in many ways it will soon be a utility that people are not going to expect less service than is available today – to the PTTI community, to the navigation community, or to people that rely on it for a variety of other applications, geodesy, etc., etc. So we don't really spend too much time patting ourselves on the back saying that we're exceeding specifications or meeting everybody's requirements. We are looking for ways to do better and looking to working with the community, both industry and other government agencies, to improve on an already-good product so that it will continue to be a national asset; and we will be good stewards of that national resource.

Here is the performance chart (Figure 9) that I would like to spend the most time on. And I will start at the top. These are the four satellites per plane; these are the planes we have on orbit. Please note the legend. As you can see, there is a little bit of activity in terms of clocks. The three Block 1 clocks are all on rubidium; that is SVN 10, 9 and 11. Nine is grounded right now because it is in eclipse season. However, there is another satellite, Block 2–A, SVN 37, that is in that same slot, so no big deal; except that Selective Availability ("SA") is turned on for all the Block–2 satellites. Some of you may have seen that. Eleven is a satellite that was qual–tested twice. Some of the parts weren't flight tested, but we flew them anyway. And it is performing very well. However, we are starting to see some problems with static–electric discharge so we give that satellite lots of care and attention. Unfortunately, the automatic features that check for proper signal on Block–2s weren't built into this satellite. It can run away and give you a bad time before we are able to set it "unhealthy" and basically turn it off. It looks like we will swap out the clocks on SVN 21 and SVN 16 in the next six months. They are displaying normal degradation and each satellite still has 3 spare clocks.

For those who are relying on GPS and have the capability to take out SA, which most of the sets do, I would stay away from 11 if you can get it out of your clock solution. If by chance you don't have that capability, then I would strongly recommend that you follow any suspected anomalies with checking on the notices and advisories that we put have out; because we have seen some problems with that clock.

SVN 10 is actually the satellite that is producing the navigation signal in Slot A–1. SVN 39 which is also in slot A–1 has been operated since November 2 without any updates to the clock or the navigation package, and we're going through and watching what we call an "extended navigation" portion of the payload test. The requirements were for it to operate and gracefully decline for 180 days. We don't expect to do that, but we are collecting data for at least two–weeks of extended navigation with no uploads. There is probably some scientific interest in that and we will be glad to share that information with anybody who has a legitimate need.

SVN–19, we're having trouble with the course acquisition code. It is not a problem for timing – well, maybe it would be. But it has been driven by interest in the navigation package to do carrier phase differential GPS on the standard positioning service; and we have a problem there that we are working on with our systems engineers.

Plane 2, all the satellites in this plane are in good shape. In August, we launched SVN–35 which has a laser retro–reflector on board as we try to sort out some clock movement versus error in ephemeris. The NRL folks are supporting this through the NASA laser network that we spoke about earlier this morning. We are excited to see some data. We don't expect it to have any immediate impact on the way we do business. In the long–term, we think we can fine–tune our Kalman filter and separate the clock error form the ephemeris error that we see in the constellation.

This satellite, SVN–31, is a second–source cesium clock; this is not a cigar, it's a thermometer. We found that it is a little temperature sensitive, and we are trying to get our arms around that. We are flying really four different companies' clocks on orbit right now. The rubidium clocks, Number 25, and all of the three Block–1 rubidium clocks are built by Rockwell. Most of the cesiums on the Block–2s were built by Frequency and Time Systems (FTS). And, we have two others: Frequency Electronics, Incorporated (FEI) built 31 and 32 and Kernco, Incorporated built 34 and one more. So we are actually flying three different kinds of cesiums. Right now, SVN 34 with a Kernco clock is the best performing clock we have on orbit.

The Federal Radionavigation Plan is updated every two years (Figure 10). The agreement was signed by the Secretary of Transportation and the Secretary of Defense. And GPS has now become kind of embedded in almost every page of this document. In terms of timing accuracy, they talk about two requirements, first, 100 percent availability at full operational capability. And second is the key that I wanted to emphasize: the guarantee by the U.S. Government (not the DoD but the personnel above the DoD), continuous GPS use for the foreseeable future; and a commitment by the President for six–years notice to any termination to GPS service as you know it today, which means free of direct charge. There is lots of talk to "get GPS out of DoD's control;" in fact, it is already being governed by the civilians who are in charge of DoD and work with other interagencies, especially the DoT, in terms of the way we do business. Let me make it perfectly clear that I **DO NOT** have a dial that changes the selective availability level at the master control station, nor does anybody in a military uniform have authority to direct that. That has got to come from the civilian sector and probably the President, in terms of changing selective availability on GPS.

Finally, a couple of issues (Figure 11). Initial operational capability and full operational capability. September 30, our commander of Space Command sent the message to the air staff saying that we think we're at an initial operation capability; the Secretary of Defense sometime this month is expected to notify the Secretary of Transportation that we have achieved initial operational capability and make it available to civil use in the transportation world. A "full operational capability" is a military term that will occur probably in February of '95; it has more to do with the maintainability and sustainability of the equipment that we use to run the operational control segment.

DoT–DoD Task Force is meeting; the report is due out this month as well. Initial indications are that, it doesn't make any radical changes to the way GPS has operated. It does make some recommendations in terms of cost reimbursement for enhanced GPS, which is differential GPS at this point. There is also some discussion about wide–area differential and local differential, using GPS. This is not really a timing issue. As I mentioned, we are testing SVN 39 and getting a lot of good information about the way the system works with a clock on orbit that is not updated and steered. That test we expect to be completed in the next couple of weeks.

QUESTIONS AND ANSWERS

Albert Kirk (JPL): On your plot of time errors, the one just before the smiley–faced plot, I detected what looked like periodicity. Can you comment on that please?

Col. Freer: We haven't been able to get any more systematic error out than we have right now. Again, it is a scale issue. If we scaled it to 100 ns, it would look like a straight line. And we do update it daily and we cannot steer one for one to the USNO time. Tom?

Tom Meyer (Falcon AF Base): I will be expanding on this tomorrow when I give my evening section, but very quickly, the steering algorithm we use within GPS Master Control Station, our common filter uses a least–squares fit of only two points. And it is a very old algorithm, not very robust, and certainly doesn't change on a day–to–day basis, as we would like to see it. So what you do see is if you introduce any sort of variation into it, you will see this oscillatory nature continue for a couple days; and then again you will see it if we introduce a couple more points that aren't on the norm or follow a predicted pattern.

Marc Weiss (NIST): I assume those RMS numbers, 15 to 20 ns, are using PPS, that is SA–capable receivers?

Col. Freer: That's right. And frankly, that is an issue that we, the Air Force, the military, is trying to deal with in terms that we have not designed a system to directly measure the effects of SA. And the FAA is concerned about that, and we are trying to sort out how to directly measure the effects of SA. We can add the math, but if something goes wrong then we don't have a direct measurement of the effects of SA and a concern (in terms of integrity) that we are guaranteeing a service that we are monitoring at the PPS level; and then making some mathematical assumptions; but we haven't closed the loop in terms of direct monitoring of the SPS signals.

Christian Veillet (Observatoire de la Côte d'Azure): You mentioned putting up GPS–35. Do you plan to have others in the near future?

Col Freer: Yes. The March launch, SVN–36, will also have a laser retro–reflector. Again, this is not an operational upgrade; it's an experiment that we're working on in conjunction with NRL and the NASA community and the clock research community. And we don't expect immediate operational impacts to the way we do business. It is a cooperative effort in terms of some research at that orbital level. The satellites mentioned in the presentation this morning, TOPEX, for instance is a low–flyer in relationship to GPS flying at a 12–hour orbit for 11,000 miles or so. There are not many satellites flying at that exact orbit with the exact time ephemeris mix that we are trying to isolate.

Christian Veillet: A second question. Do you plan in the near future to have a laser link, a LASSO–like type transfer equipment, on board of a GPS satellite?

Col. Freer: Not that I am aware of. Let me mention that we're bending metal on Block 2–R, which is the replenishment of the current constellation; and we are in the requirements phase of the follow–on to 2–R. Some of you may have heard the term "Block 2–F." That is no longer in vogue; they haven't figured out a letter; but they are still in the requirements phase in terms of deciding how to go and they haven't fully nailed that down. But I haven't heard anything about laser cross–link type stuff.

MASTER CONTROL STATION OPERATIONS

LT COL HARRISON C. FREER

FIGURE 1

OVERVIEW

PERFORMANCE

FEDERAL RADIONAVIGATION PLAN LANGUAGE

ISSUES

FIGURE 2

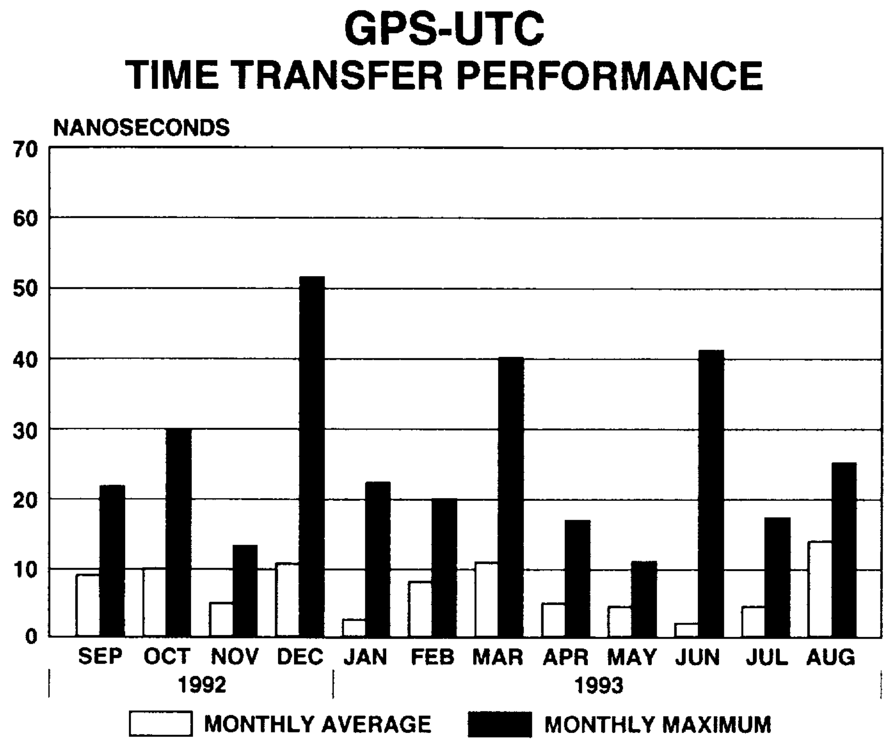

FIGURE 3

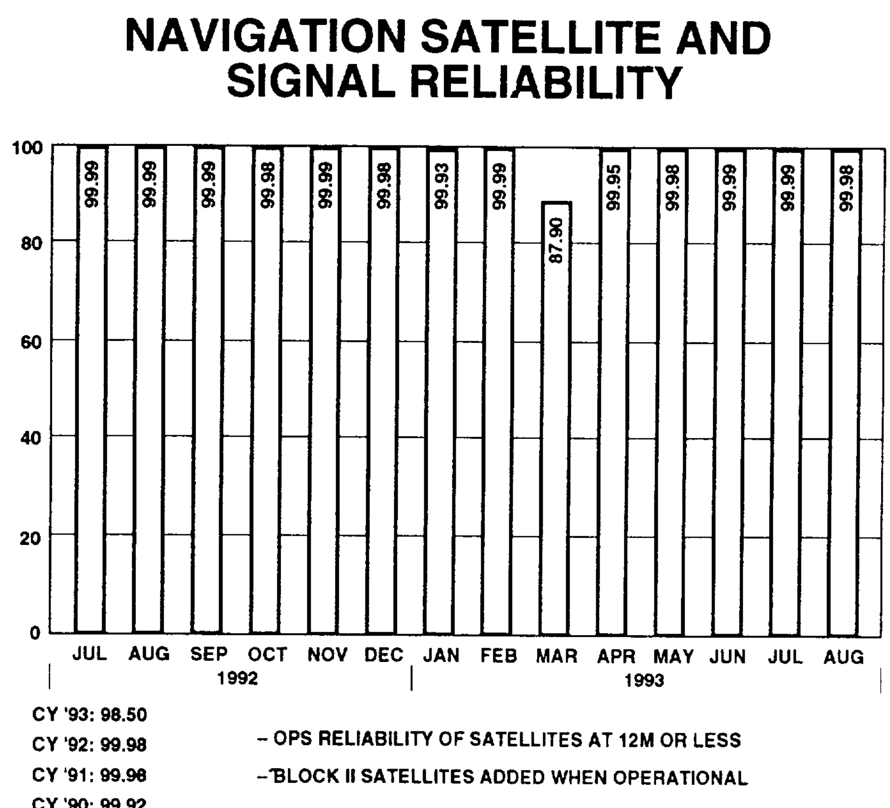

FIGURE 4

NDS PERFORMANCE AND RELIABILITY

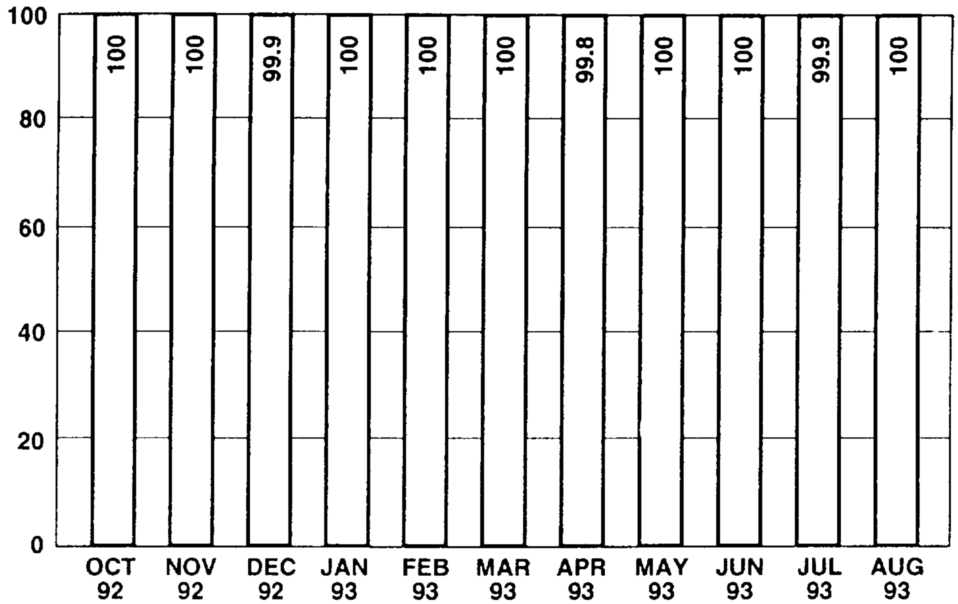

FIGURE 5

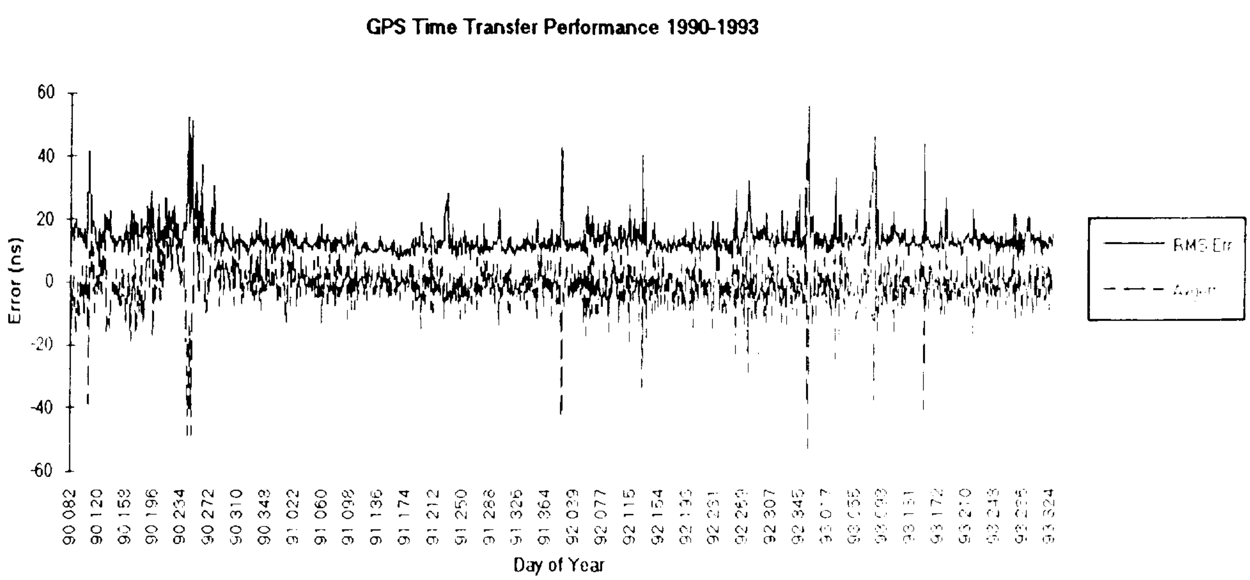

FIGURE 6

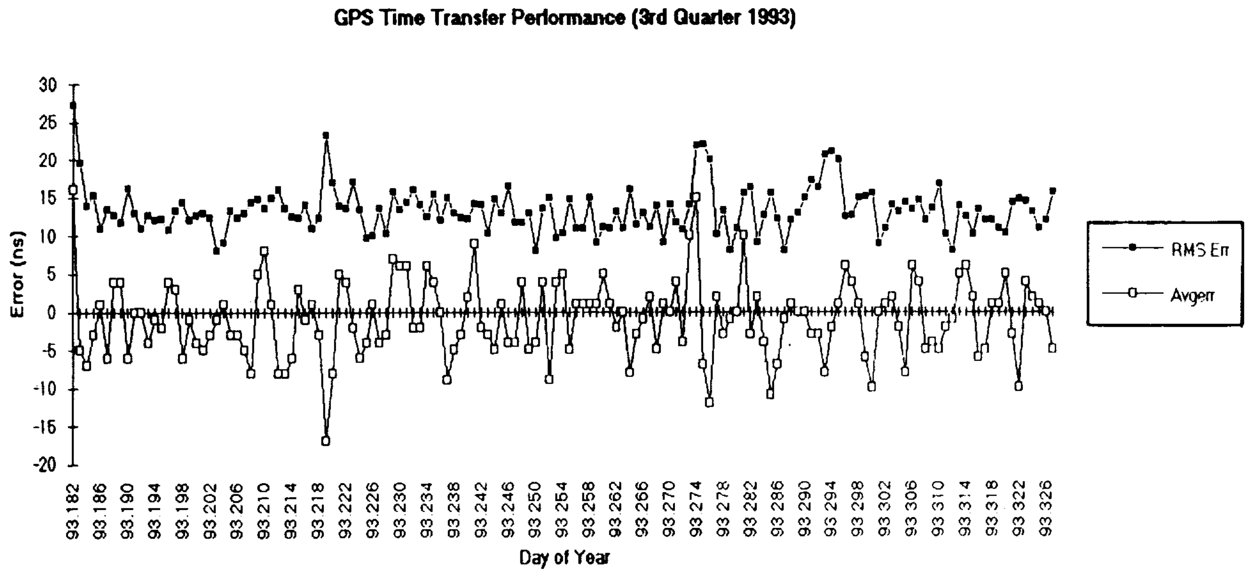

FIGURE 7

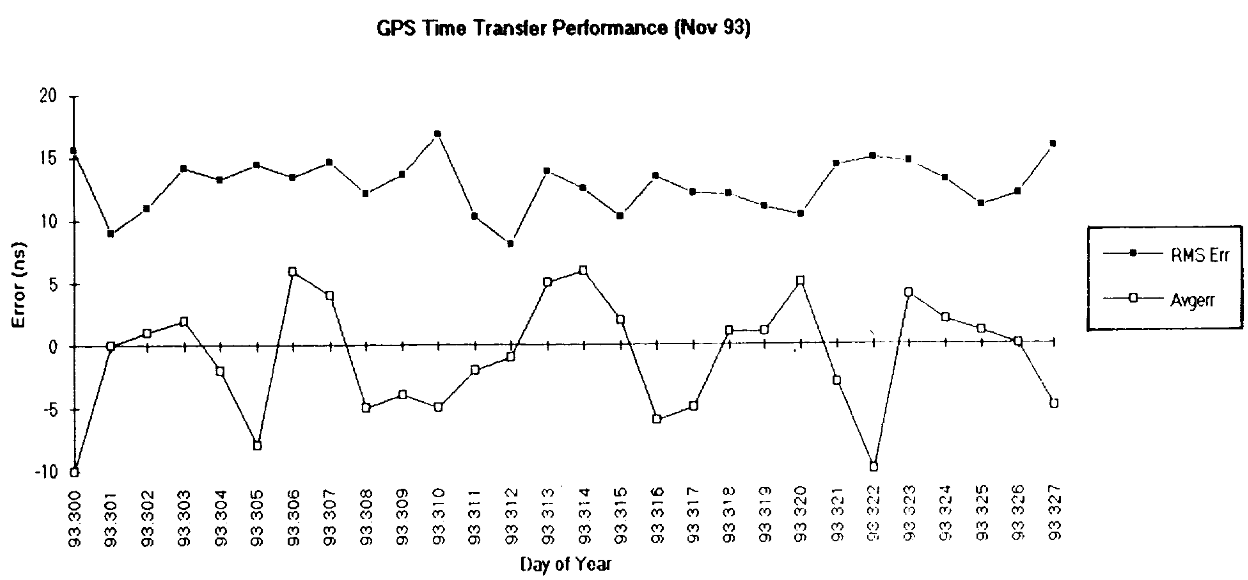

FIGURE 8

TABLE 6: NAVSTAR MISSION OPERATIONS STATUS

DECEMBER 1, 1993

ON-ORBIT VEHICLES

CLOCK OPERATIONAL PERFORMANCE OCT. - NOV., 1993

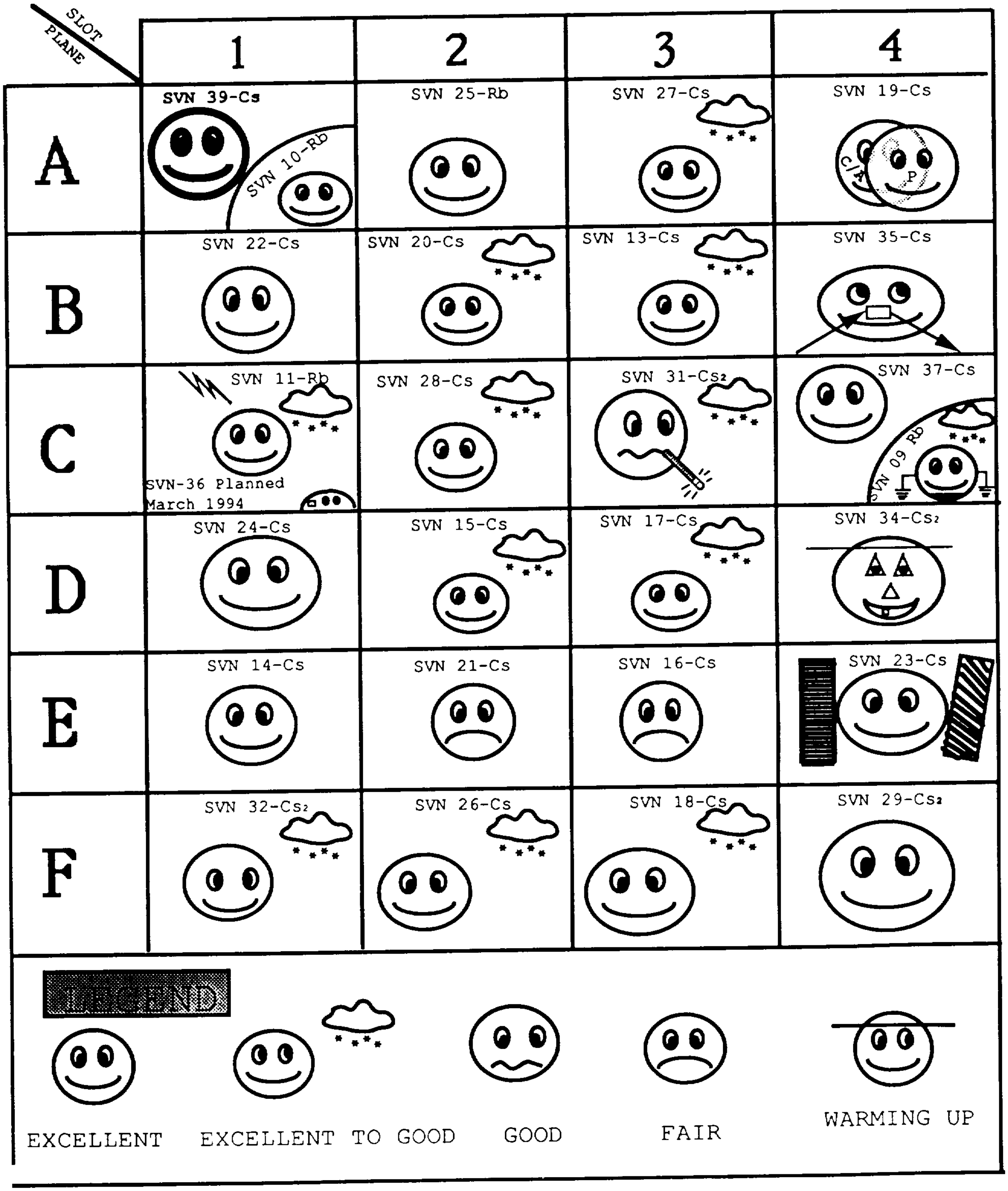

FIGURE 9

1992 FEDERAL RADIONAVIGATION PLAN REQUIREMENTS

TIMING ACCURACY (P. A-38)

PPS 200 NS **SPS 340 NS**

AVAILABILITY

100 PERCENT AT FULL OPERATRIONAL CAPABILITY (P. A-40)
CONTINUOUS OPERATION OF GPS FOR THE "FORESEEABLE FUTURE" (P. 3-43)
MINIMUM SIX YEARS ADVANCE NOTICE OF DETERMINATION OF OPERATIONS (P. 3-43)

FIGURE 10

ISSUES

INITIAL / FULL OPERATIONAL CAPABILITY

DOT / DOD TASK FORCE

EXTENDED SVN39 TEST

FIGURE 11

QUESTIONS AND ANSWERS

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N94-30644

LORAN-C TIME MANAGEMENT

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Abstract

As of October 1, 1993, the U.S. Coast Guard (USCG) supports and operates fifteen Loran–C chains. With the introduction of the Global Positioning System (GPS) and the termination of the Department of Defense (DOD) overseas need for Loran–C, the USCG will cease operating the three remaining overseas chains by December 31, 1994. Following this date, the USCG Loran–C system will consist of twelve chains.

Since 1971, management of time synchronization of the Loran–C system has been conducted under a Memorandum of Agreement between the U.S. Naval Observatory (USNO) and the USCG. The requirement to maintain synchronization with Coordinated Universal Time (UTC) was initially specified as ± 25 microseconds (μs). This tolerance was rapidly lowered to ± 2.5 μs in 1974. To manage this synchronization requirement, the USCG incorporated administrative practices which kept the USNO appraised of all aspects of the master timing path. This included procedures for responding to timing path failures, timing adjustments and time steps. Conducting these aspects of time synchronization depended on message traffic between the various master stations and the USNO. To determine clock adjustment, the USCG relied upon the USNO's Series 4 and 100 updates so that the characteristics of the master clock could be plotted and controls appropriately applied. In 1987, Public Law 100–223, under the Airport and Airway Improvement Act Amendment, reduced the synchronization tolerance to approximately 100 nanoseconds (ns) for chains serving the National Airspace System (NAS). This action caused changes in the previous administrative procedures and techniques. This paper presents the actions taken by the USCG to meet the requirements of this law.

GPS: THE FIRST IMPACT ON LORAN–C

The DOD Global Positioning System (GPS) has significantly impacted the Loran–C system, operated and supported by the USCG. The USCG originally operated Loran–C overseas based on a DOD need. When GPS was introduced, the DOD stated that their need for overseas Loran–C would terminate on December 31, 1994. Following this date, the USCG will no longer have the authority to operate Loran–C overseas. Since the summer of 1992, the USCG has been reducing its overseas operation and support. On June 30, 1992, two of the three stations forming the Central Pacific Chain (GRI 4990) were turned off. The third station, Upolu Point, Hawaii, remained on air until December 31, 1992 to meet a continuing DOD timing need.

On October 1, 1993, four of the five stations in the western Pacific, and the control and monitoring functions which form the North West Pacific Chain (GRI 9970), were turned over to the Government of Japan. The Japanese have chosen to continue to operate this chain, minus the station located at Barrigada, Guam, to meet their own needs. In fact, Japan is actively taking steps to build a new master station and to modernize equipment within the chain.

With these modernization efforts, and considering other multinational developments between Japan, Russia, China and the Republic of Korea, Loran–C will continue to serve users in this part of the world into the foreseeable future.

The USCG is actively negotiating the future of ten Loran–C stations with seven countries in the European theater. Four of these chains are impacted by the overseas withdrawal of USCG operations and support. The affected chains are: the Norwegian Sea Chain (GRI–7970), the Icelandic Sea Chain (GRI–9980), Mediterranean Sea Chain (GRI–7990), and the Labrador Sea Chain (GRI–7930). Three of the chains will be reconfigured almost immediately following December 31, 1994.

In the case of the Norwegian and Icelandic Sea Chains, all stations with the exception of Sandur, Iceland will be modernized and used as part of four new chains being developed under a multinational organization which formed the North West Europe Loran–C System (NELS). The current plan is to operate these four chains under a Time–of–Emission (TOE) control philosophy, with the master stations synchronized to UTC[1].

The current Labrador Sea Chain, a two–baseline chain formed by Fox Harbour, Canada , Cape Race, Newfoundland, and Angissoq Greenland, will be reconfigured following the closure of Angissoq. The Canadian Government has undertaken an initiative to build a new low powered master station at Comfort Cove, Newfoundland. The new chain, called the Newfoundland East Coast Chain, will have a GRI of 7270. This new chain will be supported by the USCG under a bilateral agreement with Canada.

With these turnovers, the Loran–C stations supported and operated by the USCG will be reduced to 29 stations comprising 12 chains. Five of these stations are in Canada. Three of the 12 chains will have Canadian master stations, and one of the twelve chains will have a Russian master station. These 12 chains, their GRIs, their master station location, and their Coordinator of Chain Operations (COCO) location are summarized in Table 1.

BACKGROUND OF LORAN–C DEVELOPMENT AND TIME SYNCHRONIZATION

History

The possibility of developing a UHF hyperbolic, pulsed, radionavigation system capable of covering 300–500 miles for high–flying aircraft was first realized in the United States by Alfred L. Loomis of the Microwave Committee in October 1940[2]. This committee was comprised of members from the Massachusetts Institute of Technology, government, and industry. This system, Loran–A, underwent consistent development and refinement. By the end of World War

II, there were over 60 Loran–A stations transmitting.

Equipment Milestones

Some critical milestones included: (a) establishing 100-kW peak transmitters on two abandoned USCG lifeboat stations: Montauk Point, Long Island, New York and Fenwick Island, Delaware in 1942, (b) transition from 1.95 MHz to 170 and 180 kHz (LF Loran) in 1944, (c) development by Sperry Gyroscope in 1946 of Cycle–Matching Loran (CYCLAN) under contract with the Rome Air Development Center to produce a low–frequency system for navigation and guidance in precision bombing, (d) selection of the 90–110 kHz frequency band in 1951, and (e) field–test resolution in 1954 of cycle ambiguity problems, which allowed system application to at least 1000 miles.

Physical Milestones

The "atomic" clocks which would ultimately synchronize Loran–C operations were under development in June 1955 when the first time measurements using them were obtained at the National Physical Laboratory in Teddington, England[3]. Between June 1955 and June 1958, statistical data were gathered which allowed defining the frequency of the hyperfine transitions of the ground state of Cesium–133 as 9,192,631,770 $\pm$ 20 cycles per second – the currently accepted value.

GENERAL DEVELOPMENTS

The system called Loran–B was field tested in the Chesapeake Bay between 1959 and 1962. It tried to use the RF carrier to provide more accurate information than the previous envelope matching. It was intended for use in harbors and bays for mine laying operations. It was abandoned in 1962 due to several technical difficulties such as signal scattering from large ships and keeping the three stations synchronized[4].

The CYCLAN system was the next system to be developed, and it was able to resolve cycle ambiguity by using pulsed transmissions on two frequencies, 180 and 200 kHz. This system was later abandoned because there was international reluctance to grant a frequency clearance in the required band.

BEGINNINGS OF LORAN–C

By 1957, the Navy had an operational requirement for a long–range, high–accuracy radionavigation system. This requirement gave rise first to the Cycle Matching Tactical Bombing and Navigation System (CYTAC) and then to Loran–C.

The first Loran–C chain was on the east coast of the United States and consisted of a master station at Carolina Beach, North Carolina and "slave" (now termed 'secondary') stations at Martha's Vineyard, Massachusetts and Jupiter, Florida. It was originally operated by the Navy, but it was transferred to the USCG in 1958.

The instrumentation for high-speed recording of the time of arrival (TOA) of transient signals was developed by the National Bureau of Standards (NBS) in 1957-58. The development of the necessary techniques to use Loran-C for general purpose timing began in 1959 when NBS, USNO, and the Atlantic Missile Range (AMR) jointly developed the specifications for the first Loran-C timing receivers, and Sperry Gyroscope manufactured them.

MASTER/SLAVE OPERATIONS

In the original chain, timers used a servo system for controlling the cycle and envelope of both the master and slave stations. The master cycle servo used Automatic Frequency Control (AFC) circuits tied to the operate oscillator. The AFC attempted to keep each slave station's oscillator synchronized to the master's. To do this, the slave station tracked both the envelope and the cycle of the master signal at the 30-μs point. As the slave's master-cycle servo tracked the master's signal, it provided frequency correction to the oscillator. The main problem with this method was that noise in the master's signal tended to be transmitted in the slave's signal[5].

Although the USCG assumed responsibility for chain operations, the Navy was directed to supply the timing source, UTC, to Loran-C in 1960[6]. Actual timing control between the master station at Carolina Beach, NC (also referred to as Cape Fear, NC in the literature) and the USNO began on May 22, 1961[7].

Around 1964, synchronization was changed to the so-called "free running" mode. The AFC circuits were removed, and the master cycle servo was locked down. The slave stations inserted Coding Delay Adjustments (now called Local Phase Adjustments or LPAs) by manually rotating the master cycle servo. Carolina Beach, NC, the master station for the east coast, had three rubidium oscillators and generated a 1-pulse-per-second (1PPS) marker. The USNO monitored these 1PPS signals for comparison to UTC and issued corrections as needed.

The steering of the east coast chain by USNO in 1964 was quite successful, and a decision was made in 1965 to provide a 1PPS signal from all master stations. This feature was dropped in 1968 in favor of using the first pulse of the master's phase code group A.

Initial precise steering by USNO was hampered because the three quartz oscillators at the transmitter were unstable. The NBS monitor at Boulder, Colorado revealed a diurnal frequency variation of 60 μs. This was soon traced to temperature changes in the transmitter room, to which the quartz was sensitive.

Practical steering within close limits was not achieved until late in 1961 when the quartz oscillators were replaced with the more stable rubidium units. The epoch for steering and time of coincidence (TOC) for the Loran-C chains had been previously defined to occur at 00hrs 00min 00secs on January 1, 1958[8].

UTC CONTROL

The next technological advance affecting loran occurred in 1967 when the Cesium-133 second was adopted by the horology community. This was followed by a cooperative effort between the USNO and the USCG to purchase and install 35 Cesium beam standards in the loran stations[9]. Two such standards were originally installed, and a third unit was added later. The USNO estimated that this would allow the epoch of Loran–C time to be traceable to their master clock to within ± 5 μs.

During the next six years, several major decisions were made which affected loran operations. In 1970 the Deputy Secretary of Defense informed the Secretary of Transportation that the Joint Chiefs of Staff agreed that the USCG should act as an agent of the USNO to provide precise time distribution for DOD via loran[10], [11]. In March 1971 the actual terms of agreement were signed, and the USCG then became the agent of the USNO to operate Loran–C for disseminating precise time and time interval[12, 13].

An official USCG publication of 1975 states that the transmissions of six of the Loran–C chains were synchronized to within ± 25 μs tolerance of UTC[14]. As early as 1972, however, it could be claimed that Loran–C was steered, in fact, to within ± 15 μs of UTC[15]. This tolerance was gradually improved, first to ± 5 μs, and then to ± 2.5 μs by 1974. At that time, Loran–C was officially designated the primary navigation system for the Coastal Confluence Zone (CCZ) of the United States[16].

In early 1975 the loran rate structure was modified to add four new rates beyond the available forty–eight. This was necessary to accommodate the needs of the CCZ mandate[17].

Loran–C gradually expanded to offer greater coverage over the United States continental land mass. A survey of chain functionality shows the following availability: U.S. West Coast (USWC) and Gulf of Alaska (GOA) - 1977; Northeast (NEUS) and Southeast (SEUS) United States - 1979; Great Lakes (GLKS) and Canadian West Coast (CWC) - 1980; Northern Pacific (NORPAC) - 1981; Canadian East Coast (CEC) - 1983[18].

Around 1977 the USNO began automating its Precise Time stations (PTS)[19], and by 1981 the Precise Time Reference Stations (PTRS) were being used to monitor Loran–C timing. The PTRS stations could both collect timing data and steer loran stations remotely[20].

The present continental United States (CONUS) chain configuration was attained when the so–called "Mid–Continent Gap" was closed in 1991. At that time, the North Central (NOCUS) and South Central (SOCUS) chains became operational as the result of the Mid–Continent Expansion Project (MEP). Figure 1 shows the current location of all the data acquisition sites and Loran–C stations within CONUS.

THE ERA OF PUBLIC LAW 100–223

The most recent action significantly affecting loran was the passage in 1987 of the Airport and Airway Improvement Amendments to the Airport and Airway Improvement Act (PL 100–223) of 1982. One major result of this law was that all master loran stations had to be synchronized to within approximately 100 ns of UTC by September 1989[21]. The USCG and the USNO immediately collaborated to meet the requirements of this law[22], and a legal opinion was obtained which extended the deadline to a more manageable date[23].

As a first effort, the USCG and the USNO established the so–called "administrative" control methods in an attempt to determine the technical feasibility of this mandate. Four chains, NEUS, SEUS, GLKS, and USWC were subjected to periodic combinations of time steps and frequency adjustments, essentially between February and August 1989. The results indicated that these chains could only be held to within about ±- 200 ns of UTC with 84 percent confidence[24].

A recent USCG report updated the synchronization work for loran operations between the passage of PL 100–223 and October 1993[25]. In addition to the administrative methods, direct–view, common–view, and two–way time transfers via satellites had all been tested by June of 1993 at loran station (LORSTA) Seneca, NY, the master station of the NEUS chain. The results showed that two–way satellite time transfer could easily meet the requirements of the law. Unfortunately, it exceeded the USCG budget and had to be abandoned.

Based on data gathered by the USCG, the USNO, and the National Institute of Standards and Technology (NIST), the most cost–effective means of achieving the 100 ns synchronization appeared to be Common–View Satellite Time Transfer (CVSTT). The data for this conclusion were gathered at LORSTA Seneca between January and June 1993 using CVSTT equipment which was calibrated, supplied, and installed by NIST. The initial results were highly favorable, as was anticipated based upon previous calculations estimating that this method would achieve the required synchronization to the four– or five–sigma level[26].

When fully operational, the CVTT control method will provide adequate Loran–C steering for all classes of users well toward the currently proposed 2015 date for loran operations[27].

LORAN–C MANAGERIAL ORGANIZATION

The COCO is the first–level manager of a Loran–C chain. Among the COCO'S many duties are the administrative actions of maintaining chain synchronization to UTC, as listed below.

1. All Loran–C transmissions are synchronized to the UTC time scale. This scale is maintained by the USNO and is referenced to its master clock. All Loran–C chains are monitored by USNO, and data are published at periodic intervals via Time Service Announcements (Series 4 and Series 100) .
2. The responsibility to synchronize the Loran–C system to UTC rests with the USCG. Requirements and criteria are contained in a DOD and DOT Memorandum of Understanding. Specific responsibilities are:

    a. **Program Manager:** Maintain coordination with USNO for the purpose of updating, monitoring, and modifying requirements or procedures as necessary to ensure Loran–C transmissions are maintained within the specific UTC criteria.

    b. **Regional Manager:** Coordinate inter–chain and intra–chain synchronization for all Loran–C chains in each region.

    c. **Chain Manager:** Synchronize each chain to UTC and coordinate the overall intra–chain synchronization and frequency control of the master operate standard.

(Frequency control of the master operate standard may be delegated to the COCO for oscillators under control of the Chain Manager (CM).

d. **Coordinator of Chain Operations:** Perform intra–chain coordination and control all the frequency standards, excluding the master operate standard, unless the responsibility is otherwise delegated.

SYNCHRONIZATION TO UTC TODAY

The CONUS far–field monitor sites operated by USNO for the purpose of monitoring the Loran–C stations in the United States and Canada are shown in Table 2, and the international monitor sites are shown in Table 3.

This paper does not attempt to explain the methodology of the USNO's derivation of individual chain offsets from UTC, but it is important for discussions which follow to mention that the entire process is built upon far–field monitoring. As one might expect, data collected from the far–field monitors have embedded signal path velocity changes which cannot be fully explained without some knowledge of what affects the timing equipment at the Loran–C stations. This is a question concerning the COCO, who is directly responsible for chain management.

Prior to Public Law 100–233, the USCG and the USNO used a rigid set of guidelines for managing Loran–C timing. The USCG used the USNO Series No. 4 and Series 100 time bulletins to compute time and frequency changes. With the exception of equipment malfunctions, all activity associated with chain frequency and time adjustments was preceded by a 14–day user notification.

Frequency changes, in the form of microstepper adjustments, were typically limited to magnitudes of less than 50 ns per day. Time steps, which are applied to all stations of a chain, are used to keep the chain within the prescribed tolerance of $\pm$ 2.5 μs of UTC. Time steps, rather than frequency adjustments, were often requested by the USNO so that users with special frequency needs could ignore frequency changes. Both frequency and time step changes were done world wide on Fridays at 1400Z. If a timing path failure occurred at a master station, corrective action was taken, and the USNO was immediately notified. The USNO used this information and annotated the change in the subsequent Series 4 bulletin.

Typically, all frequency and time steps were based on at least than 30 days of data. The process was strict. It relied on recorded message traffic before actions were taken, and, as discussed in a previous section, it added numerous administrative layers to the USCG's management of Loran–C operations.

The 1987 amendments to the Airport and Airways Improvement Act of 1982 introduced several management changes within the USCG.

First, this amendment required the USCG, working with the Federal Aviation Administration (FAA), to lower the synchronization of the Loran–C master stations serving the NAS to approximately 100 ns.

Second, it directed that a study would be made of the effect on users of using time-of-transmission (TOT) control versus control by the system area monitors (SAM).

Third, it required that a study would be made of the feasibility of synchronizing the time bases of the GPS and Loran-C systems to within 30 ns of each other. The purpose of this was to allow the exchange of navigation data between the two systems.

WHERE LORAN IS HEADED

As this report shows, the USCG Loran-C system has consistently expanded since its inception to include more geographical coverage and to serve more users by adopting pertinent scientific and engineering advances.

Current plans call for this trend to continue. The next immediate step is to complete several months of steering the Seneca oscillator to either UTC(NIST) or UTC(USNO). This will definitely show whether control to UTC at the designated limits of PL 100-223 is feasible using CVSTT. The necessary equipment is already in place at LORSTA Seneca to complete data acquisition.

Based on the results of this steering, GPS receivers will be installed at all Loran-C master stations in CONUS, the GOA, and the CEC and CWC chains. This will meet the first stipulation of PL 100-223 , that all master stations be synchronized to within approximately 100 ns of UTC.

In addition, several other engineering advances are being planned to modernize the Loran-C system so that it can function in the NAS in cooperation with GPS. For instance, an Automatic Blink System (ABS) has recently passed most of its proof-of-performance tests at the USCG Electronics Engineering Center (EECEN). This system will automatically warn of a signal anomaly within 10 seconds that would prevent reliably using the loran signal for a non-precision approach.

The ABS will probably be installed at all loran stations sometime during calendar year 1995. It will also generate a 1PPS signal which will help coordinate its time base with the GPS system time base and will thus fulfill the remaining stipulation of PL 100-223, that is, to coordinate the time references of loran and GPS to within 30 ns so that navigation data may be exchanged between the two systems and they can provide redundant navigational backups for each other.

Other loran developments include a new Loran Operations Information System (LOIS) which will eventually lead to fully automated gathering, archiving, reporting, and analysis of operations data for the entire Loran-C system. The LOIS application software will play a significant role in consolidating and automating loran control procedures and methodology.

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DISCLAIMER

The opinions and positions expressed herein are solely those of the authors and do not necessarily represent the policies of the United States Coast Guard or any other government agency. The content provided is for information purposes only and may not be quoted or used for any other purpose.

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Table 1
Post December 31, 1994 USCG LORAN-C Chains

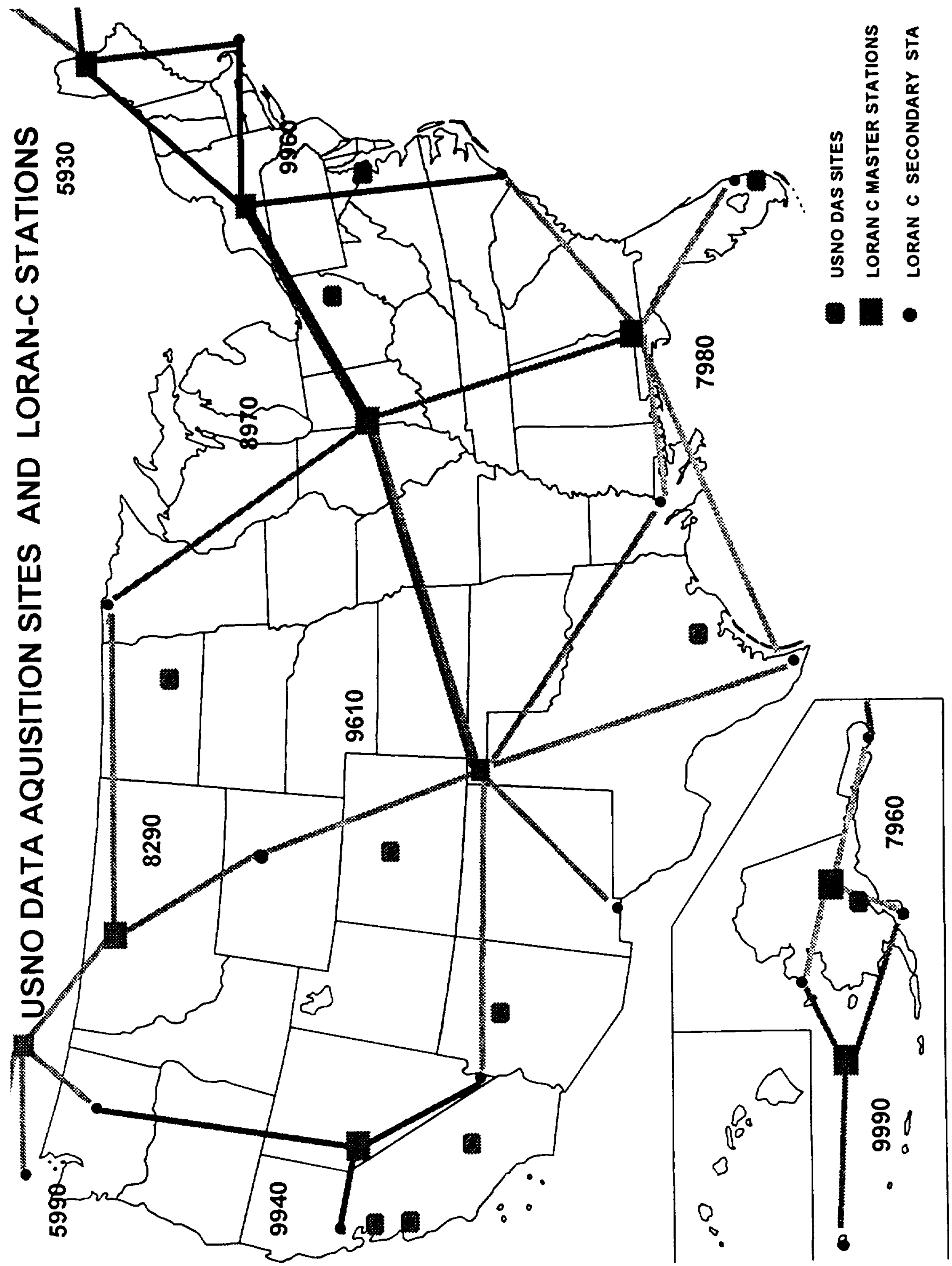
CHAIN	GRI	MASTER LOCATION	COCO LOCATION
NEUS	9960	Seneca, NY	Seneca, NY
GLKS	8970	Dana, IN	Seneca, NY
SEUS	7980	Malone, FL	Malone, FL
SOCUS	9610	Boise City, OK	Malone, FL
LABSEA	7930	Fox Harbour, NFLD	St. Anthony , NFLD
CANADIAN E. COAST	5930	Caribou, ME	St. Anthony, NFLD
CANADIAN W. COAST	5990	Williams Lake, BC	Middletown, CA
NOCUS	8290	Havre, MT	Middletown, CA
U.S. WEST COAST	9940	Fallon, NV	Middletown, CA
RUSSIAN–AMERICAN	5980	Petropavlovsk, CIS	Petropavlovsk, CIS
GULF OF ALASKA	7960	Tok, AK	Kodiak, AK
NORPAC	9990	St. Paul, AK	Kodiak, AK

TABLE 2
USNO UTC MONITORING SITES

SITE/LOCATION	CHAIN MONITORED	STATIONS
CAPE CANAVERAL, FL (1)	7980	ALL
FALCON AFB		
COLORADO SPRINGS	5990	W
	9940	M,Y
	9610	M,V
	8290	X
Flagstaff, AZ	9940	M,Y
	9610	M,V
	8290	M
NEWARK AFB, OH	8970	M,X
(WILL CLOSE)	9960	M,Z
ELMINDORF AFB, AK	7960	M,Y
	9990	Z
CHINA LAKE NAS, CA	9940	M,W,Y
	5990	Y
	9610	M,W
USCG OMSTA LAMORE, ND	8290	M,W,X
	9610	M,V
	8970	M,Y
CAPE CANAVERAL, FL (2)		
(NO CONTROL OF MEASUREMENTS	7980	ALL
HP SANTA CLARA, CA	5990	Y
	9940	W,Y
	9610	W
USNO WASHINGTON, DC	5930	X
	7980	Z
	8970	X
	9960	M
USNO MIAMI, FL	7980	M,W,Z
	9960	Y
VANDENBERG AFB, CA	5990	Y
	9940	M,Y
	9610	W

Table 3
USNO UTC OVERSEAS/INTERNATIONAL MONITORING SITES

SITE/LOCATION	CHAIN MONITORED	STATIONS
CRL RADIO TELESCOPE	9970	M
TOKYO ASTRONOMICAL	9970	M
OBSERVATORY		
BIPM PARIS, FRANCE	7970	M
GRAZ, AUSTRIA	7990	M


USNO DATA AQUISITION SITES AND LORAN-C STATIONS
5930
9960
8970
7980
9610
8290
5990
9940
7960
9990
USNO DAS SITES
LORAN C MASTER STATIONS
LORAN C SECONDARY STA

QUESTIONS AND ANSWERS

J. Levine, NIST: Have you looked at the correlations between the station data and the remote monitoring data?

Lt. Norm Mason: We have not done that yet, mainly because we haven't taken the data and refined it. Part of the problem is that we also want to look at the time of transmission and that has given us some problems. The data is not really valid enough to do a real hard look correlation.

Christine Hackman, NIST: You mentioned briefly that you had tried using two–way satellite time transfer. But you didn't say much more than that, except for it worked. Could you just expand a little bit more on what you tried?

Charles Justice: Basically we had a two–way transfer antenna set up at Seneca, New York. We had personnel from USNO helping us to install this. Then they used their two–way satellite van up there to collect the data. And it was just about that simple. I think we were only there a day or two. And from the data that they got, as short as it was, it showed that we got excellent measurements; and they were 1 below 10 ns. I can't remember exactly the level. If you are interested, we could send you the printouts of the charts that we got. But that was it. We had hoped to put these in at all of our master stations because we were pretty certain from those results, and also from two–way work at NIST and USNO being done for several years at least. I know it goes back at least a few years. We were pretty sure that it would more than meet the 100 ns requirement that the public law stated. But that is when we found out that our source of funds was going to dry up; we then had to drop the project because we couldn't do anymore. We were originally going to set up the antennas at all the master stations and get the modems and everything else necessary. But that is as far as we could take it.

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Report on NATO PTTI

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Abstract

This paper covers the work of the NATO Working Group on precise time and frequency (AC302/SG4/WG4) since its inception in 1988 to the end of 1993. The aim of the group was to produce STANAG 4430 detailing a standard interface for the transfer of precise time & frequency to assist the interoperability of NATO forces. The design of the interface is outlined together with the concepts leading to the design. The problem of providing and maintaining a traceable UTC in military user systems is described.

Background to Precise Time Standards in NATO

The NATO nations' forces already have, or are bringing into service, a range of systems that require precise time and frequency (PT&F) for their operation as well as for the real-time transfer of information between them. There is already a sizable precise time user community with an increasing number of users as further PT&F dependent systems are brought into service. Numerically the largest PT&F user community is expected to be AJ communications, PT&F user systems will include the following:

- identification
- data links
- V/UHF AJ communications
- satellite communications
- radar systems

The provision of precise time for user systems has been dealt with on a system specific basis. Until recently there was no overall military policy, the associated PT&F infrastructure to coordinate their operation and to support interoperability has yet to be deployed. Future operations may well involve NATO forces in increased cooperation, such operations will depend on the ability of forces to communicate rapidly and reliably.

AC302/SG4/WG4– The NATO Precise Time & Frequency Working Group

In 1988 the Precise Time & Frequency Special Working Group was established to produce STANAG 4430, with the objective of aiding NATO interoperability by defining a standard interface for the transfer of precise time & frequency between equipments. The aim of the STANAG was to define a common interoperability interface as well as stopping the proliferation of user specific 'standards'. The secondary objective was to provide an alternative interface for use on systems to overcome the problem of one PT&F user on a platform being unable to transfer time to another system due to interface and message incompatibilities. The nations providing the major contribution to the STANAG were France, Germany, Netherlands, Norway, UK and the USA.

Initially the WG reviewed the PT&F user base and identified fundamental issues such as time distribution architectures, time references and time dissemination methods currently in use. As a result of the group's work it became apparent that interoperability was more complex than the definition of a standard interface and included the standardisation of a time reference, the management of time, its dissemination and military operational issues. The working group have nearly completed the draft of STANAG 4430, it is anticipated that it will be circulated within the nations during 1994.

The Management of Precise Time

Within the scientific community precise time is generally considered to be time that is accurate to a millisecond or better. Some military systems require time to at least this accuracy but even those requiring accuracies of a second will benefit from the automatic acquistion and maintenance of time. The management of time to millisecond accuracy or better requires that the time reference be identified. Most nations maintain their own time references using atomic clocks; time from these references is known as UTC(laboratory) e.g UTC(USNO). (UTC is universal coordinated time and USNO is the US Naval Observatory.)

National clocks are synchronised by the BIPM in Paris, currently their objective is to maintain synchronism to a few microseconds; it should be noted that, in general, the coordination and management of UTC is a civilian activity. Figure 1 shows how national UTCs have been maintained with respect to BIPM. As UTC is the time reference used by national governments and civilian users it is appropriate that it should also be used by NATO. UTC is adjusted to retain synchronism with the earth's rotation (the latter is less consistent than the time given by an atomic clock and may vary by a millisecond in a day). UTC synchronisation with the earth's rotation is maintained by the addition or subtraction of a 'leap second' as appropriate. Leap seconds are only applied at the end of July or the end of December. The application of leap seconds is controlled by a civilian organisation the International Earth Rotation Society (IERS).

UTC user systems have to develop strategies to accommodate the leap second change, and to take account of time dissemination systems with different ways of including leap seconds.

In some broadcast time references, leap seconds are only included within some hours of its application, and not necessarily simultaneously for all transmitters. NavStar GPS broadcasts GPS time (which corresponds to UTC at the time the system was started), the time message includes the number of leap seconds required to correct GPS time to UTC. Leap second changes can lead to confusion for UTC users; this can be avoided if the leap second information is included in the time message so that the user system can automatically compensate at the correct time.

PT&F Architectures

Figure 2 shows a generic time distribution architecture, which includes time transfer interfaces at points A, B and C. (This was the architecture used by the group to collect data on user systems.) The time reference is disseminated to the user system at interface A. A local reference, disciplined to the disseminated UTC, can then pass the time to the systems on the user platform. A platform reference can also be disciplined to the reference UTC via the local reference or directly from the time dissemination system. In this context the platform may be a military base, a ship, an aircraft or other user such as a man–pack radio. If the platform is required to have an autonomous capability then it must have some form of platform oscillator capable of maintaining time consistent with the integrity required by the platform user systems. For an aircraft this may be a few hours for a ship it could be days or weeks.

Time Management – TFOM

Systems having a PT&F autonomous capability must also manage the time within the system. An allowance should be made for the gradual increase in uncertainty in the accuracy of the time following synchronisation from an external time dissemination system. Uncertainty arises from unquantified errors in the distribution of time around the system as well as drift in the 'flywheel' oscillator. Oscillator drift will be exacerbated by environmental effects such as temperature changes and vibration. The time message should include a time figure of merit (TFOM), this is the current uncertainty in the system time accuracy with respect to UTC. When the TFOM exceeds system limits the performance of user systems can be expected to deteriorate. Comparison of the platform's TFOM with that of an external dissemination source, or of another platform, identifies whether the platform clocks accuracy will be improved or degraded by accepting time from that source. The degree of time management required within a system depends on the system specification.

Definition of the Draft STANAG 4430 Interface

The definition of the interface covers the time message information message, two different formats for the transmission of the message, the electrical interface and the connector specification. The interface can pass the following information:

- 1 pulse per second signal

- Standard Time Message (STM)
- Extended Have Quick Message (XHQ)
- An optional 5MHz signal

The interface is bidirectional enabling the information to be transferred in the direction required for interoperability. To ensure maximum utility the interface can be implemented as a bidirectional interface, a transmitter or a receiver. The implementation chosen depends upon the requirements of the system to which it is connected and the purpose of the port. For example a simple user may only require a time fill in which case only the receive function need be implemented. An interoperability port on a timing centre may only be required to transmit time, in which case only this function need be implemented.

The contents of the time information message are based on the groups analysis of the requirements of the systems analyzed, consideration of future requirements and the need for backwards compatibility to existing standards (e.g. Have Quick 2 and NavStar GPS PTTI). The time message format is shown in figure 3. The message, up to the TFOM, is the same as the Have Quick message. Additional information is given in the last two fields the leap second indicator shows if a leap second has been applied, and the last field the day on which it is to be applied. The TFOM is coded in two parts the first gives the TFOM decade (compatitable with the PTTI message), the second part gives additional precision (i.e. the TFOM is in exponent and mantissa form).

The design of the message and of the electrical coding scheme takes account of currently used standards and maintains a degree of compatibility with the NavStar GPS PTTI (precise time & time interval) interface as well as Have Quick 2. The interface disseminates the time message in two electrical formats one compatible with Have Quick 2 (an extended Have Quick format) and the other using an industrial standard interface and chip sets (the standard time message format using the EIA RS–485 standard). These formats are capable of transferring time with different accuracies, operating with different interconnecting cable lengths and having different noise immunities. This arrangement was chosen to simplify the interface required between the STANAG 4430 interface and current user equipment as well as making it more readily applicable as an interface between equipments. The specified connector uses a standard MIL–C–83723 shell with standard pins and inserts. The one pulse per second time marker, is available for high precision timing, and the 5 MHz signal for precise frequency users and oscillator calibration. Implementation of the standard frequency signal is optional, as not all systems can use it and some will be unable to generate the signal to the required accuracy and stability.

Application of the STANAG 4430 Interface

The standard interface requires an electrical connection so that the transmitting and receiving systems must be capable of making a physical connection. The connection could be a cable from a timing centre to the user, a cable connecting two user platforms or an interface for a travelling clock or electronic transfer device (ETD). These methods of time transfer meet the NATO military forces interoperability requirement of the interface. Interoperability is enabled since the interface receiver and transmitter can be on different platforms, of the same or different nations, and a standard message is transferred. The interface can also be used to transfer the time message between user systems on a platform, assuming that it is cost effective to do so. This application enables platform user system interoperability but is not directly enabling NATO military forces interoperability.

Implications of the MOR on PT&F

A NATO Military Operational Requirement (MOR) for precise time & frequency has been developed and the implications of its implementation are currently under review. The key requirements contained within the MOR are given in below.

The MOR requires that the reference time in user systems is referenced to UTC this is partly met by the use of NavStar GPS, the time message also includes leap second correction and is available to all user equipments.

The MOR requires that UTC be available continuously, as well as at the start and during a mission. The provision and maintenance of UTC requires a calibrated path from the time reference (typically a laboratory atomic clock) through to the reference clock in the user equipment. The infrastructure providing this traceability is likely to require time reference centres, which could be located at selected military bases, and probably deployable units to support assets away from their home base. To maintain UTC, and meet the requirement for autonomous operation, implies the availability of a 'flywheel' oscillator on platforms; the latter to be disciplined to UTC by a time processor. Output to users could be via a STANAG 4430 interface and broadcast transmissions possibly using Have Quick or MIDS.

The co–ordination of UTC is the responsibility of international civilian authorities who may not be able to maintain this function if they are denied access to long distance time transfer systems during wartime. Consequently, the implementation of the MOR has implications for the continual maintenance of UTC, its international co–ordination and the implementation of leap seconds.

The STANAG 4430 interface meets part of the MOR in particular it has an application in the transfer of time to a user system or platform at the start of a mission. The standard interface enables the transfer of PT&F to users, of any NATO nation, by any other nation, if available at external system and platform interfaces.

Conclusions

The NATO working group on PT&F has made considerable progress in defining a standard interface, the details are given in draft STANAG 4430. The STANAG defines not only the electrical and mechanical interface but also a standard time message; the specification is based on an analysis of the PT&F requirements of current users as well as an assessment of future user needs. Consideration has been given to the backwards compatibility of user equipments requiring compatibility with Have Quick and NavStar GPS PTTI formats. The aim of the interface is to support the interoperability of NATO forces, the STANAG contains information to assist with the design of timing architectures and to allow the traceability of the user systems UTC to that of the reference UTC.

Figure 1

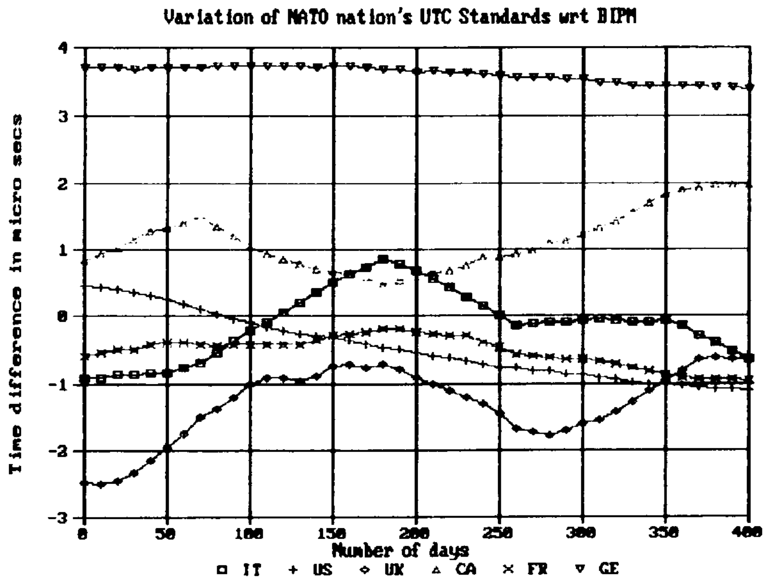

Figure 2

Generic Time Distribution System

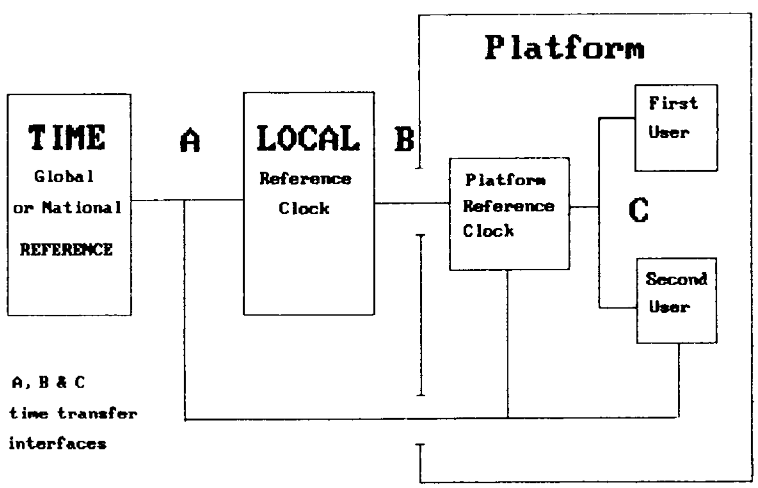

Figure 3

HOURS	MINUTES	SECONDS	DAYS	YEARS	TFOM	LEAP SECOND INDICATOR	LEAP SECOND DAY

Figure 1

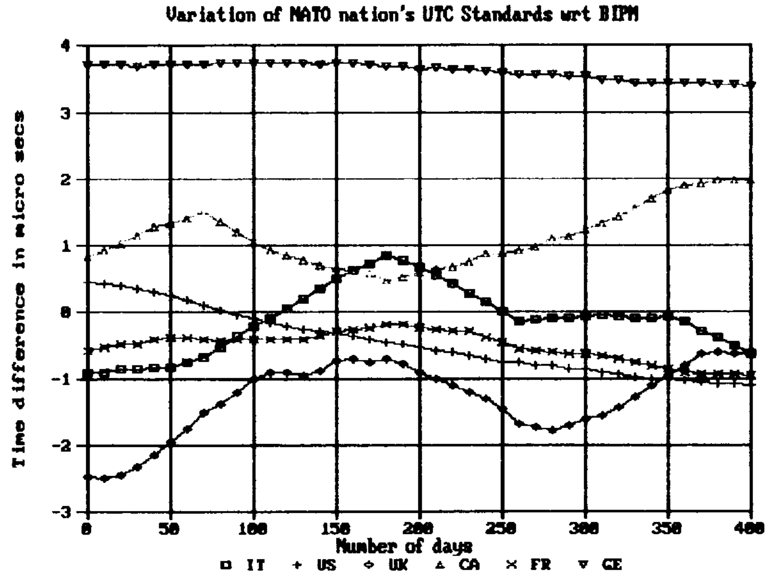

Figure 2

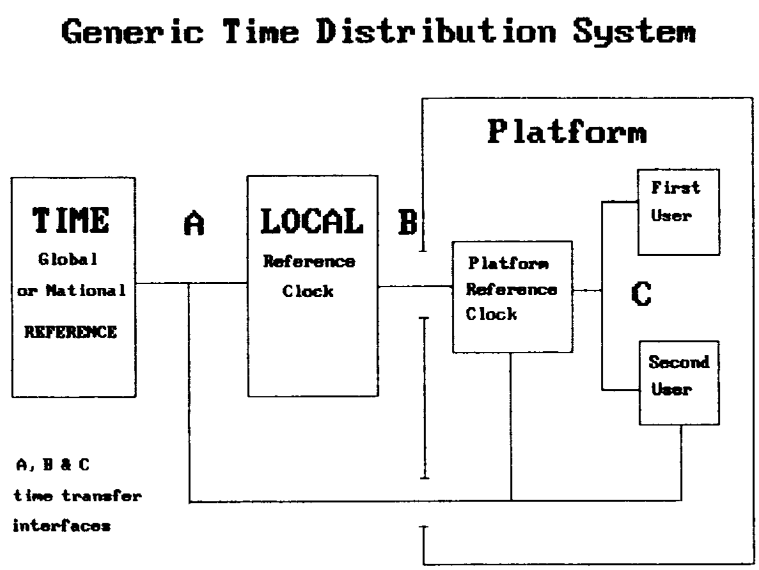

Figure 3

HOURS	MINUTES	SECONDS	DAYS	YEARS	TFOM	LEAP SECOND INDICATOR	LEAP SECOND DAY

6141 N94-30646

Two-Way Satellite Time Transfer: Overview and Recent Developments

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Abstract

The experiment using small earth stations for transatlantic two–way satellite time transfer between the USA (USNO, Washington, DC) and Germany (DFVLR), Oberfaffenhofen) has had its 10th anniversary this year. Pseudo Random Noise coded time signals were phase modulated and demodulated at each stations using a modem developed by Professor Hartl and his staff.

Recently, during the last two weeks of August 1993, six European time laboratories have used the INTELSAT 307E satellite for line–up tests and preliminary time transfer sessions using the same type of MITREX modem. This opportunity was given by INTELSAT, thanks to the help of Dr. Veenstra.

The need for a uniform format for the exchange of data was felt heavily after these sessions. This problem was foreseen and addressed in international working parties.

During April 1993 in Task Group 7/2 of the ITU Radiocommuncation Sector (formerly CCIR), a very intense discussion has taken place about what procedures should be recommended for TWSTFT and what items the header and data lines of the resulting data fields should contain. A difficulty is that two different methods of calibration of the earth station delays exist which results different sets of delay data to be exchanged. Further study and discussions are necessary.

Also, a meeting of the CCDS Working Goup on TWSTFT addressed this in October 1993. The outcome of the discussions and the prospect for future developments will be presented.

Introduction

Today the best, that is the most uniform and accurate, time scales are produced by cæsium atomic clocks. The unit of time, the second, is defined on the quantum mechanical properties of atoms of Cs–133. Its accuracy and long term stability has not been surpassed yet and for this reason caesium clocks are used by the national timing centres for time scales. These clocks can contribute to the formation of the International Atomic Time (TAI) if a good quality comparison method to the BIPM is used.

The delay calibration for the signal path of the remote clock in the wanted accuracy regions of 10 ns or better for state of the art cesium clocks is a great problem, especially for radio links which are changing with distance, ionosphere, troposphere, air humidity and air density, temperature, earth conductivity and so on.

To avoid most of these influences by cancelling in first order the Two Way Satellite Time Transfer (TWSTT) scheme has been introduced: at both clock sites the time signals are transmitted to a common satellite at the same instant and on both sides the signal from the other clock is received and measured. After the exchange of the measured data the difference of the two clocks is calculated, and the delays cancel due to the complete reciprocity of the signal paths. The inaccuracy of the result is the departure from the assumption of complete reciprocity.

Two way time comparison equation

From fig 1 we can see that the difference of the clocks at station 1 and 2 can be determined.

TA(k) is the time scale at station k
TI(k) is time interval reading (1 pps TX - 1 pps RX)
TT(k) is transmitter delay
TR(k) is receiver delay
TU(k) is uplink delay
TD(k) is downlink delay
TS(k) is satellite delay
TCU(k) is the Sagnac correction needed in the uplink
TCD(k) is the Sagnac correction needed in the downlink

The time scale difference TA(1) - TA(2) can be obtained from:

$$TA(1) - TA(2) =$$

$$0.5xTI(1) - TI(2) \quad \text{TIC Reading differences(1)}$$
$$+0.5xTS(1) - TS(2) \quad \text{Satellite delay difference(2)}$$
$$+0.5xTU(1) - TD(1) \quad \text{Up/Down difference at 1(3)}$$
$$-0.5xTU(2) - TD(2) \quad \text{Up/Down difference at 2(4)}$$
$$+0.5xTT(1) - TR(1) \quad \text{Transmit/Receive diff. at 1(5)}$$
$$-0.5xTT(2) - TR(2) \quad \text{Transmit/Receive diff. at 2(6)}$$
$$+0.5xTCU(1) - TCD(1) \quad \text{Sagnac effect at 1} \quad (7)$$
$$-0.5xTCU(2) - TCD(2) \quad \text{Sagnac effect at 2} \quad (8)$$

The right hand expression items (2) to (6) are 0 when full symmetry is obtained; the accuracy depends on the departures from symmetry and these are discussed below.

Departures from delay symmetry

Satellite delay difference

If in the satellite the same frequency, the same receive antenna, transponder channel and transmit antenna is used, then the delays TS(1) = TS(2). This is not the case when different frequencies, transponders or different spot beams are used for the reception and/or transmissions from each station, i.e. the transatlantic Intelsat satellites. In this case TS(1) and TS(2) or at least the difference TS(1) - TS(2) should be measured before the launch of the satellite. If not available, the difference might be estimated from detailed drawings of the satellite transponders and its wiring.

Another problem is that when the antennas for two different spot beams are not collocated there can be a separation of several meters, and its time difference effect may vary depending on the satellite orientation with respect to station 1 and 2. Every meter difference in separation may cause up to 3 ns non–reciprocity error!

If the signals from both stations cross each other at the satellite at the same moment, or at least the satellite is not moving in the time between the signals pass the satellite, then the up and down path lengths are equal. However, if the satellite is moving at a range rate of i.e. 3 m/s, then the signals experience the double value of 6 m/s, so if the signals pass the satellite within 0.01 s then this correction amounts up to 0.5 x (6 / c /0.01) = 100 ps, where c = speed of light.

Up/Down propagation delay difference

Ionosphere

The up and down link signals differ in carrier frequency and they experience a different ionospheric delay equal to 40.3 * TEC * (1/c) * ($1/fd^2$ - $1/fu^2$). For TEC = 1 * 10^{18} electrons/m2 and for 14.5 /12.0 GHz this ionospheric delay = 0.932 ns - 0.639 ns = 0.293 ns. So the correction for TU(k)-TD(k) is smaller than -0.3 ns.

Troposphere

The troposphere gives a delay depending on the water content of the air, air density and temperature, but this delay is not frequency dependent and its influence on the up and down propagation delay is equal and no correction for TU(k)-TD(k) is needed.

Transmit/Receive Station delay difference

The difference of the transmit and receive section including the up– and down convertors, modulator and demodulator (modem), feeds, wiring, etc. has to be determined at each station. Methods proposed to obtain this have been:

- collocation of both stations
- subsequent collocation of a third (transportable) earth station at both stations
- using a satellite–simulator + calibrated cable.

The last method is the least expensive and can be used frequently. This method is explained in the literature and consists of the calibration of a auxiliary cable, measurement of the sum of the transmit and receive delay, measurement of the sum of the auxiliary cable delay and the receive delay and calculation of the receive and transmit delay from the measurements.

The internal transmit and receive delay of the modems have to be determined too. This can be done by collocating the modems and measuring the sum of the transmit delay of one modem and the receive delay of the other; so the difference of the transmit delays of the two modems is found, not the real values. Another absolute method is indicated in the literature, but this requires opening the modem and making a temporary modification. Modem delay TT(k)-TR(k) asymmetries of -526 ns have been measured.

Sagnac effect

Due to the movement (rotation around the centre of the earth) of the earth stations and the satellite during the propagation of a time signal to and from the satellite a correction has to be applied to the propagation time of the signal. This amounts for one way from satellite down to station k:

$$TCD(k) = \Omega/c2 * Y(k) * X(s) - X(k) * Y(s) \quad (1)$$

where:

$$\begin{aligned}
\Omega &= \text{earth rotation rate} = 7.2921 \times 10^{-5} \text{ rad/s} && (2)\\
c &= \text{speed of light} = 299\ 792\ 452 \text{ m/s} && (3)\\
r &= \text{earth radius} = 6367\ 000 \text{ m} && (4)\\
R &= \text{satellite orbit radius} = 42\ 150\ 000 \text{ m} && (5)\\
(k),(s) &= \text{station (k), satellite (s)} && (6)\\
X(),Y() &= \text{geocentric coordinates in meters} && (7)\\
& && (8)
\end{aligned}$$

If only Latitude and Longitude are known, then for geostationary satellites for which LA(s) = 0:

$$TCD(k) = \Omega/c2 \times R \times r \times \cos(LA(k)) \times \sin(LO(k) - LO(s)) \quad (9)$$

where: LA(), LO() are the latitude and longitude, respectively.

X(), Y() can be calculated from:

$$\begin{aligned}
X(k) &= r\cos(LA(k)) * \cos(LO(k)) \quad , \quad X(s) = R\cos(LA(s)) * \cos(LO(s)) && (10)\\
Y(k) &= r\cos(LA(k)) * \sin(LO(k)) \quad , \quad Y(s) = R\cos(LA(s)) * \sin(LO(s)) && (11)\\
& && (12)
\end{aligned}$$

The uplink Sagnac effect TCU(k) is equal to TCD(k) but of opposite sign:

$$TCU(k) = -TCD(k)$$

Total Sagnac correction Two–Way:

$$0.5TCU(1) - TCD(1) - 0.5TCU(2) - TCD(2) = -0.5$$

$$2TCD(1) + 0.52TCD(2) = -TCD(1) + TCD(2)$$

Example:

LA(VSL) = 52 N	LO(VSL) = 4 E	LO(sat) = -53 E	TCD(VSL) = +112.42 ns
LA(USNO)= 39 N	LO(USNO)= -77 E	LO(sat) = -53 E	TCD(USNO) = -68.83 ns

link VSL -> USNO: TCU(VSL)+ TCD(USNO) = -112.42 + -68.83 = -181.25 ns

link USNO -> VSL: TCU(USNO) + TCD(VSL)= +68.83 + +112.42 = +181.25 ns.

Achievements and status of TWSTT

The two–way method using microwave carrier frequencies and satellites has been used already in 1962 on the Telstar satellite between the United Kingdom and the USA (Fig.2).

The use of bi–phase modulation with PN code has been reported in 1974 and the use of a dedicated modem (Mitrex) for high precision time transfer has been reported in 1983 giving 0.5 ns precision.

Since August 1987 the time scales of USNO, NIST and NRC are routinely compared using the two–way Mitrex method 3 times per week on a US domestic satellite. Results show a precision of 1 ns at 1 s averaging time.

An excellent result has been reported from TUG, using a EUTELSAT ECS satellite for two–way time transfer between France and Austria during LASSO experiments and also common view GPS measurements were taken in 1990 and 1991. This work included a careful calibration by collocating the French portable station and the Austrian station. The difference between two–way and GPS was 3 ns with a precision of also 3 ns.

Three TWSTT experiments in Japan (CRL) using 1.8 m antenna were conducted: a. ranging in 1989, b. TWSTT over 120 km distance in March 1992 and c. the third experiment TWSTT between Japan (CRL) and Korea (KRISS) in April 1992. The results were: a. precision 0.43 ns @ C/No = 59 dBHz, Allan deviation $3 \times 10^{-10}\tau^{-3/2}$; b. precision 0.94 ns, Allan deviation $2 \times 10^{-9}\tau^{-3/2}$; c. difference GPS-TWSTT 10 ns accuracy level, precision 0.94 ns , Allan deviation $2 \times 10^{-9}\tau^{-3/2}$. A Mitrex 2500A modem was used as well as a Mitrex compatible prototype I–modem (Imamura, CRL).

In Germany a TWSTT between PTB (Braunschweig) and FTZ (Darmstadt) took place starting September 1992 using the German domestic satellite Kopernikus. Both stations were VSAT's from identical design: 1.8 m antenna, EIRP 50 dbW, G/T 22 dB/K, upgraded MITREX 2500A modem. The precision obtained was 300 ps which was consistent with the expected value at C/No between 65 and 70 dB/Hz. The difference with GPS measurements was up to 20 ns (at TZ the GPS receiver coordinates were not highly accurate).

In Italy, an experiment between IEN (Turin) and ISPT (Rome) was performed during March to June 1993 using Olympus satellite and upgraded MITREX 2500A modems; some unexplained periodic instabilities (10^{-15} ns) were observed. Olympus has become inoperative, an other European satellite will be used in the future.

In the UK, NPL has studied and measured during 1992 the delays of elements of the NPL TWSTT earth station and their temperature dependence in the 10 ps range. Some interesting typical results: variations of ± 1 ns in the total delay asymmetry during 3 days; ± 2.5 ns uncertainty of absolute delay asymmetry values; Mitrex 2500 delay asymmetry (510.1 ± 2) ns, temperature coefficient -63 ps/°C; satellite simulator mixers TC = 12 & 20 ps/°C, power delay coefficient 20 ps/dB, frequency delay coefficient 5 ps/MHz, uncorrelated changes with time 20 ps.

In 1992 a transatlantic TWSTT line-up test (Fig. 3,4,5) between USNO and TUG (Austria) has been established using the INTELSAT VA (IBS) satellite at 307° E using a VSAT at TUG. The elevation from TUG was only 6°. A precision of 0.7 ns was obtained and a modified Allan deviation of $1.3 \times 10^{-9}\tau^{-3/2}$. The difference between GPS and TWSTT measurements, after applying Sagnac correction and all other known corrections, was about 350 ns; so this is the sum of the unknown non-reciprocity in the satellite delay and in the earth station equipment delay.

Recently, during the last two weeks of August 1993, six European time labs (TUG, NPL, PTB, FTZ, VSL, OCA) have used the same INTELSAT 307° satellite for line-up tests and preliminary TWSTT (Fig. 6). The first results (Fig. 7–10) show a modified Allan deviation ranging from 1 to 3 $\times 10^{-9}\tau^{-3/2}$ at an EIRP of 47 dBW from the stations. The possible deterioration with multiple use was tested with clean carriers as well as with PRN coded signals. Also the deterioration as function of EIRP was tested. Not all results are yet fully examined and understood. A three station closure error will be also examined. A longer term test has started in november with sessions 3 times per week. Also a line-up test for a new transatlantic TWSTT including USNO and NIST also using the INTELSAT 307° satellite is foreseen end 1993 and beginning of 1994.

Support from International Organizations

The remarkable results with the TWSTT have been recognized by international bodies that deal with accurate time scales and its dissemination.

In EUROMET (EUROpean cooperation of national standards labs on METrology), in the field of time and frequency, a project concerning the use of two–way has been initialized in 1987 and in several European countries steps have been taken to implement two–way at the national standards institutes for time, i.e. Germany, UK, France, Austria, Netherlands, Italy (Fig.11). Bottlenecks were the costs and delivery time of earth stations, the availability of modems and to get the necessary permissions for the transmitting earth stations. Also the national signatories of satellite organizations had to be approached for transponder time.

The Comité Consultatif pour la Définition de la Seconde (CCDS) adopted a Recommendation in 1985 which was confirmed in 1987 by the 18th Conférence Géneral de Poids et Mesures

(C.G.P.M.) to implement two-way satellite links using PRN-coded signals for the transfer of International Atomic Time.

In 1989 the CCDS asked the Bureau International des Poids et Mesures (BIPM) to establish ad hoc working groups to coordinate activities on such time links (Fig.12). Since then two ad-hoc working-group meetings have been held: in June 1989 in cooperation with the EUROMET Project members at VSL in Delft, Netherlands and in October 1992 at TUG in Graz, Austria. Recommendations were made. In Europe the 12.50 to 12.75 GHz down link and the 14.0 – 14.5 GHz up link would be used on i.e. ECS or Intelsat satellites. The Mitrex coding would be used as a start, and possible shortcomings could be studied. The INTELSAT 307° satellite as proposed by Veenstra was preferred for transatlantic links, and could also be used for US and European regional links.

During the CCDS meeting at the BIPM in March 1993 the ad-hoc working group was transferred into a permanent "Working Group of the CCDS on Two-Way Satellite Time Transfer". This Working Group has met on 20 and 21 October at the NPL in Teddington (UK). After status reports from the labs, the data-format for the exchange of TWSTT data was discussed in connection with a ITU-R draft Recommendation on TWSTT. A flexible data format was agreed together with designations of labs (Figs. 13-16). Also makers of TWSTT modems (MITREX, SATRE, ATLANTIS, NIST) updated the status of their modems. A report on INTELSAT with respect to TWSTT was given by Dr. Veenstra. Also the calibration of TWSTT earth station delays were discussed. A co-location of European stations with an transportable USNO earth station will be organized in 1994. The goal is to combine this with a VSL satellite simulator to obtain as correct as possible absolute delay measurements. This is expected to solve the problem that even from a visiting third station the individual delay corrections at two earth stations cannot be determined. NPL has offered to edit a TWSTT Newsletter, the first issue has been distributed in October 1993. Contributions can be sent to John Davis, NPL, Teddington, Middlesex, United Kingdom, TW11 0LW.

Also in the International Telecommunication Union (ITU), the ITU-R (the former CCIR) Study Group VII in Geneva has adopted a question to study two way time transfer and for this purpose a Task Group (TG7/2) has been established in 1991 (fig. 17). Its task will be to issue Recommendations about the use of TWSTT (including procedures and data format) and how to avoid or solve encountered problems. This TWSTT question was recently designated urgent by the ITU Radiocommunication Assembly in November 1993.

In April 1993 the first Meeting of TG7/2 was held in Geneva. A very thorough discussion about delay calibration methods and the data format took place. A preliminary draft recommendation was adopted, but the content of two Annexes that will give more details about the calculation and measurement procedures as well as the data format have to be finished by the participants by mail and will then be adopted at the next formal meeting in the fall of 1994. Cooperation and coordination with other Working Groups like the CCDS and EUROMET has been sought; technical matters should be discussed in TG7/2 and organizational matters concerning the contribution to TAI should be discussed in the CCDS Working Group although some overlap may occur. As a consequence, the above mentioned ITU TG7/2 data format document was discussed and a first draft agreed at the CCDS TWSTT meeting in Teddington October 1993.

Conclusion

Very promising results with Two–way Time Transfer have been obtained and interesting experiments are being planned. The use of small earth stations (VSAT's) at the premises of the timing centres has now been achieved. There is still much to do to obtain the inherent good absolute accuracy of TWSTT.

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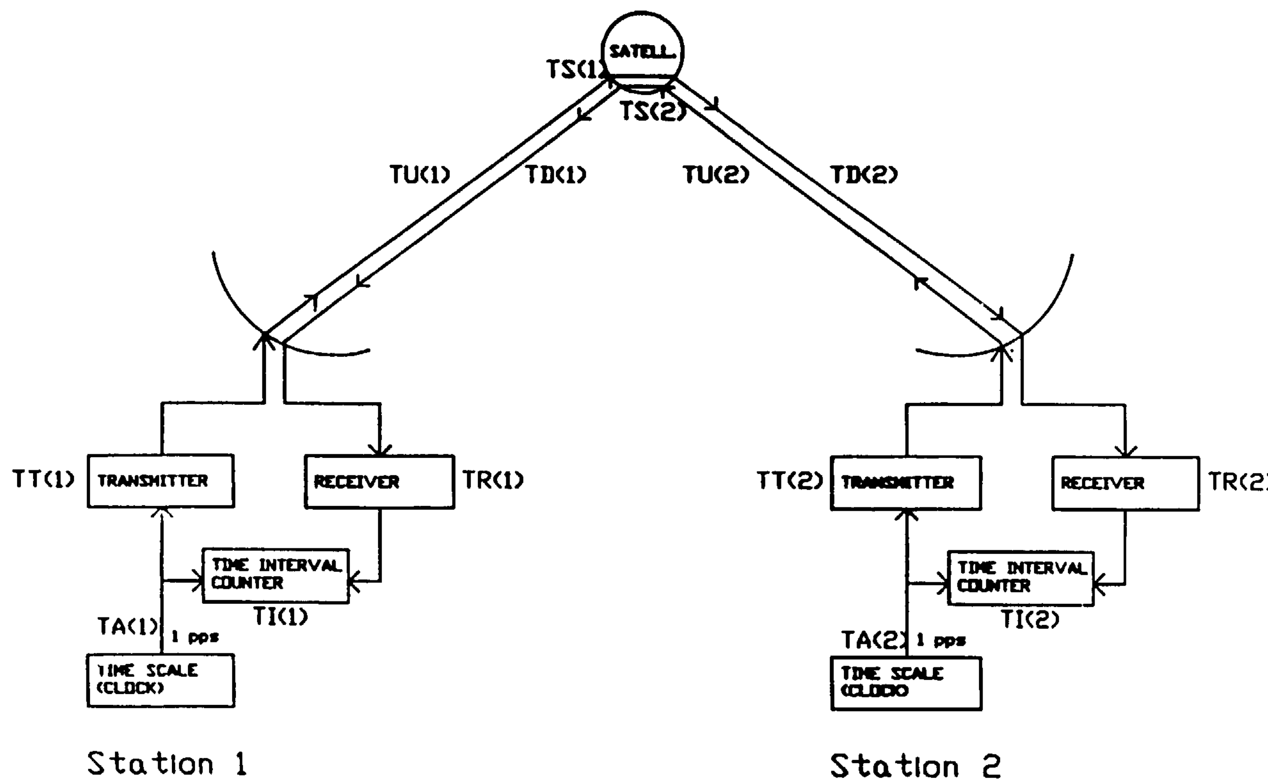

Fig. 1 Basic Two-Way Satellite Time Transfer scheme

1962 Telstar UK, USA

1974 PN code & BPSK

1983 MITREX: Transatlantic USNO, DFVLR; <0.2W, 55 dBHz
small antenna 2.4 m, 1 ns Intelsat 325

1985 NAVEX experiment Space Shuttle German DFVLR

1987 MITREX NIST, USNO, NRC routinely 3x/week

1990 MITREX TUG(A), OCA(F), LASSO & GPS ECS

1992 MITREX Transatlantic TUG, USNO Intelsat 307
Japan (CRL) - Korea (KRISS) Intelsat 177
Germany: PTB - FTZ Kopernicus sat

1993 MITREX Italy: IEN (Turin) - ISPT (Rome) Olympus
W-Europe: TUG(A), PTB(G), FTZ(G),
NPL(UK), OCA(F), VSL(NL)

1994 Plans: long term experiment W-EUR 3x / wk + US

Fig. 2 Progress of TWSTT

INTELSAT V-A(F13) at 307 E (53 W)

Stations: NIST, USNO, TUG, VSL, PTB, NPL, OCA, FTZ
(IEN, LPTF, NRC)
Occasional Use / No full connectivity

Transatlantic
West Spot (USA) Uplink 14.0 GHz
West Spot Downlink 11.7 GHz
East Spot (W-Eur) Uplink 14.0 GHz
East Spot Downlink 12.5 GHz

Useful for transatlantic Time Link for BIPM
International Atomic Time (TAI)

for regional links in USA and W.-Europe
but not coincident any more

(see Veenstra, Proc. PTTI, 1990)

Fig. 3 Transatlantic link USA-Europe

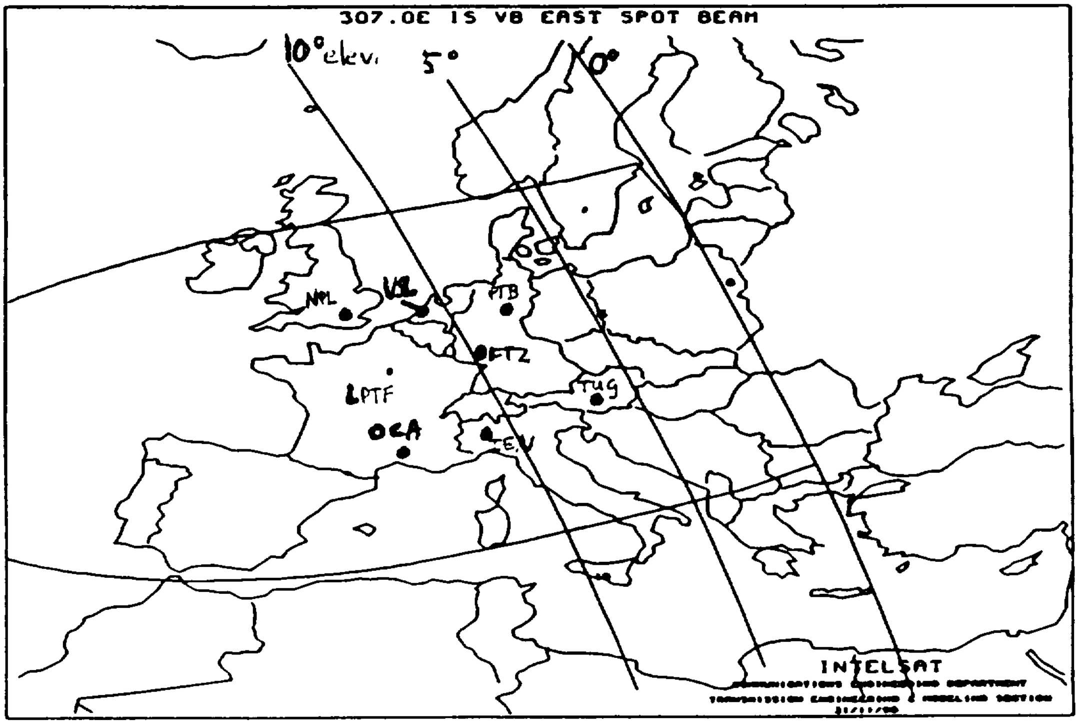

Fig. 4 Footprint Europe East Spot INTELSAT 307

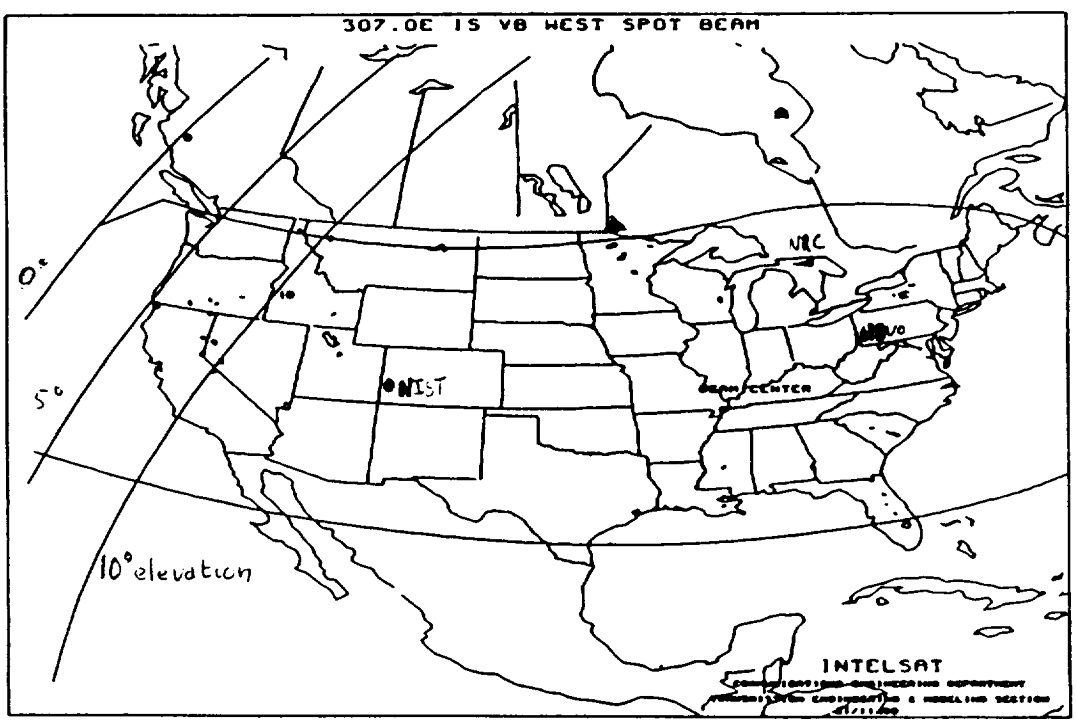

Fig. 5 Footprint North America West Spot INTELSAT 307

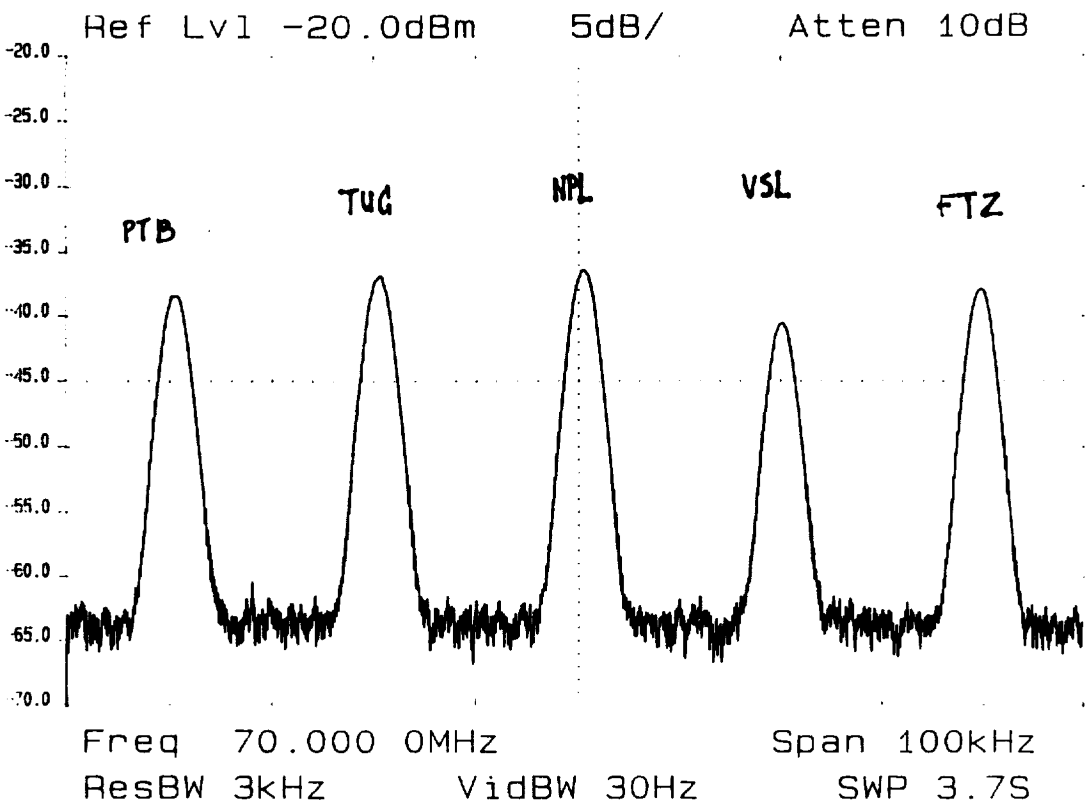

Fig. 6 Clean Carriers of the European Labs offset by n * 20 kHz

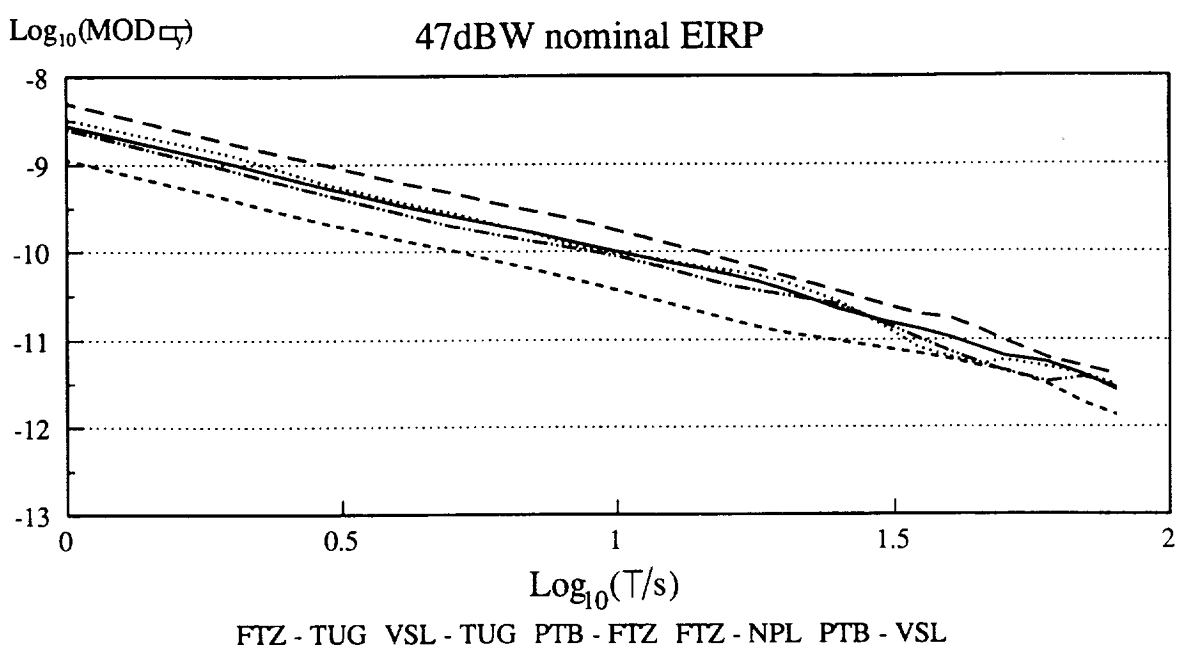

Fig. 7 Stability plot of different TWSTT pairs

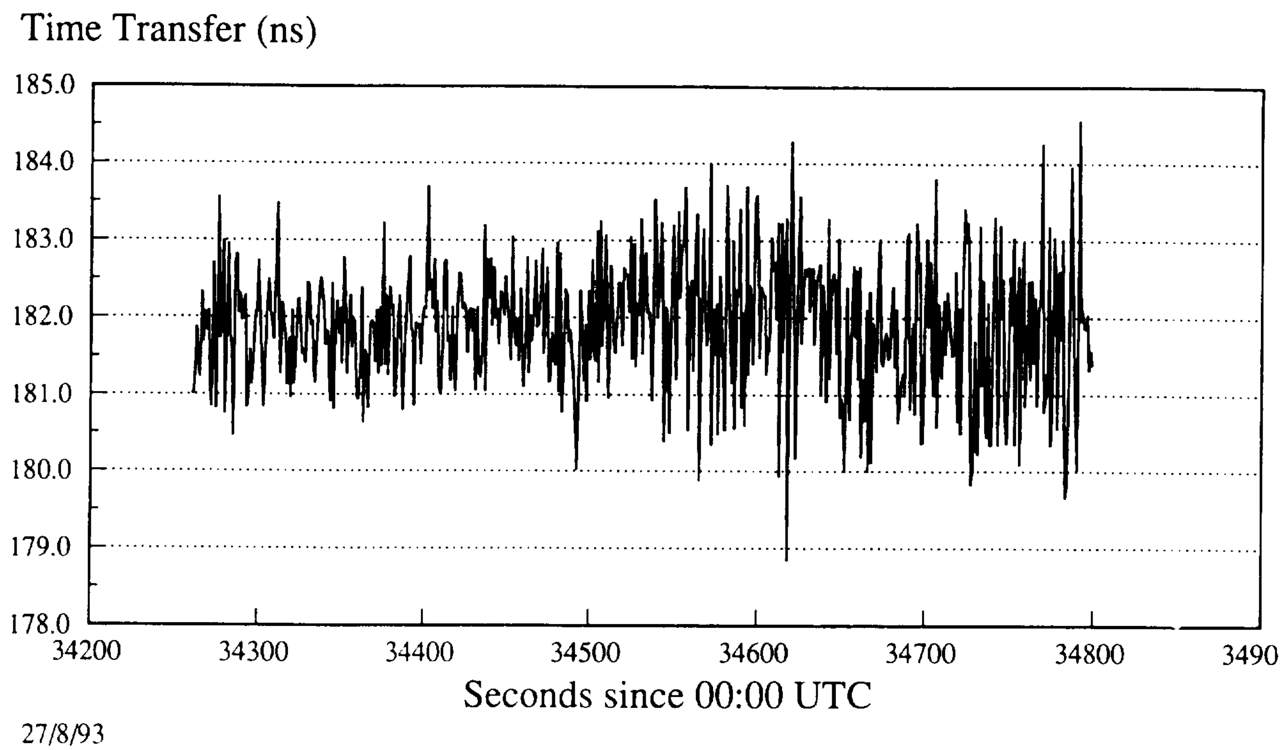

Fig. 8 Run of TWSTT data VSL-TUG

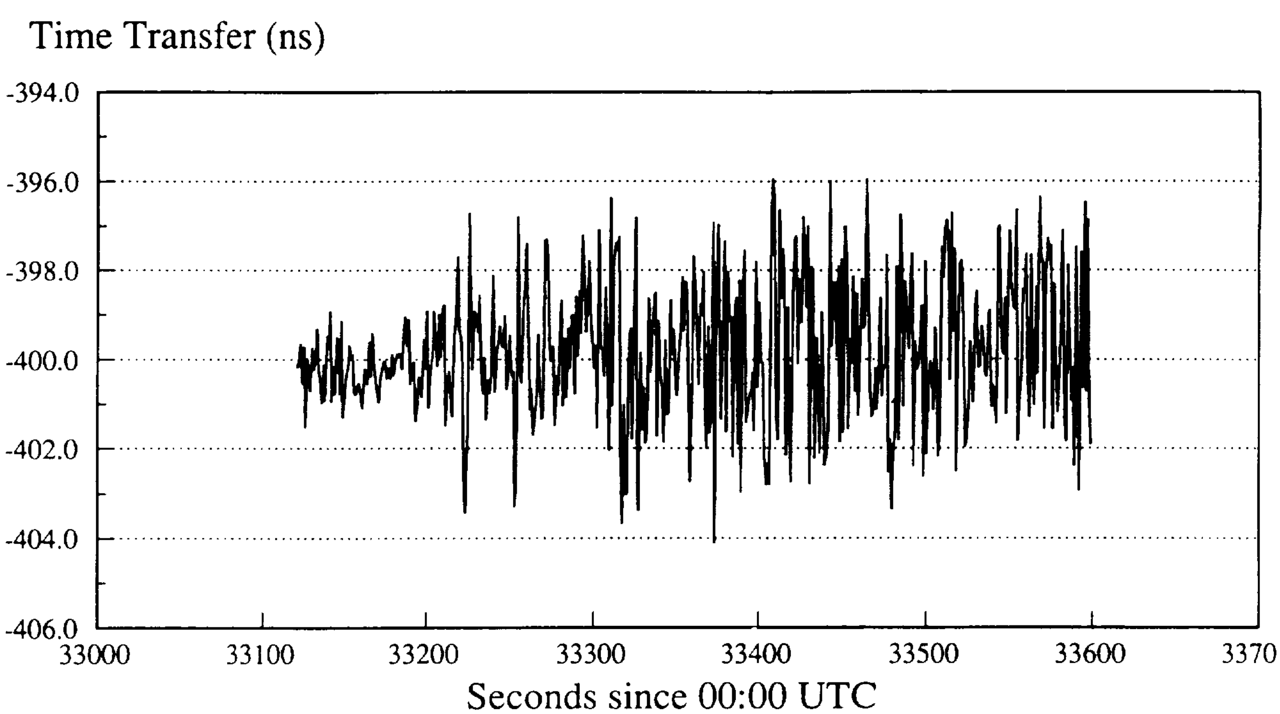

Fig. 9 Run of TWSTT data VSL-NPL

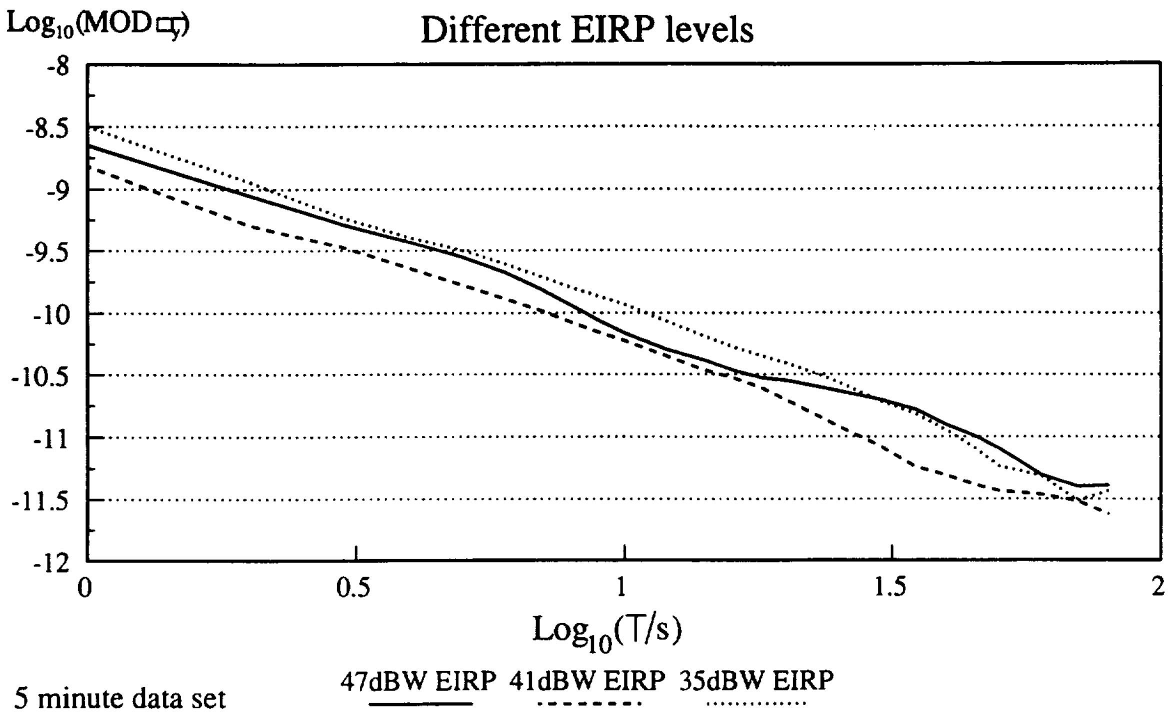

Fig. 10 Stability plot NPL-VSL at different EIRP levels

EUROMET

Project 93

Satellite Time and Frequency intercomparison using PRN codes (Two-Way method)

Participants:

NL (VSL)	G. de Jong
AT (BEV, TUG)	D. Kirchner
DE (PTB, FTZ)	P. Hetzel, A. Söring
FR (LPTF,OCA)	P.Uhrich, F.Baumont
GB (NPL)	J.Davis, P.Pearce
IT (IEN)	F. Cordara

- get earth stations ready
- select satellite, get transponder time
- measurement schedule

Fig. 11 EUROMET TWSTT Project

Convention of the METER

CCDS - Comité Consultatif pour la Définition de la Seconde

CGPM - Conférence Générale des Poids et Mesures

BIPM - Bureau International des Poids et Mesures, Sèvres (F)

1985 CCDS, 1987 CGPM: Recommendation to support the use of PRN on Two Way for International Atomic Time

1989 CCDS: Recommendation that the BIPM establish and coordinate (regional) ad-hoc working groups for Two Way

1993 CCDS Working Group on Two-Way Satellite Time Transfer
How to use TWSTT for TAI formation
Chaired by: Cl. Thomas (BIPM)
Secretariat: W. Levandowski (BIPM)

Fig. 12 CCDS Working Group

TWSTFT DATA FORMAT

LAB Designations

LAB	DESIGNATION (ASCII char)	TX CODE (MITREX)	FREQ. OFFSET (kHz from center)
TUG	A	0	-20
NPL	B	1	0
VSL	C	2	+20
FTZ	D	3	-40
PTB	E	4	+40
OCA	F	5	+60
NIST	G	6	+80
USNO	H	7	-80

Fig. 13 Agreed TWSTT data format: Lab designations

TWSTFT DATA FORMAT

Legend

```
jjjjj        = Modified Julian Date
hh           = UTC hour
mm           = UTC minute
ss           = UTC second
L            = designates the LOCAL lab. by an ASCII char.
R            = designates the REMOTE lab. by an ASCII char.
*            = indication at the start of a line of text
[ ]          = designates an option
|            = designates a choice
0.nnnnnnnnnnnn =
        time interval in seconds to 12 decimals (res. 1 ps)
```

Fig. 14 Agreed TWSTT data format: Legend

TWSTFT DATA FORMAT

Data file format

```
FILENAME = Ljjjjjhh.mmR    where jjjjj, hh, mm give
           the nominal start date of the TWSTFT session

HEADER:
* Ljjjjjhh.mmR
* UTC(LAB) - CLOCK = 0.nnnnnnnnnnnn [jjjjj hhmmss]
* CLOCK - 1PPSREF= 0.nnnnnnnnnnnn [jjjjj hhmmss]
* 1PPSREF - 1PPSTX = 0.nnnnnnnnnnnn [jjjjj hhmmss]
* DATA = [1PPSREF - 1PPSRX]|[1PPSTX - 1PPSRX]|[TESTLOOP]|[.]

DATA:
jjjjj hhmmss 0.nnnnnnnnnnnn
  |     |         |
  |     |         |
jjjjj hhmmss 0.nnnnnnnnnnnn
```

Fig. 15 Agreed TWSTT data format: Data Format

TWSTFT DATA FORMAT

EXAMPLE of Data file format

Contents of File A4926610.56B of data measured at TUG from a TWSTFT session with NPL on MJD 49266 scheduled at 10h 56 min :

```
* A4926610.56B
* UTC(LAB) - CLOCK = 0.000000123456 49266 101000
* CLOCK - 1PPSREF = 0.000000012345 49266 101500
* 1PPSREF - 1PPSTX = 0.000000001234 49266 102000
* DATA = 1PPSREF - 1PPSRX
49266 105616 0.270924666406
49266 105617 0.270924663805
49266 105618 0.270924660170
49266 105619 0.270924657628
49266 105620 0.270924654270
```

Fig. 16 Agreed TWSTT data format: Example

ITU - International Telecommunication Union

ITU-R - Radiocommunication Sector, (formerly CCIR: Comité Consultatif International de Radio)

SG7 - Study Group 7, Science Services
WP7A - Working Party 7A, Time and Frequency
TG7/2 - Task Group 7/2, Standard T/F from Satellites

1991 New Question to Study Two Way Time Transfer through Communication Satellites:

- long-term stability
- time accuracy
- frequency comparison capability
- performance compared to other methods
- causes & cures systematic delay variations
- standard data (exchange) format for comparisons

Fig. 17 ITU-R Task Group 7/2 on TWSTT

QUESTIONS AND ANSWERS

J. Levine, NIST: Have you looked at the correlations between the station data and the remote monitoring data?

Lt. Norm Mason: We have not done that yet, mainly because we haven't taken the data and refined it. Part of the problem is that we also want to look at the time of transmission and that has given us some problems. The data is not really valid enough to do a real hard look correlation.

Christine Hackman, NIST: You mentioned briefly that you had tried using two–way satellite time transfer. But you didn't say much more than that, except for it worked. Could you just expand a little bit more on what you tried?

Charles Justice: Basically we had a two–way transfer antenna set up at Seneca, New York. We had personnel from USNO helping us to install this. Then they used their two–way satellite van up there to collect the data. And it was just about that simple. I think we were only there a day or two. And from the data that they got, as short as it was, it showed that we got excellent measurements; and they were 1 below 10 ns. I can't remember exactly the level. If you are interested, we could send you the printouts of the charts that we got. But that was it. We had hoped to put these in at all of our master stations because we were pretty certain from those results, and also from two–way work at NIST and USNO being done for several years at least. I know it goes back at least a few years. We were pretty sure that it would more than meet the 100 ns requirement that the public law stated. But that is when we found out that our source of funds was going to dry up; we then had to drop the project because we couldn't do anymore. We were originally going to set up the antennas at all the master stations and get the modems and everything else necessary. But that is as far as we could take it.

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P-13

OPTICAL TECHNIQUES FOR TIME AND FREQUENCY TRANSFER

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Abstract

Light has been used as a mean for time synchronization for a long time. The flight time was supposed to be negligible.

The first scientific determination of the velocity of the light was done by measuring a round trip flight time on a given distance (France 1849). The well known flying clock experiment leading to Einstein General Relativity is another example (1905).

The advent of lasers, particularly short pulse and modulated ones, as well as the improvements of the timing equipments have led to new concepts for time and frequency transfer.

We describe in this paper some experiments using different techniques and configurations which have been proposed and tested in this field since the beginning of the space age. Added to that, we set out advantages, drawbacks and performances achieved in the different cases.

INTRODUCTION

The development of lasers and space techniques have again put into focus optical time and frequency transfer techniques. This area is so far one of the most advanced and has the best potential for very accurate time and frequency transfer.

The definition we have adopted in this paper is that the information about time and frequency transfer is carried by an optical beam which can be modulated. The most widely used method is intensity modulation (continuous wave or pulsed beam). It can also be frequency modulation or the rotation of the polarization.

Optical techniques already existed before lasers, but actually it is with their advent in the mid 50's that more and more precise experiments have been made. The advance of civilisation has led to the need for more and more precise dissemination and synchronization in the time and frequency domain. Accuracies reach the nanosecond level for day to day applications or the picosecond level for research.

Actually three different methods have evolved successively and have coexisted. This is still true nowadays where the three techniques and their application still coexist.

The method we call "one way" was the most intuitive. It was also the only possible method as long as we did not know how to modulate a signal. The first artificial modulations were also one way mode, until the modulation was fast enough to get evidence of the speed of the light, leading then to two way methods.

The need for time transfer at such distances that the two sites are not in direct view, has led to use of "relays" (satellites, etc..), because the transfer with "multiple steps" did not give the necessary precision. The double two way was adopted since then.

The improvement of techniques are such that we are far from reaching the limits of these three methods. The evolution in time and frequency transfer techniques leads into prediction that we will reach the subpicosecond domain in the next 10 or 20 years.

HISTORIC

For thousands of years optical observations were sufficient to regulate daily activities. When religions began to appear, it led to the need for calendars based on ephemeris:

- Solar ephemeris : Incas, Egyptians, Greeks, Romans
- Lunar ephemeris : Pre hellenic, Mesopotamian

Some religious events are still related to the motion of the Moon and the Sun:

- Easter, Passover, Ramadan, Civarâtri.

Navigation has required new methods for providing time, and these have endured until the coming of the "marine chronometer".

Knowing the direction of the sun is not enough to determine one's position on the surface of the Earth, it is also necessary know the time of a zero longitude. Therefore, the ephemerides for navigation were based on the movements of celestial bodies such as the Jupiter satellites, planetary eclipses and even lunar eclipses and occultations. The rapid advance of sea navigation, and the high number of accidents drew inventors to study other methods, for more precise and more accessible time than obtainable by astronomical methods.

One of the most successful and durable has been the time Ball. The time Ball is used to check one's chronometer for sea navigation. The inventor was Captain Wanchope of the Royal Navy. There was a Ball on a staff, and someone would raise it. Someone else was watching the clock, and at a particular time, he lowered the Ball. It was later done by direct telegraphic signals. The first time the Ball was dropped in England was at Greenwich Royal Observatory in 1833. The first North American one was also very early in the 1840 's. It was lowered at the Naval Observatory in Washington. The Time Ball was utilised up to the 1930's. Useage began to decrease when radio signals became important. If you can get time at sea, you are really no longer interested in getting time only when you are at seaport. The Time Ball has been also employed to give accurate time to railroad networks and cities.

Simultaneously military people in order to coordinate the attacks of their armies developed some other optical methods for synchronization such as fires, flares, etc...

All these methods presented above are what we define as "one way". These techniques have improved a lot with the advent of lasers. The modulation is being carried by other media then air (optic fibers, etc..). In particular, lasers have lead to better precision, to longer range, to diversification of the transit media, and to directivity assuring discretion of experiments.

ONE WAY TECHNIQUES (Fig.1)

In the development of this technique three steps could be considered :

A. PASSIVE MODE

1. Visible very distant object as a reference for direction. The modulation of the direction and/or the amplitude of the beam is made by the rotation of the earth (sunrise, sunset, sundials). It gives only the Local Time and is dependant on the position of the observer on the earth, thus it does not allow any navigation.
2. Very distant objects in the sky whose relative position and/or intensity is time dependant (movement of celestial bodies). It gives Ephemeris Time which is the same for the whole earth. The development in England of the first marine clocks decreased the interest in these two methods.

Let us mention here that the most recent developments in the study of optical quasars as frequency standards and frequency transfer could be linked to this family. The excellent stability of their frequencies make them more precise and accurate.. They have the advantage of being accessible. Therefore, they could be used in place of, or compete with hydrogen masers. Combining Local Time and Ephemeris Time makes navigation possible. In the two techniques presented here only the direction is important, thus they are independant of the travel time of the light between a beacon and an observer. The determination of the time is made in a passive mode which means that the observers use only natural phenomena.

B. ACTIVE MODE

The next one–way techniques are active ones, which means that the synchronizing event is short. A phenomena is considered as short when its value is small or equal to the accuracy expected. We will consider two groups of techniques, mainly created by man. Fires, flares, etc are part of this category.

1. The velocity of the light is considered as infinite.

   It means that the travel time is negligible. The accuracy ranges from minutes to seconds for distances up to a few hundred kilometers. The Time Ball concept was the last and most accurate development. In this case the accuracy reaches the limit of human reflexes (0.1s) for distances up to 3O kilometers. Even for such distances the travel time of 100 μs could be neglected in respect to the accuracy (0.1s). The advantages of this first method are the simplicity and the non–saturation (unlimited numbers of users could participate at the same time). The disadvantages are the consequences of the advantages, simplicity means a rather poor accuracy and non-saturation leads to the lack of discretion.

2. The velocity of light is considered as finite.

   Although electro–optical methods were able to modulate the light up to 100 MHz and pulses in the nanosecond range, it is only with the advent of lasers that light was used for more accurate time and frequency transfer, because of their coherent light beam (directivity and high peak powers). The signal was originally carried by air as in the older methods, but also through optical fiber developed industrially in parallel with the laser. The accuracy of measurements obtained with these methods is such that the velocity of the light has to be taken into account. The transit time between the two ends of the link could be determined by two different ways.

   a) It can be computed using a model knowing the distance and the meteorological parameters (pressure, temperature, and possibly relative humidity). The accuracy for time transfer could be then around 50 ps over short distances and the precision for frequency transfer about 10^{-17} over 100 s. This has been the method commonly used so far.

   b) A differential measurement of the travel time between two wavelengths could provide a better determination of the index of refraction correction.

      - The sensitivity of the process is greatly dependant on the choice of the two wavelengths which must be as far apart as possible. As an example, for air transmission and the two colors 532 nm and 698 nm the differential measurement has to be at the level of 1/40 of the expected accuracy for the time transfer. This figures would become 1/9 for the pair 532 nm and 355 nm.
      - The pair of wavelengths must cross the transiting medium with an attenuation as low as possible. This factor limits the transmission through air at wavelengths longer than 400 nm if the distance is longer than 20 kilometers.
      - The bandwidth of detectors must cover both wavelengths (for example a S20 photocatode is limited between 200 nm and 700 nm). This is particularly true when only one detector is used which is the case with a streak camera (picosecond resolution).

      This method promises accuracies up to 50 ps over very long distances and 10^{-18} for frequency transfer precision over 100 seconds or more. It means that we need a differential time measurement very accurate which is difficult to achieve, technically speaking.

TWO-WAY TECHNIQUES (Fig. 2)

In two way techniques, the flight time is not determined by a differential measurement but directly. The round trip flight time of the light between transmitter and receiver is measured. It is assumed that the only delay is half of that of the two way travel time. The concept for two way appeared as early as 1849 with Fizeau and his Tooth Wheel Experiment over a distance of 17.266 km.

Before the development of lasers, some range–finders based on round trip time determination were designed, opening the possibility for time and frequency transfer. But then the level of time keeping and the needs in time and frequency transfer were not at the level of such expensive, state of the art equipment. These needs appeared at the same time as the development of different laser sources (Gas Solid, Dye, Solid state). Soon some experiments were set up. Ranging and time transfer accuracy went from microseconds to nanoseconds almost immediately.

Several forms of light modulation appeared following the laser development:

- pulse modulation with pulse duration ranging from microseconds (free–running, 1960) to nanoseconds (Q Switched, 1964) to picoseconds (Mode Locked, 1970) and even to femto and atoseconds (mode locked and pulse compression).
- continuous waves (CW) where the modulation could be a sinusoidal variation of the intensity or a rotation of the plane of polarisation at constant speed.
- quasi CW often operating in a continuous mode–locked mode (series of equally time spaced picosecond pulses).

The first experiments were made in open air, optical fibers did not exist yet. It is obvious that the two paths of the light go through the same medium. The meteorological parameters are stable enough for round trips shorter than a few seconds.

With the growing use of optical fibers (OF), the control of the light propagation medium was greatly improved.

The advantages of optical fibers are :

- all weather operation
- very efficient energy budget link,this is due to the very low losses of optical fibers around 1.3 micrometers, the design of laser diode emitting at that wavelength, and the development of very fast and efficient detection diodes. These two diodes matched together. It has to be noted also that the coupling of the emitting and receiving devices to the OF is tight.

The parameters modifing the travel time are slowly changing, temperature, in particular. It should be controlled.

This is particularly important for frequency transfer. A "zero delay change" method could be designed where the one–way delay is maintained constant by a variation of the temperature of the optical fiber via a feedback loop taking into account the two way round trip delay. OF are often used in cables grouping several ones and it is possible to determine the round trip time using two different OF one for each travel direction. Only a very small differential error is possible as the thermal conditions of two fibers in the same cable are very close to each other. When time and frequency transfers are concerned the delay of the transmission from one point of the link to the other is measured "in situ". A two wavelength system is not necessary as long as the two way travel time is short enough to assume that the travel delay is the same for the two directions of flight.

For time and frequency transfer at very long distances, the atmosphere cannot be neglected. Then the travel delay is not the same for the two directions of flight (relativity experiment on circum solar spacecraft).

If not, the two way method used with two colors could provide the differences of the two directions of flight times, making a differential measurement at the two ends of the link. When the two way energy or power link budget is too difficult to achieve from one side, both equipments could be active. The target side could detect the signal and reemit it with an optical transponder with its known delay. The concept could be useful for solar or planetary probes.

DOUBLE TWO WAY TECHNIQUES

If the two points to be synchronized are not in direct access or view (distance, obstacle,..) a relay could be used. In this case a double two way link is set up. This could be done in several ways.

1. LASSO concept Fig. (3 A)

The two ground stations are laser ranging equipments measuring the travel time of the light from the station to the relay and back. The epochs of emissions are also recorded. The equipment of the relay consists in the retroreflector panel and a time intervalometer linked to a light detection device. The time differences of the on-board detected signals are transmitted by telemetry to the stations.

2. AJISAI concept Fig. (3 B)

The target (spacecraft) could be completely passive consisting of mirrors. Each station sends a signal to the target and reaches the other station by reflection. The travel times from one station to the other is the same in both direction and therefore cancel. The disadvantage of the method is its poor efficiency caused by the low probability of specular reflection from a station to the second one. This efficiency is somewhat improved by the very large number of mirrors on board the satellite.

As for the two way, the target could be equiped with optical transponders working in one of the two preceding modes.

FUTURE OF OPTICAL TIME AND FREQUENCY TRANSFER

The bandwidth accessible by an optical beam is tremendously wide. This allows very high frequency or modulation of very short pulses. Up to now the useful bandwidth was limited to some tens of gigahertz. At these bandwidths one must take into account the dispersive effect of the medium of transmission. As an example, a light pulse of 10 ps at the minimum bandwidth compatible with the Fourrier transform is widened by 10 ps if it travels through two 20 km paths of standard atmosphere. By convolution of the original pulsewidth and the broadening, one can see that the returning pulse has a 14 ps duration. By adding some extra hardware such as prisms or gratings the pulse could be recompressed to 10 ps. A minimal pulsewidth, for each travel distance through a dispersive medium, could be computed. If one wants to use shorter pulsewidth at higher frequency modulation, one has to take into account the difference between phase and group velocity. This remark is particularly true for time transfer and is far less important for frequency transfer with the new compression technologies developed for laser pulse generation; subpicosecond and even subfemtosecond measures could be conceived.

The optical time and frequency transfer is still at its infancy and improvement of the accuracy by two or three orders of magnitude could be predicted (Atosecond domain).

CONCLUSION

In the past, we have always acted, as if infinite air space, infinite radio space, infinite energy and raw materials exist. We rapidly come to the point when the infinite character of resource approximations are no longer valid, and we have heavy pressure to plan and organize. It is now the era when time and frequency technology will become one of man's most valuable and useful tools.

The quality of time and frequency information depends upon two things: the quality of the clocks that generate the information and the fidelity of the information channels that disseminate the information. The use of light in the techniques for time and frequency transfer, which was a new approach, is now maturing.

The intrinsic qualities of this new concept is a big step forward :

- the bandwidths of the optical beams can be very wide ;
- the sensitivity to ionospheric effects is small compare to the radio techniques;
- it is easy to obtain good link budget thanks to the high directivity of the optical or laser beams;
- finally it is difficult to detect an optical emission that is not directed to you (confidentiality)

Some problems still have to be overcome, some new applications still have to be studied and new experiments have still to be imagined. This should lead to a new level of scientific achievement in particular.

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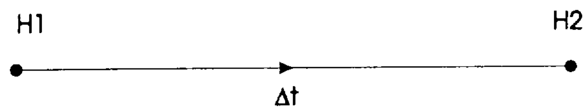
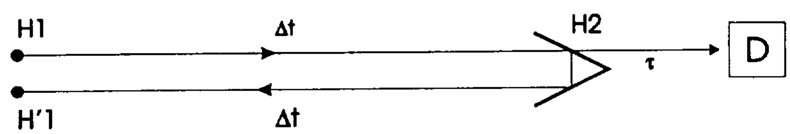
ONE WAY (Fig.1)



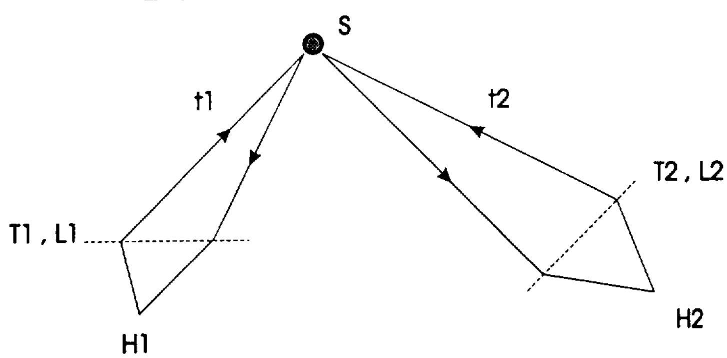
$$H2 - H1 = \Delta t$$

TWO WAY (Fig.2)



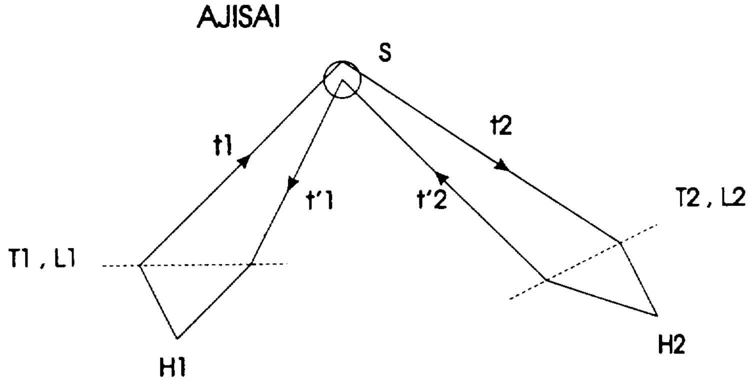
$$2\Delta t = H1 - H'1 \qquad H2 - H1 = \Delta t + \tau$$

DOUBLE TWO WAY (Fig.3a)
LASSO



$$H2 - H1 = (TS1 - TS2) + (t2 - t1) + (T2 - T1)$$

DOUBLE TWO WAY (Fig.3b)
AJISAI



$$H2 - H1 = ((t1 + t2) - (t'1 + t'2)) / 2$$

QUESTIONS AND ANSWERS

J. Levine, NIST: I just wanted to comment that the geological community for many, many years has been making measurements that are very similar to your measurements for the point of view of earthquake predictions. The measurements are made through the atmosphere; they typically measure baselines up to 30, 40 or 50 kilometers long, with an uncertainty of about 10 to the minus 7 or 10 to the minus 8. If you turned those measurements around and thought of them not as distance measurements but as time measurements, that results in time transfer of between one and ten ps. That is very, very old data. Some of the measurements use multiple wave lengths; some of the measurements use single wave lengths. There are one–way and two–way measurements. Now all of those techniques use not pulses, as you have discussed, but modulation on the laser beam itself; and there are a lot of technical advantages to that. And you might want to consider those kinds of schemes in the future for your measurements too.

Jean Gaignebet: I will just make a comment. When you want to make time transfer with a light, you need not know the index you are crossing because you are not correcting to the distance. You have directly the time of flight. We are going to more than one wave length for this reason.

The second problem is the kind of modulation. If the gain of your link is high enough, you could use modulated beams. If the gain is very low, and that is what we have when we range on long distance targets, the closed retro–diffusion is completely perturbing your phase measurement. So for long distances, you are driven to pulse systems.

J. Levine: The modulation is only from point to point on the ground.

Jean Gaignebet: Quite short distances.

J. Levine: Up to 50 kilometers perhaps.

Jean Gaignebet: Yes. I know that the system designed in France, and it uses the direction of the polarization of the beam which is rotating at 100 MHz. That is working up to 50 kilometers. Then the retro–reflector panels have to be so large in order to keep the gain that you cannot do it because the corner cubes are depolarizing your beam.

J. Levine: That is absolutely true. The comment that I was making was with respect to point–to–point measurements on the ground.

G. Thomas Becker, Air System Technologies, Inc.: This is a two–part question. Surely there is a very large path attenuation from ground to satellite and back. What is that, and would not the resulting received optical signal be so weak that there is a large integration time in the detector? How do you overcome that?

Jean Gaignebet: The figure in attenuation range is between ten to minus 16 to ten to minus 22, which means that we are often working in single–photon detection systems. Even for LASSO work, lunar laser ranging stations have physically a few photons per shot. So all the technology has to be developed to keep the accuracy at such low levels. We are working very fast in microchannel PM tubes, always in the geiger mode. One of the advantages is that often we have a very good ephemeris of the satellite. So we could have a very narrow range gate, and have almost no noise or very weak noise in this gate.

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GPS COMMON–VIEW TIME TRANSFER

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Abstract

The introduction of the GPS common–view method at the beginning of the 1980s led to an immediate and dramatic improvement of international time comparisons. Since then further progress brought the precision and accuracy of GPS common–view intercontinental time transfer, from tens of nanoseconds to a few nanoseconds, even with SA activated. This achievement was made possible, mainly by the use of ultra–precise ground antenna coordinates, post–processed precise ephemerides, double–frequency measurements of ionosphere, and appropriate international coordination and standardization. This paper reviews developments and applications of the GPS common–view method during the last decade and comments on possible future improvements, whose objective is to attain sub–nanosecond uncertainty.

I. INTRODUCTION

The excellence of world–wide unification of time realized by the establishment of International Atomic Time (TAI) and Coordinated Universal Time (UTC), depends on the quality of the participating atomic clocks and the means of time comparison. In the pre–GPS era (until the early 1980s) the technology of atomic clocks was always ahead of that of time transfer. The uncertainties of the long–distance time comparisons, by LORAN–C, were some hundreds of nanoseconds, and large areas of the earth were not covered. The introduction of the GPS has led to a major improvement in world- wide time metrology with respect to precision, accuracy and coverage.

The common–view method was suggested in 1980 by the NBS[1] and since 1983 has been used by an increasing number of national timing centres for accurate time comparisons of atomic clocks. At present, of 45 national time laboratories contributing to the establishment of TAI only 3 are not using GPS.

The nature of GPS orbits is such that satellites are observed every sidereal day at nearly the same location on the sky, so scheduled common views are repeated every 23 h 56 min. The common–view schedule, established by the BIPM and distributed to the national laboratories is kept without change for about 6 months, when a new schedule is issued. Two stations or more, following the schedule, receive the signals of the same satellite at the same time and communicate the data to each other through electronic mail, to compare their clocks. The main advantage of this method is that satellite clock error contributes nothing (GPS time disappears in the difference) so it is of utmost interest during implementation of Selective Availability (SA). The data are processed by the BIPM for the computation of international time links directly involved in the establishment of TAI and UTC.

With GPS, continental and intercontinental time comparisons are performed with a precision of a few nanoseconds. This makes it possible to measure, for integration times of only 1 day, the frequency differences between remote atomic clocks at the level two or three parts in 10^{14}. But this is by no means the limit of the possibilities of GPS. Geodesists, using a new generation of receivers, expect to measure pseudo–ranges with uncertainties of 10 cm or less and hence to reduce ephemeride errors also to less than 10 cm. These developments bring the hope that time comparisons may be achieved with uncertainties of 300 ps or less. Such performance is required to meet the challenge of the upcoming new generation of time and frequency technology.

A specific problem in the use of GPS for time transfer is that it is a one–way system. In addition, most laboratories use only the L1 frequency. This affects the propagation delay in many ways: this is so even if the common–view method, in some cases, diminishes ephemeride and ionospheric errors. Here we review these perturbations and outline possible solutions. The use by time laboratories of GPS time receivers of different commercial origin raised the question of the standardization of this equipment. Major recent progress in this domain is briefly described. Finally we report on possible assessments of the precision and accuracy of the GPS common–view method mainly by comparing it with other methods of accurate time transfer.

II. SOURCES OF ERRORS

II.1. GROUND ANTENNA COORDINATES

It has been found that inaccurate antenna coordinates (reaching sometimes several tens of metres) are the cause of large errors in GPS time transfer[2]. For 1 ns accuracy in time comparisons, ground–antenna coordinates should be known in a global terrestrial reference frame with an accuracy of 30 cm or better. In practice national time metrology laboratories use the ITRF reference frame which is similar to the WGS 84, used by the GPS, but is more accurate[3,4]. About 10% of the laboratories have coordinates at a level of 10 cm, 50% at a level of 50 cm. The remaining laboratories have coordinates with uncertainties ranging from 1 m to 10 m. Work continues for the improvement of these coordinates.

II.2. SATELLITE EPHEMERIDES

The uncertainty of the GPS broadcast ephemerides ranges from 5 m to 30 m without SA[5,6]. The common–view method reduces the impact of ephemeride error for short baselines. It ranges from one to several nanoseconds for a single common view. However for intercontinental distances the impact of this error can be amplified and in some cases may reach tens of nanoseconds for a single common view.

According to available information the error in broadcast ephemerides introduced by SA should be about 100 m. This would introduce an error for long distance common views exceeding 100 ns in some cases. At present SA does not contain the component of ephemeride degradation and takes form only of clock dither degradation.

To reduce ephemeride error for long–distance time links, post–processed precise ephemerides should be used[5]. At present, several institutions compute precise ephemerides and make them available to the public. The best known precise ephemerides are provided by the IGS, the NGS and the DMA with a delay ranging from some days to one month. Their precision ranges from 0.5 m to 3 m. The DMA precise ephemerides are expressed in the WGS 84 reference frame and those of the IGS and the NGS in the ITRF reference frame. In the case of SA ephemeride degradation, the use of precise ephemerides will be necessary[5]. The precise ephemerides are applied from October 1993 to the GPS intercontinental common–view links used for the computation of TAI.

II.3. IONOSPHERIC REFRACTION

The single–frequency C/A–code time receivers, largely used in time laboratories, compute ionospheric delay from broadcast parameters and a model which has an uncertainty that may be as large as 50% of the evaluated delay. This means that for low elevation observations, unavoidable for long distance links, and during the day, uncertainties of ionospheric delay range from 5 ns in periods of low solar activity to 50 ns in periods of intense solar activity. However, for links of up 1000 km the path through the ionosphere is approximately the same on the two observation sites and errors in the estimation of ionospheric delay almost disappear in the common–view approach. This is not the case for long distance links.

Fortunately the GPS uses two frequencies which allow us to measure the ionospheric delay. Dual–frequency codeless receivers provide measurements of ionospheric delay with an uncertainty of a few nanoseconds[7,8] and dual–frequency P–code receivers provide these measurements with an uncertainty of about 1 ns. During implementation of AS, when P–code is replaced by a Y–code which is inaccessible for non–authorized users, the P–code receivers switch automatically to codeless mode. The use of codeless and P–code receivers to measure ionosphere is still limited in time laboratories. The long distance links between Europe, East Asia and North America, used for TAI computation, are already corrected by ionospheric measurements using codeless receivers.

II.4. TROPOSPHERIC REFRACTION

At radio frequencies the troposphere is a non–dispersive medium, and its effect on pseudo–ranges and time comparisons cannot be estimated from dual frequency measurements as is done for the ionosphere[9]. Instead, models are used for the estimation of the tropospheric delay. It has been assumed that for the needs of GPS time transfer at the level of 1 ns to 2 ns, and for observations performed at elevation angles above 30°, a simple global model is sufficient. However, in the practice of common–view time transfer over long distances (9000 km), elevations of 20° are sometimes unavoidable. We have also observed that different types of receivers use different tropospheric models[10]. For example, a comparison of two receivers has shown differences of 1.0 ns at 60° elevation, 1.8 ns at 30° and 3.2 ns at 20°. To obtain an accuracy of a few hundreds of picoseconds in GPS time transfer, more sophisticated models of the troposphere with the inclusion of local meteorological measurements, will be necessary[10,11].

II.5. INSTRUMENTAL DELAYS

Several experiments on the relative calibration of receiver delays have been performed by moving a GPS receiver, used as transfer standard[12,13,14,15], between sites. The resolution is of the order of 1 ns for 1 – 2 days of simultaneous tracking. However, only few of these receivers have been checked. Some received a single visit and very few received two or more visits. Our experience concerning the long-term stability of receiver delays is limited and drifts or steps of several tens of nanoseconds could occur without being noticed. Furthermore, a sensitivity to the external temperature of some types of GPS time receivers has been reported in last few years[16].

II.6. MULTIPATH PROPAGATION

Multipath propagation arises from reflections at objects located around and under a GPS antenna. Resulting instantaneous errors can be as large as several tens of nanoseconds[17,18]. Fortunately, these errors are partially averaged over 13-minute tracks. Still, special care should be taken in the installation of a GPS antenna. An ideal installation would provide total isolation of the antenna from its environment. One approach to this ideal situation would be to install the antenna on the top of a high tower[19]. Another option is to locate the antenna directly on the ground in an open flat field with no obstacle within a radius of several tens of meters. In practice, good locations are difficult to find. In any event GPS antennas should be located in open areas and equipped with protection planes to eliminate reflection from below.

II.7. LACK OF STANDARDIZATION

For the GPS time comparisons, the receiver software, the adopted reference frames and the constants should be identical. Unfortunately, differences have been found between the receivers of different origin[10,20]. An important advance has recently been made by the Group on GPS Time Transfer Standards: a set of standards for track monitoring and data processing has been issued in the document Technical Directives for Standardization of GPS Time Receiver Software[21]. These standards should be soon adopted by receiver designers and users. The use of standardized procedures is particularly critical during implementation of SA (see paragraph on SA below).

III. GPS COMMON-VIEW TIME TRANSFER DURING SA AND AS

Selective Availability (SA) and Anti-Spoofing (AS) are intentional degradations of GPS signals and navigation messages designed to deny the full accuracy of the system to unauthorized users such as the international community of time metrology (Most authorized users of GPS belong or are affiliated to the US Department of Defense). The issue of SA and AS is closely linked to the history of the GPS. It was developed in the 1970s and may be subject to change in the rapidly evolving international environment of the 1990s.

According to information currently available, SA should consist of:

- a satellite clock dither, the effect of which is removed by a strict common view, and
- a bias in the ephemerides of about 100 meters, which changes frequently, and has an effect in common view, which is roughly proportional to the distance[22].

Up to now, SA consisted only of clock dither, except for a few short periods during which the ephemerides were also degraded. This means that the effect of SA can be entirely removed by a strict common view. At present, time receivers use different time scales (UTC or GPS time) to monitor tracks and synchronization of common views is limited to several seconds. After implementation of the standards noted above, all receivers will use a unique time scale, UTC, and synchronization of observations from remote sites will easily be completed within 1 second. To cancel all the effects of SA the receivers should also process the short period data according to a common scheme. The implementation of standards will also resolve this question.

Although present implementation of SA does not include ephemerides degradation, this does not mean that such a degradation will not occur in the future. To overcome the problem of the possible degradation of ephemerides, various approaches are being studied[6]. One of these is to derive corrections to broadcast ephemerides affected by SA from post-processed precise ephemerides.

The AS is implemented by jamming the P–code and replacing it with a Y–code accessible only to authorized users. AS affects neither single–frequency C/A–code time receivers nor double–frequency codeless ionospheric measurements systems. Of course AS does affect double frequency P–code receivers. In the case of AS these devices switch from the P–code mode of measurement of the ionosphere to the codeless mode.

IV. DATA PROCESSING

At present all GPS common–view time links used for the computation of TAI are processed at the BIPM according to a common scheme. First it is ensured that the tracking intervals at the two laboratories have strictly the same start time and length (usually 13 min) to overcome the effects of the clock dither brought about by SA. The value of the time link is then computed at the midpoint of the tracking interval. For the links between Europe and East Asia, and Europe and North America, ionospheric measurements and precise ephemerides are applied according to the method described in[6,23].

Following this a Vondrak smoothing[24] is performed on the values UTC(i)−UTC(j). This acts as a low–pass filter with a cut–off period which ranges from about 1 day for short distance links (up to 1000 km) to about 8 days for long distance links (9000 km). These periods were chosen as being approximately the limit between the time intervals in which measurement noise is dominant, and the longer intervals in which clock noise prevails. Finally, smoothed values are interpolated for 0 h UTC of standard dates (MJD ending by 9).

V. ERROR BUDGET

The typical error budget of Table I is given for distances of 1000 km and 5000 km, and for the usual tracking durations of 13 minutes, when applying the common view mode[25]. Two cases are considered: a single common view and a daily average of 10 common views. This budget is established for normal operating conditions. Much larger errors may occur in the case of a defective receiver, lack of delay calibration, poor environment of the antenna, adoption of wrong antenna coordinates, etc...

Table I. Typical error budget of GPS time comparisons in common view (CV), at distance d, C/A-code. (Unit: 1 ns)

	For a single CV		For 10 CV, average over 1 day (1)	
d=	1000 km	5000 km	1000 km	5000 km
Satellite clock error (cancels in CV mode)	0	0	0	0
Antenna coordinates (2)	20	20	7	7
Satellite ephemerides	2	8	1	3
Ionosphere (day time, normal solar activity, elevation > 30°)	6	15	1	3
Troposphere (elevation > 30°)	2	2	0.7	0.7
Instrumental delay (relative)	2	2	2	2
Receiver software	2	2	2	2
Multipath propagation	5	5	2	2
Receiver noise (13-min average)	3	3	1	1
Total	22	27	8	10

(1) The noise of the laboratory clocks and the rise time of reference pulses bring non-negligible contributions, which are not considered here.
(2) Assuming uncertainties of the order of 3 m. In practice, errors of coordinates can sometimes reach 30 m to 40 m.

Table II gives a revised error budget for GPS time links, using receivers which are presently in operation, based on the following suppositions:

Table II. Possible error budget, with optimum operation, in common view (CV), at distance d, C/A–code. (Unit: 1ns)

	For a single CV		For 10 CV, average over 1 day	
d=	1000 km	5000 km	1000 km	5000 km
Satellite clock error (cancels in CV mode)	0.0	0.0	0.0	0.0
Antenna coordinates	0.6	0.6	0.2	0.2
Satellite ephemerides	0.3	1.0	0.1	0.3
Ionosphere (measures)	1.0	1.0	0.3	0.3
Troposphere (elevation > 30°)	2.0	2.0	0.7	0.7
Instrumental delay (relative)	1.0	1.0	1.0	1.0
Receiver software	0.0	0.0	0.0	0.0
Multipath propagation	1.0	1.0	0.3	0.3
Receiver noise (13 min average)	3.0	3.0	1.0	1.0
Total	4.0	4.2	1.6	1.7

- error of antenna coordinates of 10 cm (the figures for a single CV correspond to the worst direction at both sites),
- error of satellite precise ephemerides of 1 m (in the worst direction for a single CV),
- measured ionospheric delay with existing ionospheric measurement systems,
- modelled tropospheric delay (as in Table I),
- measured relative instrumental delays by receiver transportation,
- identical and correct receiver software,
- good shielding of the antennas against multipath propagation,
- receiver noise as in Table I.

Among these suppositions, the compatibility of receiver software is not yet realized. However, the largest improvements arise from the adoption of accurate coordinates for the antennas, precise satellite ephemerides and measurement of ionospheric delay. The estimates of errors in Table II are conservative, nevertheless we observe that the contribution of GPS to the uncertainties of time comparisons at 5000 km distance, on daily averages of 10 common views, can be of the order of 2 ns, using C/A–code only.

VI. EXPERIMENTAL ASSESSMENTS OF THE PRECISION

If the data points are regularly spaced, we can use the time–domain stability measures $\sigma_y(\tau)$, mod$\sigma_y(\tau)$, and $\sigma_x(\tau)$[26]. Applied to a time link, mod$\sigma_y(\tau)$ allows the characterization of the types of noise that are present. In the case of white noise phase modulation (PM), the value of $\sigma_x(\tau)$ for the data spacing is the standard deviation of the white noise, which directly gives the measurement uncertainty. $\sigma_y(\tau)$ allow us to estimate the frequency stability with which clocks can be compared.

In practice it appears that, for intercontinental links without ionospheric measurements and precise ephemerides applied, the white noise phase modulation can be identified for averaging times up to about 3 days, but is not the dominant source for times of one day and over when both corrections are applied. For a single intercontinental common view not corrected for ionospheric measurements and precise ephemerides, uncertainty given by this method is 16 ns. With both corrections applied, the uncertainty of a single measurement reaches 3–4 ns, and decreases to 2 ns when averaging several measurements over a period of one day[27].

Another way to estimate the precision of the common–view measurements is from the standard deviation of the residuals to the smoothed values. This is strictly correct if the smoothing has removed only the measurement noise. For short distance links up to 1000 km, where there is no need to apply ionospheric measurements and precise ephemerides, and for the stations having most accurate coordinates, these standard deviations range from 2 ns to 3 ns. For long distance links with accurate coordinates, but without applying ionospheric measurements and precise ephemerides, standard deviations range from 7 ns to 12 ns; with these two corrections applied standard deviations are of about 3 ns[23,27].

It should be noted that such a precision of measurements makes it possible to access the true performance of the best clocks presently available: by averaging a few measurements over one day, a frequency stability of two or three parts in 10^{14} is realized for the link between two clocks.

VII. EXPERIMENTAL ASSESSMENTS OF THE ACCURACY

A partial test of the accuracy of GPS common–view time transfer is provided by the so–called closure around the world. Totally independent checks are provided by the comparison of GPS with other available techniques of accurate time transfer.

VII.1. CLOSURE AROUND THE WORLD

A partial estimation of the accuracy is attained by using three intercontinental links encircling the Earth to establish the closure condition: the three independent time links should add to zero[23]. However the symmetry of this condition hides possible inaccuracies in the participating links due to lack of calibration, wrong calibration of GPS time equipment, or seasonal changes in receiver delays due to variations of temperature. The experiment involved three laboratories, the OP in Paris, the CRL in Tokyo and the NIST in Boulder. All three laboratories used with codeless ionospheric measurement equipment and had ground–antenna coordinates expressed in the ITRF reference frame with uncertainties ranging from 10 cm to 50 cm. The experiment was conducted over 13 months and is described in detail in [27]. Figure 1 gives the final results. We observe a bias of several nanoseconds which varies with time. The origin of this bias is not understood. It may result from the use of a particular set of precise ephemerides, from ionospheric measurements which are not sufficiently accurate, from tropospheric modelling which is not sufficiently accurate, from combination of these factors or from other causes not understood.

VII.2. COMPARISON WITH TWO–WAY TIME TRANSFER

The Two–Way Satellite Time Transfer (TWSTT) technique has been developed for point–to–point time transfer at the level of several hundreds of picoseconds in precision and accuracy. While the white noise phase modulation of a GPS time comparison is smoothed out when averaging over one– or several– days of common–view data, depending on the distance and the clocks compared, the TWSTT white noise phase modulation is removed over 2 minute averaging time. TWSTT thus presents the great advantage of giving a precise comparison value in real–time.

For about one year the time scales UTC(OCA) at Grasse, France, and UTC(TUG) at Graz, Austria, separated by about 800 km, were compared by means of GPS common–view and Two–Way Satellite Time Transfer[28]. The GPS ground–antenna coordinates at both sites were expressed in the ITRF reference frame with uncertainties of 10 cm. At the end of the experiment, both links were independently calibrated by measuring the differential delays of the GPS receivers and the differential delays of the satellite Earth stations. These calibration were performed by transporting of one GPS receiver and one satellite terminal to the other site. The results obtained by the two methods differ by about 3 ns, but reveal a seasonal variation of about 8 ns (Fig. 2) which, most likely, is mainly the result of temperature–dependent delays in the GPS receiving equipment used.

VII.3. COMPARISON WITH GLONASS

For about 3 months a caesium atomic clock at the BIPM in Sèvres, France, and a hydrogen maser at the VNIIFTRI in Mendeleevo near Moscow, Russia, were compared by GPS common views and GLONASS common views[29]. The two sites are separated by about 3000 km. GPS ground–antenna coordinates were expressed in the ITRF reference frame with uncertainty of 30 cm at the BIPM and 70 cm at the VNIIFTRI. GLONASS ground–antenna coordinates were expressed in the SGS 85 reference frame with uncertainty of about 5 m at each site. The GPS and GLONASS time equipment at each site were differentially calibrated. The results of the experiment are given by Figure 3. We note that the GPS and GLONASS results differ by a fairly constant bias with peak–to–peak discrepancy of about 40 ns. The mean of these differences over the duration of the experiment is 32 ns. The root mean square of the residuals to the mean, which is taken as an estimation of the confidence of the mean is, 13 ns.

The bias of 32 ns between the GLONASS common views and the GPS common views arises partially from an approximation in the calibration of the GLONASS equipment and partially from the large error in the GLONASS ground–antenna coordinates. The noise affecting the GLONASS common views is also partially due to coordinate error, to the absence of a tropospheric correction and to an imprecise estimate of the ionospheric correction. The estimated precision and accuracy of the GPS common-view link is 3 ns to 4 ns.

VII.4. COMPARISON WITH LASSO

The LASSO is a laser technique which should allow the comparison of remote atomic clocks with precision and accuracy of 100 picoseconds or better. The first successful time transfer using LASSO was carried out between the OCA in France and the McDonald Observatory in Texas. At the same time, GPS common-view time transfer was organized between these two sites [30]. The estimated precision and accuracy of GPS time link, after differential calibration of GPS time equipment, is several nanoseconds. Figure 4 shows the comparison between two techniques. We observe a bias of about 192 ns, which is certainly due to non-calibration of the laser equipment. This calibration is being performed and the results should be known soon.

Although LASSO, because of its sensitivity to weather conditions, is inherently unsuited for operational duties, it is certainly an excellent tool for the assessment of the accuracy of GPS, GLONASS and Two-Way time transfers.

VIII. CONCLUSIONS

The use of GPS for time and frequency transfer demonstrates the outstanding potential of this system. The permanent operation, world-wide coverage, low equipment cost and fully automatic reception make GPS the most effective system for time and frequency comparisons. During the last five years, the performance of this technique has been improved by a factor of 10.

For time metrology applications the use of ultra-precise ground-antenna coordinates is necessary. In addition, for intercontinental links, measurements of ionosphere and precise ephemerides must be used. With receiving equipment commercially available at present, the precision of a single GPS common view is 3-4 ns for continental and intercontinental links. This precision drops down to 2-3 ns for integration times of 1 day and longer. For the same integration times, frequency differences between atomic clocks are measured at the level of two or three parts in 10^{14}.

The accuracy of GPS common-view time transfer can be estimated at several nanoseconds and is severely limited by the changes in the delays of the analogue C/A-code receivers, developed in the early 1980s.

To meet the challenge of sub-nanosecond GPS common-view time transfer, required by the upcoming generation of clocks, some of the issues to be addressed are:

* Use of accurate digital P-code receivers[31].
* Use of ultra-precise ephemerides.
* Improvement of measurements of the ionospheric delay.
* Improvement of the estimation of the tropospheric delay[10,11].

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List of Acronyms and Abbreviations

AS	Anti–Spoofing
BIPM	Bureau International des Poids et Mesures, Sèvres, France
CRL	Communications Research Laboratory, Tokyo, Japan
CV	Common View
DMA	Defense Mapping Agency
GLONASS	Global Navigation Satellite System (Globalnaya Navygatzyonnaya Sputnikovaya Systema)
GPS	Global Positioning System
IERS	International Earth Rotation Service
IGS	International Geodynamic Service
ITRF	IERS Terrestrial Reference Frame
LASSO	Laser Synchronization from Satellite Orbit
MJD	Modified Julian Day
NBS	National Bureau of Standards
NGS	National Geodetic Survey, Rockville, Maryland
NIST	National Institute of Standards and Technology, Boulder, Colorado
OP	Observatoire de Paris
OCA	Observatoire de la Côte d'Azur, Grasse, France
SA	Selective Availability
SGS	Soviet Geocentric System
TAI	International Atomic Time
TUG	Technical University Graz, Graz, Austria
TWSTT	Two–Way Satellite Time Transfer
UTC	Universal Coordinated Time
UTC(i)	Universal Coordinated Time as realized by laboratory i
VNIIFTRI	Russian National Time & Frequency Service, Mendeleevo, Russia
WGS	World Geodetic System

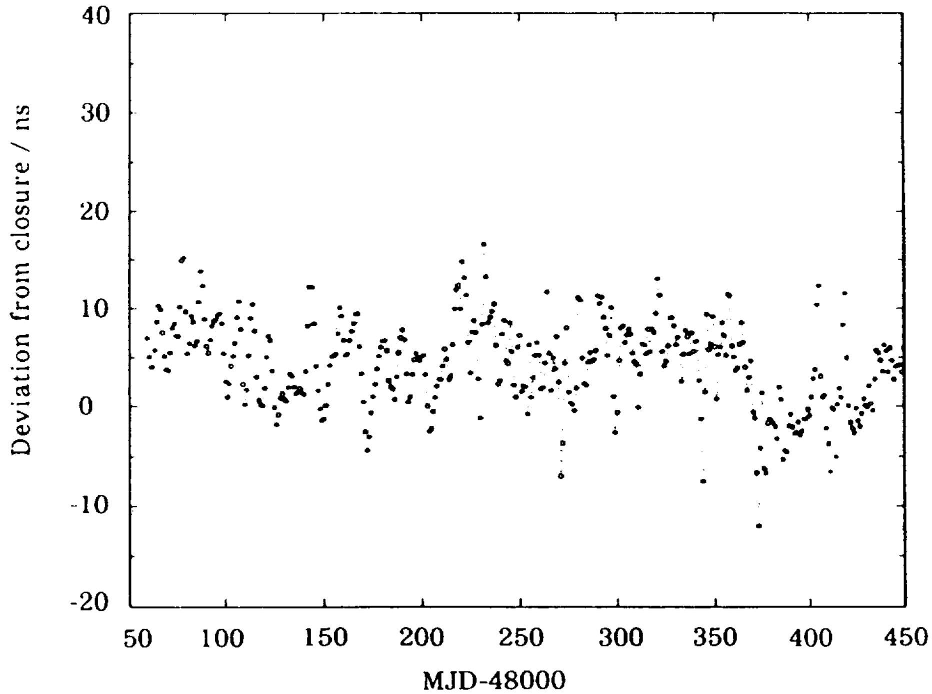

Figure 1. Deviation from closure around the world via OP, NIST and CRL with data corrected using measured ionospheric delays and DMA precise ephemerides.

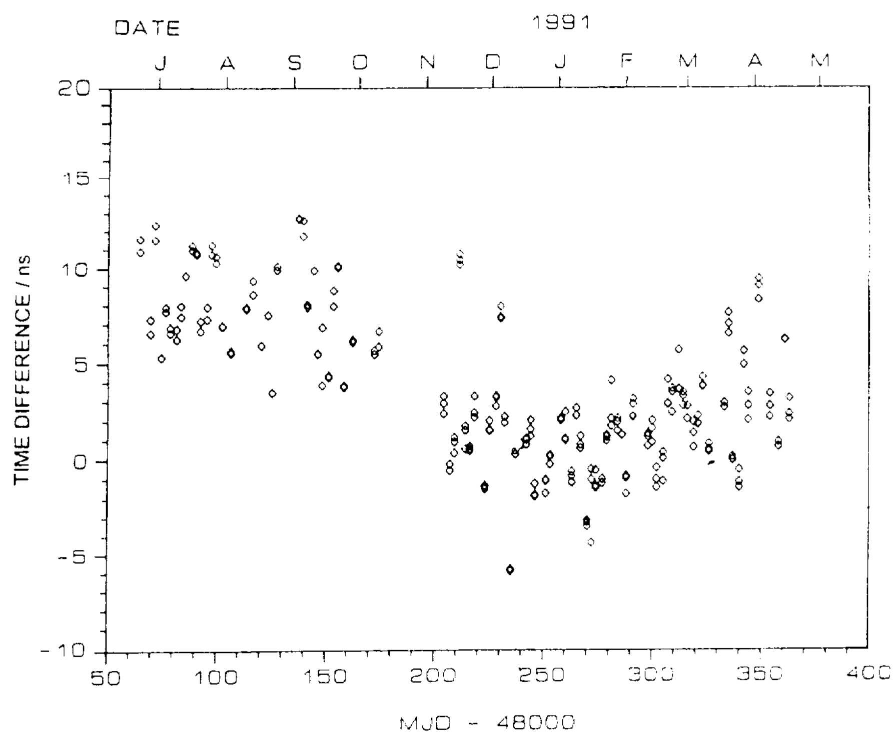

Figure 2. Difference between [UTC(TUG) - UTC(OCA)] obtained by Two-Way measurements and [UTC(TUG) - UTC(OCA)] obtained by GPS common-view measurements.

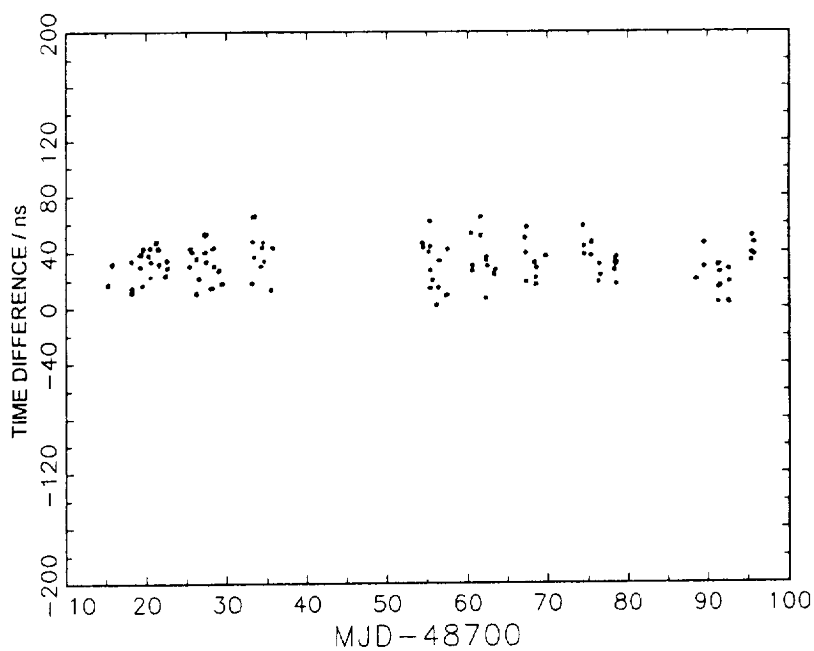

Figure 3. Difference between [BIPM Cs Clock - VNIIFTRI H Maser] obtained by Two-Way measurements and [BIPM Cs Clock - VNIIFTRI H Maser] obtained by GPS common-view measurements.

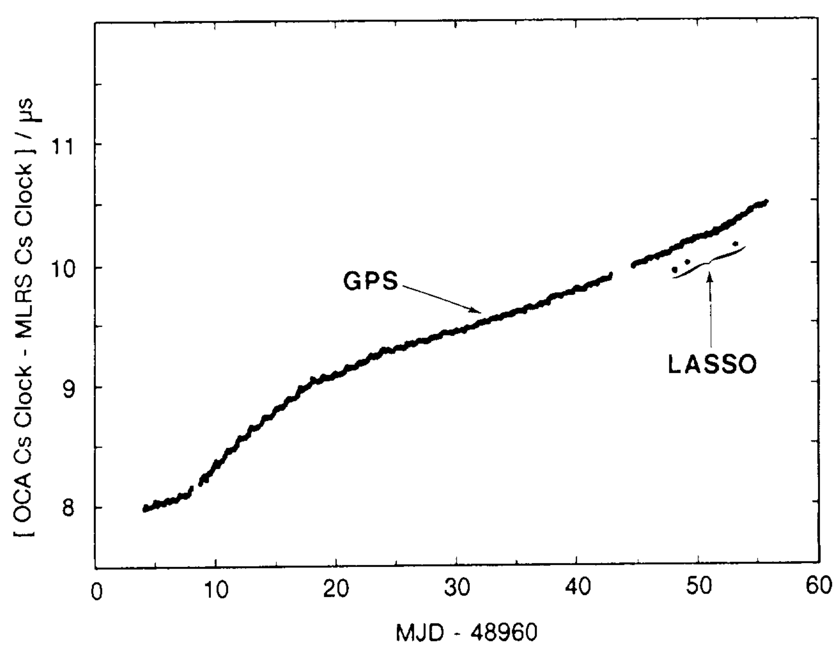

Figure 4. [OCA Cs Clock - MLRS Cs Clock] obtained by GPS common-view measurements and by LASSO.

QUESTIONS AND ANSWERS

Richard Sarrica, Hewlett–Packard: On your GPS temperature plot, what was that actually the temperature measurements of? Was that satellite temperatures?

W. Lewandowski: No, it was just the external temperature of the laboratory. You know, just simple temperature outside the laboratory, near the antenna. We have done this for other status comparing to receivers. This is a very rough comparison. But it shows this immediate effect.

Richard Sarrica: So temperature affects the electronics of the system?

W. Lewandowski: The antenna, maybe the bandpass filters in the antenna. We don't understand the principal of the effect. We have discussed this with the manufacturers. And only some of the receivers are affected by this. All are affected at the level of one ns, I believe. But some have a huge effect of temperature, as big as two ns per degree Celsius of value. They are very expensive thermometers.

Richard Sarrica: So the hope is that once those are characterized, you can then subtract those out also.

W. Lewandowski: To subtract this – one can try to model this and to subtract, but I believe it is not the way to do it.

Harrison Freer, GPS NASA Control Station: You made mention of modeling the troposphere and it relates to this question; and you mentioned temperature as one of the variables you looked at. Have you looked at the other variables, humidity and those kinds of things, to again model tropospheric differences in your process?

W. Lewandowski: Tropospheric modeling was, as I said before, not yet well addressed. And we will have during this meeting a paper by Dr. Kirchner on this; and I expect that this will the first item in trying to resolve this problem.

David Allan, Allan's Time: I wish to comment further on this temperature effect. It is not conclusive at all and it is still being investigated. But it seems that those receivers which down convert and send an IF signal down have less temperature effect than those which send the direct RF signal down. But we don't know for sure. Those are just some of the first experimental data.

W. Lewandowski: Yes, and especially NBS–type receivers which we always use down convert this one frequency; and they are less sensitive to temperature. The time receivers which were transformed from geodetic receivers to time receivers, in general they don't down convert their one frequency and they are sensitive to temperature. But that is not conclusive. I would not like to say that all of them do this. But we observed this in our practice.

Claudine Thomas, BIPM: I have one more comment. You spoke about the technical directives of GPS receivers. This has been accepted in Metrologia and will be published in the next issue in January of next year, Volume 31. Everyone can get it. It is signed by the chairman of the group who is Dave Allan, and also by the secretary.

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Cascaded Clocks Measurement and Simulation Findings

Don Chislow and George Zampetti
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1. Introduction

This paper will examine aspects related to network synchronization distribution and the cascading of timing elements. Methods of timing distribution have become a much debated topic in standards forums and among network service providers (both domestically and internationally). Essentially these concerns focus on the need to migrate their existing network synchronization plans (and capabilities) to those required for the next generation of transport technologies (namely, the Synchronous Digital Hierarchy (SDH), Synchronous Optical Networks (SONET), and Asynchronous Transfer Mode (ATM). The particular choices for synchronization distribution network architectures are now being evaluated and are demonstrating that they can indeed have a profound effect on the overall service performance levels that will be delivered to the customer. The salient aspects of these concerns reduce to: (1) identifying that the devil is in the details" of the timing element specifications and the distribution of timing information (i.e., small design choices can have a large performance impact), (2) developing a standardized method of performance verification that will yield unambiguous results, and (3) presentation of those results. Specifically, this will be done for two general cases: an ideal input, and a noisy input to a cascaded chain of slave clocks.

The method most commonly used by network providers in recent years is a master–slave or hierarchical timing configuration. An attractive feature of a hierarchical timing configuration is that existing digital transmission facilities, between digital switching nodes can be used for synchronization distribution. At the same time this will not diminish the traffic carrying capacity of a particular carrier system. Care must be exercised, however, in the choice of the primary and secondary transmission facilities and routes when designing this synchronization network because the integrity of the facility directly affects the service availability to the subscriber. Since timing error will increase with hierarchical level the objective is not to have too many levels. Further, additional levels and more complex topologies leave the network vulnerable to the formation of timing distribution loops[1]

An unfortunate consequence of a synchronous networks such as SDH or SONET is that each

[1]A timing loop is a configuration wherin the master or controlling timing unit is influenced or steered by a lower level timing element. This arrangement will contaminate the behavior of the higher order timing element and will result in performance degradations.

network element (NE) by definition terminates and recycles timing information. This is because each SDH NE has a clock in it to maintain the frequency tolerances required for transmission continuity. The process of synchronizing these clocks leads to a delay "breathing" phenomenon as they try to maintain lock with a reference.

In order for clocks in telecommunications equipment to maintain lock with an upstream master reference signal they are required to develop an estimate of the phase and frequency characteristics of that reference with respect to a local oscillator. The ability to calibrate the frequency of a slave clock to a network timing reference consequently becomes a critical factor because the calibration will translate directly into the slip performance during an outage. When clocks are cascaded the characteristics of the local oscillator, its control circuitry, together with noise all contribute additional phase variations that work to contaminate the estimate. So much so in fact that the error can be much greater than the drift of the oscillator and this can compromise investment in implementing a quality oscillator.

These facts serve to underscore one of the guiding principles of synchronization planning. That is, to minimize the number of slave clocks through which timing is chained.

2. Synchronization Distribution

The distribution of telecommunication network synchronization for the Plesiochronous Digital Hierarchy (PDH) is to a large extent hierarchical in plan (or master–slave arrangements). Furthermore, the topological flow of synchronization trails through a network are to a large extent influenced by the manner in which the network is configured to transport information. The reasons for doing this are essentially twofold. First, that management and administration of the synchronization follows the same path that the information payloads follow, and second as a result of this no new facilities are required to provide this capability. The first situation allows for straightforward trouble isolation and problem resolution. In the second case one can realize considerable economic efficiency. Consequently, there is strong motivation to build upon these advantages and integrate future services into this plan. The introduction of transport technologies such as: SONET, SDH and ATM present new challenges to the original synchronization distribution plan.

The basic objective of synchronization distribution is the creation of equal time scales at each location (within some time or frequency error budget. Typically, this budget is arbitrarily based on service objectives and bounded by performance and/or economic constraints). To achieve this the synchronization element[2] (SE) must follow the master not the reference. The distinction being that the master timing source dictates the performance of the network, whereas the local reference (which in many cases is a noisy representation of the master) may have deviated from it. It is therefore the function of the SE to detect any deviation from the last known satisfactory estimate of the master and disconnect from the reference before it can be misinformed by such deviations and forced in the wrong direction. This functionality requires the SE to support multiple tasks. Principally those are: (1.) minimizing the noise, and (2.)

[2] a synchronization element is used ubiquitously to refer either to an SETS, an SSU, a BITS, or NE clock. In general, any device that generates or re-generates timing information; colloquially, a "clock."

detecting and removing transient phase movements. The latter serves to minimize the error when the SE is in a hold–over state.

The synchronization network reference chain intended for deploying SDH follows a quasi–hierarchical approach shown in Figure 1[1,2].

The nodes are to be connected by network elements (NEs) each with internal timing elements compliant with a developing international recommendations. As illustrated, the chain should not exceed K slave clocks compliant with recommendations G.81s[3] and G.812[4]. Further, it is stated that the value of N will be limited only by the quality of timing required by the last network element in the chain typically. (Currently this number is considered to be approximately 10 maximum). It is assumed that each Synchronization Supply Unit (SSU) or Synchronous Equipment Timing Source (SETS) represents a physically distinct building location. Note also that the function of the SSU is to only provide a timing interface for the SDH elements and the immediate tributary interface NEs to which they may connect.

Note that each SDH NE that receives a G.811[5][3] traceable signal and generates a new output signal (in effect re–cycling the timing) for use by another SE in the synchronization trail represents an intervening clock to a down–stream office or NE. It was pointed out that each intervening clock will degrade the timing stability of the entire synchronization trail by some amount. Further, the number of intervening clocks that can be cascaded together will be limited not only by the stability of the regenerated and transported signals, but also by the ability of each SE to prevent clock re–arrangement phase movement, as well as other transient activity from propagating through the network. Overall, it seems reasonable that network performance will be improved if the number of intervening synchronization elements is kept to a minimum. There is however, serious interest on the part of service providers to consider more complex transport architectures such as self healing ring topologies. Such discussions have placed the number N as high as 22.

Alternatively, proposals for distribution of synchronization information within a SONET based network follow the architecture shown in Figure 1b. The difference here being that the Building Integrated Timing Supplies (BITS) serve to externally time each SONET NE that would be used to distribute timing. In fact there may not be any intervening "line timed"[4] SONET NE that is in the timing distribution path. The BITS clocks serve to provide an equal level timing interface which will prevent transient signal propagation and hold–over stability in excess of the NE itself. Moreover, the BITS clocks also supply timing to the entire office. This is not the case, however, for the SSUs in the SDH network. In many administrations that intend to implement SDH networks it is common practice to segregate timing entities within an office and dedicate them to specific service technologies, i.e., data, voice, etc. The reasons for this are primarily a combination of historical precedence (i.e., it was always done that way), and differing philosophical approaches to office operations and practices.

The control of (E1[5], or DS1) slips in the PDH and pointer adjustment activity in SDH, or SONET requires that all E1/DS1 and SDH/SONET timing devices operate at the same frequency within

[3] Effectively, a reference quality signal.

[4] A network element timing configuration in which the output (any direction) is determined by the input line signal.

[5] E1 is a 2.048 Mb/s international primary rate signal. DS1 is a 1.544 Mb/s American primary rate signal.

some achievable bound. This can be accomplished provided that the frequency characteristics of these synchronization elements (SEs) can be traced to a primary reference source (PRS) or G.811[5] type device. This concept is in agreement with the hierarchical master–slave timing distribution method just discussed. A pre–requisite for implementing this methodology is that all the clocks in the timing distribution chain remain synchronized to a free–running clock of equal or higher performance level. This will ensure that during failure conditions slave clocks will be able to maintain synchronization with each of the other SEs. As mentioned earlier, the process of synchronizing these clocks will lead to a breathing phenomenon as they try to maintain lock with one another.

3. Synchronization Element Clock Model

The synchronization element in this investigation is viewed as a "narrow bandwidth" digitally controlled clock. An internal block diagram illustrating the components that have been modelled is provided in Figure 2.

The classic type 2 loop filter (two integrators) that is used in the model study reflects the majority of known telecommunications NE clocks. Noise is initially introduced through the oven controlled crystal oscillator (OCXO). This represents a simple random walk–frequency modulated (RW–FM) process characteristic of crystal oscillator technology. The level of the random walk noise process is set to 5×10^{-11} at 1000 seconds. Effectively what is presented is a servo–control mechanism that will suppress low frequencies from the OCXO (by roughly 40 dB/decade) and high frequencies from the reference input (by approximately 20 dB/decade).

Peaking effects from the input reference are limited by design of the quantizing phase–detector, and represent a challenge to properly suppress in the face of introducing additional phase error by applying tighter filter bandwidths. Therefore properly managing changes in the loop gain so that corresponding increase or decrease in the system bandwidth does not allow wander to accumulate as the network size increases, or the phase error at any one particular clock is excessive is the ultimate goal.

4. Measurement Tools

The primary reason to select a particular measurement parameter is intimately related to its fundamental properties: time or frequency. Spectral characteristics are crucial because appropriate communication filters needed to be developed. Similarly, "time–difference" is important because time and phase relationships are key from the telecommunications perspective. Principally, because the general level of customer performance is related to slip activity in NE buffers. Further, the telecommunications network when studied was found to be similar to a measurement system as opposed to those timing characteristics that are indicative of a frequency standard. Because of this, the fundamental property of interest (for network measurements) becomes that of phase or time (e.g., slips), not frequency as would be the case for a frequency standard. Examples of this include network synchronization, phase–locked servo systems and time distribution systems.

In order to extract meaningful information from the data set generated from the model described in the previous section, a set of comprehensive measurement criteria must be agreed. It has been demonstrated that neither time or frequency domain characteristics alone are sufficient to properly describe the performance of clocks. It is rapidly becoming common practice to employ (at minimum) two criteria, those being, maximum time interval error (MTIE) and time variance (TVAR) type measurements to accomplish the objectives stated above. Essentially these criteria have stood the test of time and practice and have emerged as a minimal set of measurement tools.

Attributes common to each criterion are born out by the measurement process itself, that is, each can be viewed as a two stage process: a linear filter, followed by a statistical estimate. The measures outlined in the following have been shown to accurately and consistently describe real network situations. Further, they have utility as diagnostic tools. The significance of this is explained in what follows.

4.1 MTIE

MTIE is reasonably straight forward to describe. It represents the peak to peak time error (variation) between the device under test and an arbitrary reference in a given observation interval. Another interval will yield another MTIE value. Typically, one will view the error signal with increasing time, sliding the observation interval along in the process to obtain an historical record of this signal. The MTIE for the complete data set is the maximum of all the individual MTIE samples. It is noteworthy to point out that there is no filtering action that takes place in the computation of MTIE[6]. The process is simply one of peak detection and memory storage.

The purpose behind maximum time interval error as a performance measure is to constrain peak variations in network timing signals. As such MTIE is well suited to characterize network synchronization effects. Establishing an MTIE bound seeks to ensure that clock phase movement will not accumulate significantly during reference or hardware impairments. By controlling phase movement the number of slips which accumulate in the PDH network and down stream reference switching occurrences are limited. Further, by prescribing a phase slope requirement (via an MTIE specification) will help ensure that error conditions will not propagate.

This process is particularly useful to describe network transient events and slip phenomena because it directly corresponds to the peak-to-peak fill or depletion of data in network buffer stores. It should be noted however, that similar phenomena is also related to the frequency at which these movements occur. Unfortunately, MTIE does not provide information about rate of change of phase movement in a buffer or timing reference signal qualification (yet another source of error). See Figure 3.

4.2 TVAR

These difficulties call for the investigator to treat the problem in a different fashion, that is to examine the broadband $\frac{1}{f^n}$ noise characteristics of the error signal. This is accomplished with the use of the well established Modified Allan Variance[4]. For the purposes of the telecommunications community this criterion has been modified to better represent those needs and has taken the form of a new measure known as time variance (TVAR). TVAR is the square of a 2 sample standard deviation and because of that demonstrates similar computational properties to that of the standard variance, with one notable exception: a single variance estimate is distribution dependent and will exhibit high scatter if the noise process being measured is divergent in the window of observation. Alternatively if two sample variances are calculated and then averaged until all the data are exhausted, the result is a convergent sequence.

The square root of TVAR (or time deviation TDEV) is proportional to the rms change in the mean value of the time errors averaged over an interval, τ. This is the principle difference between the TVAR and the standard variance. The standard variance computes the *rms* level of time values not average differential of those same values. It is worth mentioning that TVAR is normalized so that it will reduce to the standard deviation for a white noise phase modulated process. The utility of this type of variance is that it is extremely efficient in computing a wide band spectral density.

Thus TVAR represents the effective power output of a software–based filter the input of which is the phase modulated waveform. The filter characteristics are characterized by a bandpass filter. The upper cut–off frequency of this filter is approximately equal to the reciprocal of the observation period. The lower cut–off frequency is roughly one decade below this value and the filter response peaking occurs at about half the upper frequency value. See Figure 4.

4.3 ZTIE

Examining both MTIE and TVAR one may discover yet a third measure that may prove useful. Colloquially, this is referred to a ZTIE, or Z–transformed TIE[6]. It is an intermediate process between MTIE and TVAR because the computed value is the peak of the averaged first difference of the time sample values. ZTIE captures the peak power in a manner analogous to MTIE. In addition, an analogous bandpass filter function filter function similar to that for TVAR is employed, the center frequency of which, is controlled by the choice of averaging time, τ. The conceptual relationship requires slightly more explanation, but crudely, ZTIE provides a measure of peak power measured through a bandpass filter. See Figure 5.

By building upon the computational utility of TVAR certain efficiencies may be realized using ZTIE. Since this criterion retains peak power, which was explained to be very valuable with regard to providing network performance information, it is reasonable to conclude that to prescribe certain network performance limits that ZTIE would find utility as a performance monitoring metric. Principally because it can be calculated and acted upon while in service. Further, since the computation of ZTIE does not have to repeat the difference operation, as for TVAR, it can be thought of as representing a running snap–shot of peak network phase and frequency performance effectively marrying the attributes of MTIE and TVAR.

As shown in reference [7], ZTIE is very effective in illustrating both the short term peak jitter noise component as well as the long term frequency bias. The advantage gained using ZTIE is that in essentially one simple computation each of these characteristics may be derived. Moreover, ZTIE provides a utility as a calibration tool because if the computation are done in–service then the frequency of the slave clock can be steered to the network reference in a very orderly fashion. This capability has direct implications for the network slip performance during reference outage periods.

Figure 5a depicts the computational concepts of each of the data gathering processes by applying the appropriate filters to the observed data.

The block averaging exhibits time dependent low pass filter characteristic the main lobe occurring at 1/T. The averaging function serves to suppress jitter and discriminate between flicker noise PM and white noise PM. This low pass filter attribute has been demonstrated to be significant in removing strong high frequency signals often found in telecommunications timing signals.The first difference function, shown next, provides suppression of the f^{-n} divergent power law noise process. This is analogous to a single pole filter producing 20 dB per decade roll–off noise rejection. This is adequate to ensure a stationary noise process for input phase noise, the dominant component of which is white FM. This function has the additional feature that it limits phase bias as well. Finally the second difference function provides an additional degree of noise suppression equivalent to a second order filter producing 40 dB per decade roll–off. This will ensure a stationary process for noise that behaves like random walk FM, which is the most divergent type of noise observed for general oscillator applications.

The advantage gained by separating these various filter processes into their constituent parts is that it becomes evident that each can convey useful information. Specifically, by examining the result of the first difference operation it can be observed that it this operation will not suppress the frequency bias term.The consequence of this is that it ZTIE correctly reflect frequency drift and transient offsets that TVAR will suppress. Moreover, because ZTIE is well behaved for non–divergent noise processes and exhibits a similar trend to that of TVAR it is much more valuable than MTIE in representing the correct trend of the noise process. Note that for conciseness the simulation results are presented for the TVAR case only. Since the simulations were run for Gaussian noise processes, the peak performance is well behaved. The MTIE and ZTIE data for this well controlled case provides little additional insight.

5. Simulation

The simulation results provided build upon earlier efforts to diagnose the statistics of telecommunication network timing performance[7]. The results enable an analysis of timing distribution topologies and permit educated speculation about the effect of degraded synchronization conditions on network performance. As was mentioned earlier these results have implications for the current asynchronous network design, but are particularly relevant to SONET, SDH and ATM network engineering (i.e., with regard to accommodation of timing signal variations and slip performance).

It is necessary to define the following model parameters to adequately define the timing signal generator at each node. For each of the cases examined the following constants apply:

1. Simulation time: 500K seconds
2. Proportional control factor: 221

3. Integral control factor: 8192
4. Damping factor: 3.0
5. Sampling time: 1.0 seconds

The phase–lock loop (PLL) parameters within the synchronization elements are representative for stable slave or transit node (OCXO) type timing devices. In the noisy environment scenario the noise signal is introduced at the first clock only.

5.1 Noise Free Linear Clock Model

Initially it is assumed that the timing reference at the source node is ideal. That is the initial phase error is zero and that phase variations are initially centered with respect to any buffer elements within the synchronization elements. The SEs are configured to reflect the cascaded timing chain as shown in Figure 1a & 1b. Figure 6 illustrates the TVAR performance for a linear chain of SEs.

The key feature that this graph makes evident is the significant growth of noise at the natural frequency of the control loop even for this over–damped situation. This noise growth under ideal input conditions is typical of telecommunication network SE designs. Notice that the short term stability remains well with in reasonable limits (i.e., minimal likelihood of pointer generation for SDH or SONET systems, and cell delay variation or loss for ATM systems). The growth of long term instability, however, will impair the holdover calibration values and make trouble isolation more difficult. This is because the actual source of the holdover value contamination may be far removed from the site at which the symptoms first begin to appear (in a network).

5.2 Noise Free Non–Linear Clock Model

The identical simulation to that in Section 5.1 is now repeated, that is, with respect to the hypothetical reference connection, but in this instance the phase (quantization) detector is deliberately modified to sample the signal in a non–linear manner. The point of emphasis here is that each SE in the chain will exhibit the same "large signal" time constant damping behavior as in the previous case, but the loop will also exhibit a wider bandwidth for low level input noise. The significance of these characteristics are borne out when the chain is subjected to actual network noise stresses. This behavior is illustrated in Figure 7a.

5.3 Discussion of Results

It is instructive to make a side–by–side comparison of the results of the linear and non–linear simulations. In Figure 8 the data are plotted in terms of decibels (dB) to emphasize the substantial difference in the growth of the phase noise as the clocks are cascaded. As seen in the figure the worst case instability is reduced by over 40 dB. This comparison dramatically illustrates the impact that a relatively small "implementation" issue such as, quantization phase error mapping, can have on overall network performance.

5.4 Verification of Simulation Results

In an effort to verify the validity of the simulation results a test fixture was designed to examine the behavior of an actual chain of 8 network synchronization elements (clocks). These clocks represented the improved design, employing the non-linear algorithms just discussed. Data were collected over a 72 hour period and compared to the previous results. Figure 9 reveals how well the simulated data compare with the actual network clocks. As shown the measured results compare favorable with the simulation model. Moreover, the figure also indicates the phase noise reduction between the linear model and the measured data, by roughly a factor of 10 for the example shown. Any small variance observed between the model simulation and the measured data is well within expected limits associated with correlated temperature effects.

5.5 Noisy Linear Clock Model

Although for many practical purposes it is common to consider synchronization signals at the point of origination as noise free, but in reality this is never really the case. Furthermore, "good" signals can arbitrarily and capriciously degrade and become unstable as a result of noise bursts, signal anomalies or related transient phenomena. Consequently, it is not difficult to appreciate that timing signal transport and signal processing along or within a chain of elements traversing a telecommunications network, will inevitably degrade the timing signal further. It is the signal emanating from the final transport NE that is the issue of concern. It is this signal that will eventually be delivered as a reference to synchronize some other clock within the subtending network(s). It is the purpose of this section to investigate the extent to which this signal can be degraded and to offer suggestions that could improve the situation.

The input signal characteristics used to evaluate the effect on the chain of cascaded clocks is described in reference 8[8]. This template which effectively serves as a worst case network noise reference was selected on the basis of an evaluation and extensive survey that was performed on existing network clocks by various participants in ANSI[6] T1X1.3. It represents the peak noise effects of timing signals from switching systems, cross–connect equipment as well as transport systems. It is noteworthy to point out that this template is based on peak performance of observed data over the short term $\leq$1000 seconds and is not intended to model actual long term network instability, but merely serve as a baseline for the development of SONET NE clock filter specifications.

The timing reference at the source node is now represented as the noise signal the characteristics of which are indicated in Figure 10. As before the initial phase error is zero and the phase of each clock is initially centered. Again the timing reference connection is the cascaded chain shown in Figure 1a & 1b. Figure 10a illustrates the TDEV performance for such a chain of SEs.

In this instance the input noise dwarfs the injected oscillator noise so much that it is no longer a factor in contributing to the short term stability. This type of noise if it does become a factor will only become apparent at very long integration times.

This figure not only describes the effect that a noisy input signal has upon the output from the

[6]American National Standards Institute

final clock in the reference chain, but moreover, reveals the underlying filtering and (oscillator) noise injection process that occurs between each of the clocks in the chain. This becomes evident by observing the substantial improvement in short term stability brought about by the low pass filtering of the first few clocks. This improvement soon vanishes with increasing observation time because of the peaking effect brought on by cascading the multiple filter poles. At this point the oscillator noise characteristics can no longer be filtered and due to the cascaded filter elements contribute to the injection of noise into the characteristics of the output signal. From this point on, the resultant behavior of the chain is dominated by the effects of the (cascaded) internal oscillator(s) because there is essentially no other possible source of noise in this controlled simulation environment.

Essentially, this simulation identifies the fact that these network clocks are trading–off high frequency noise rejection for low frequency noise peaking[7]. It is important to note that this is not meant to imply poor performance, but only that this is the best the performance that could be achieved. The results also correlate well with what one would expect to observe when measuring the end of a timing distribution path in a telecommunication network. It is therefore, concluded that the model adequately reflects the characteristics of a telecommunications network.

The essential feature of this comparison is the response of the non–linear implementation to the accumulated effects of large signal noise levels. It will be demonstrated in what follows that the non–linear implementation is able to maintain noise levels very near those of the original noise–free input because of a sophisticated non–linear gain control mechanism. Further, this mechanism relies on the aspect of the precise manner in which the integral and proportional gain factors are modified with respect to a previously stable condition. Hence, while there is the possibility for predictive correction the possibility for over–correction, or mis–correction is not allowed. In effect providing a "clutch" mechanism in the servo–control process.

5.6 Noisy Non–Linear Clock Model

When the same noise source is applied to the reference connection as diagramed in Figure 1, employing cascaded non–linear clocks described in Sections 3 and 5.2 the simulation results at first glance appear curious. Interestingly enough, the salient feature of Figure 10b is that the network output response is exactly the same as for the linear clock model. The short term stability is not at all affected by the input noise or influenced by the non–linear phase quantizer; moreover, the longer term instability noise values peak in the same manner as did the linear example. Perhaps surprisingly, this is precisely what one should expect to see. The significance of this result is that the response of the non–linear control loop compensates for the noisy input such that for higher noise levels the non–linear design reduces the loop gain effectively reduces the impact of the noise. Whereas, the well designed linear clock must filter the input.

In this example, however, the gain is reduced to be equivalent to that of the linear model. Further, lower noise levels will cause the gain to be increased so that the control loop will be tightly locked to the input signal (as it should) and its performance will match that of the linear model. The focus here is not that we have achieved analogous performance but the manner in which it has been done. Clearly, the two models differ in how they process the input noise. As

[7]This effect is also referred to as the Gibbs phenomenon.

noise levels increase either suddenly or slowly as by some network breathing phenomenon the non–linear implementation will manage its proportional and integral gain factors independently such that the performance exceeds the linear implementation. Conceptually, this must be the case because simply brute force filtering the input must approach a limit. Moreover, depending on the type of input noise the performance of the linear implementation is also limited because it is generally optimized for particular noise types, whereas the non–linear implementation manages several types handily.

It is also noteworthy to point out that in each scenario, as the number of cascaded elements increases the affect of filtering is progressive and barely noticeable. Essentially, the noise "transfer (function)" characteristics develop an increasingly steeper roll–off as would be expected from linear system filter theory. Recall that our hypothetical reference connection is a linear system for this noisy signal model. It is merely the individual synchronization elements that process the data in a non–linear fashion.

6. Summary

By examining the characteristics of the clock model described in Figure 3 and contrasting these with an understanding of network behavior that has been put forward one can postulate how the so–called boundary conditions might be manipulated to achieve an (overall) advantage at the expense of perhaps minor network effects.

Figures 10a and 10b demonstrate the results of the empirical trials undertaken to evaluate the impact of these performance trade–offs. If these figures included more detail of the higher frequency regions (times less than 256 seconds) it would be seen that the short term noise is slightly elevated in comparison to the well designed linear clock model. This, however, does not portray the correct picture because the linear approach does not adequately manage transient phenomena and the dynamic behavior of the telecommunications network. Alternatively, the non–linear design is able to make decisions necessary to manage such behavior. Notice also, that for the non–linear approach the stability values for times in excess of 1000 seconds are dramatically lower, so much so that it appears as if the size of the hypothetical network could be extended indefinitely. This of course is not practical, but the rather radical improvements brought about by implementation of the non–linear clock design hold great promise for bounding network stability in the face of ever increasing network complexity and the timing requirements that would obtain from them. In particular, the consequences of introducing SDH and SONET ring architectures pose formidable challenges to network synchronization engineering.

Finally, to reiterate the key points regarding the implementation of such non–linear clock designs as described herein: since the model has the potential to shift into a wide bandwidth mode by virtue of the input noise level and become unstable, some form of fail safe mechanism must be implemented to control this possibility. It was seen that this action can be prevented by virtue of building–in a "clutch" mechanism that prohibits the measurement decision circuitry from dwelling on a particular level too long so that changes in the control–loop gain may be gracefully managed. The control of the proportional and integral gain factors are managed to ensure stable modes of operation as the (non–linear) clock switches from wide band–width to narrow band–width based on a real time measurement of the input noise.

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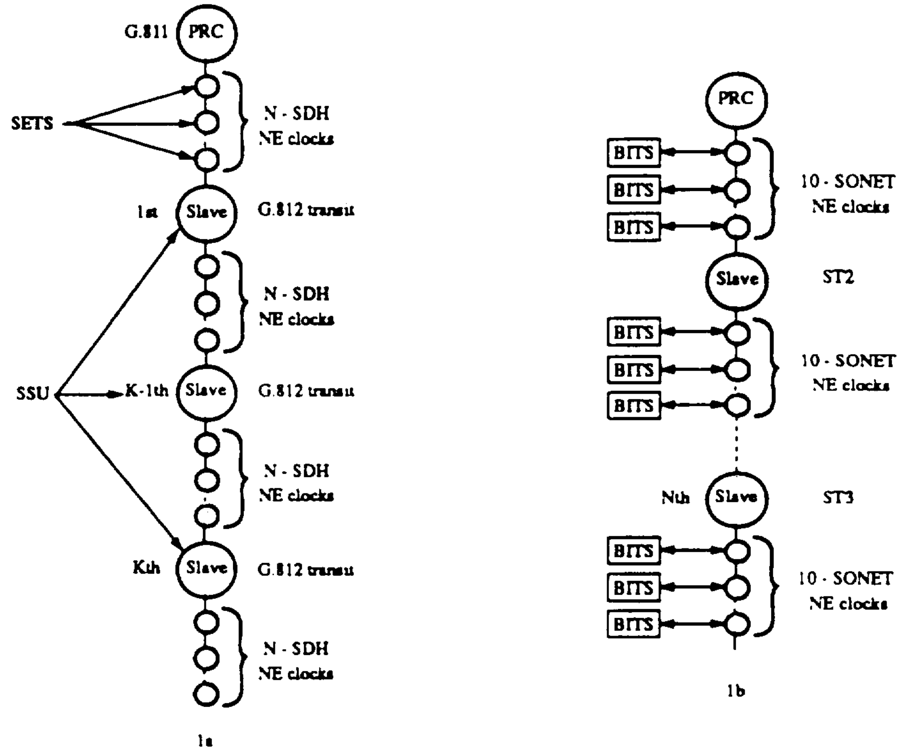

Figure 1. This is Figure 6.4/G.803 from IUT recommendation G.803, 1993

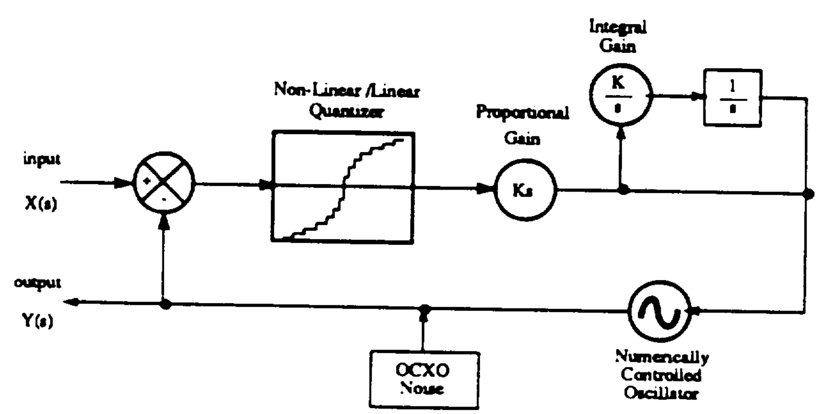

Figure 2. Generic clock architecture

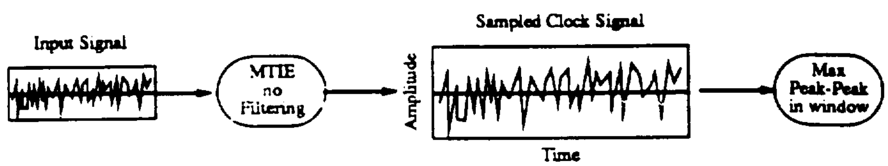

Figure 3

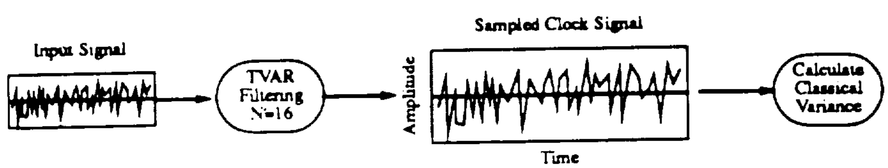

Figure 4

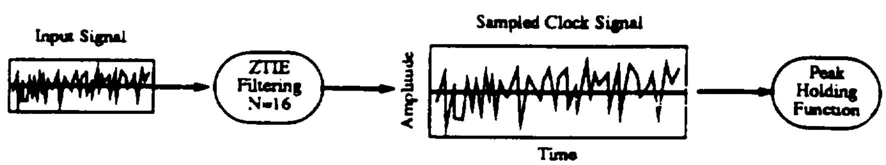

Figure 5

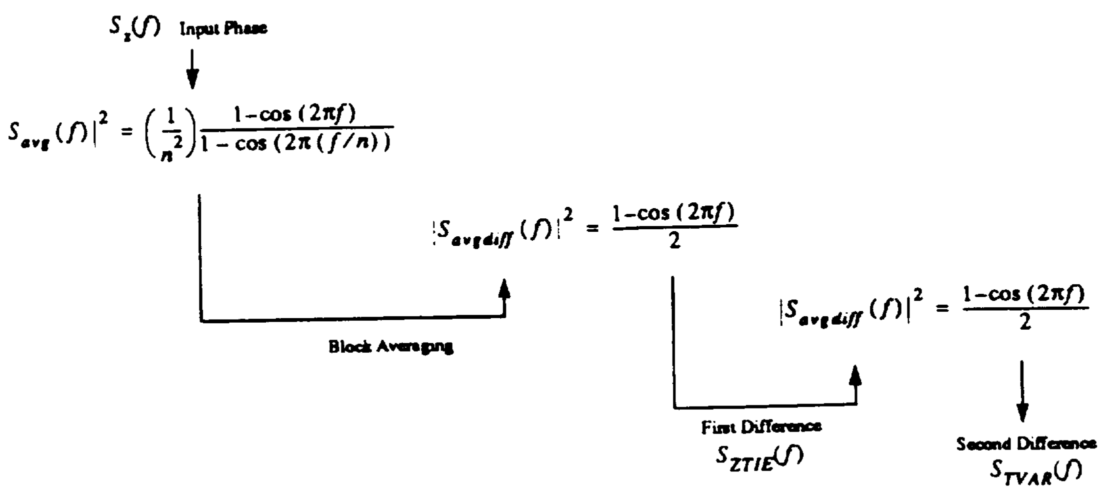

Figure 5a. Illustration of TVAR and ZTIE processing shown in the frequency domain as filter transfer functions.

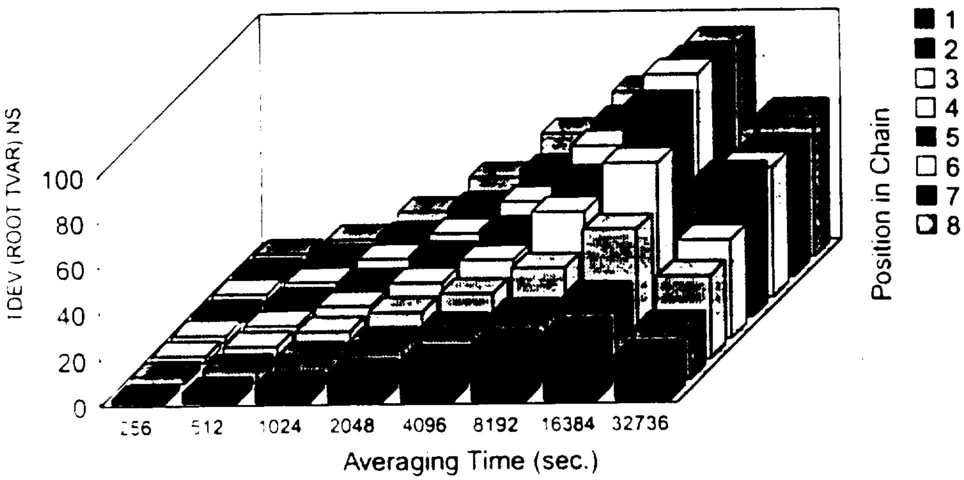

Figure 6. Linear Cascaded Clocks
Eight overdamped clocks

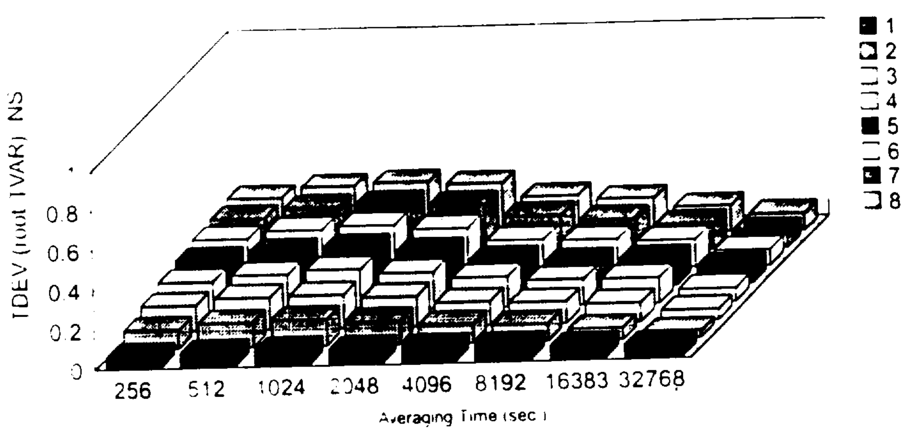

Figure 7a. Non-linear quantized cascaded clocks
Eight well designed clocks

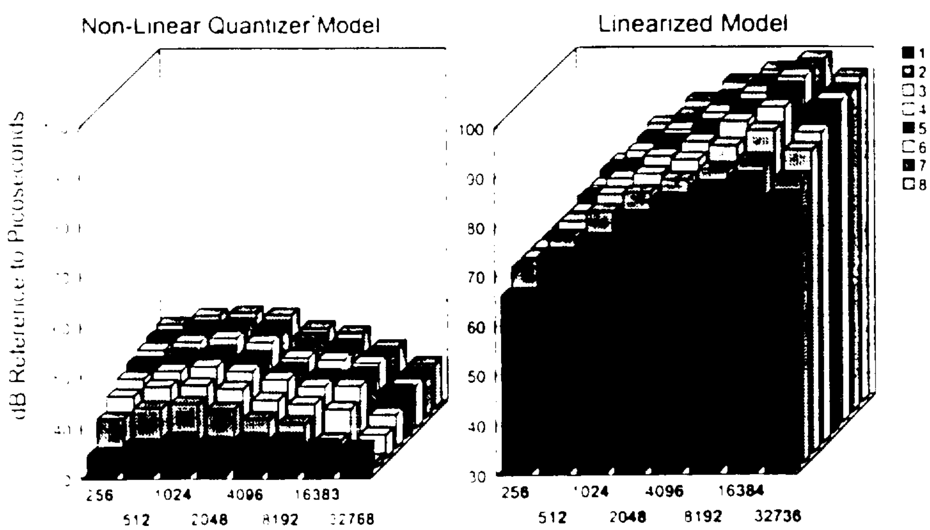

Figure 8. Comparison of Performance (Ideal Input)

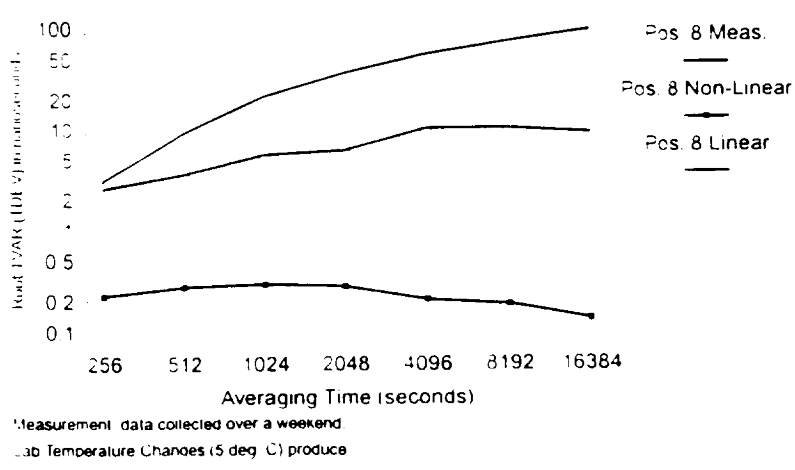

Figure 9. Simulated vs. measured performance
Last clock in chain (ideal input to first clock)

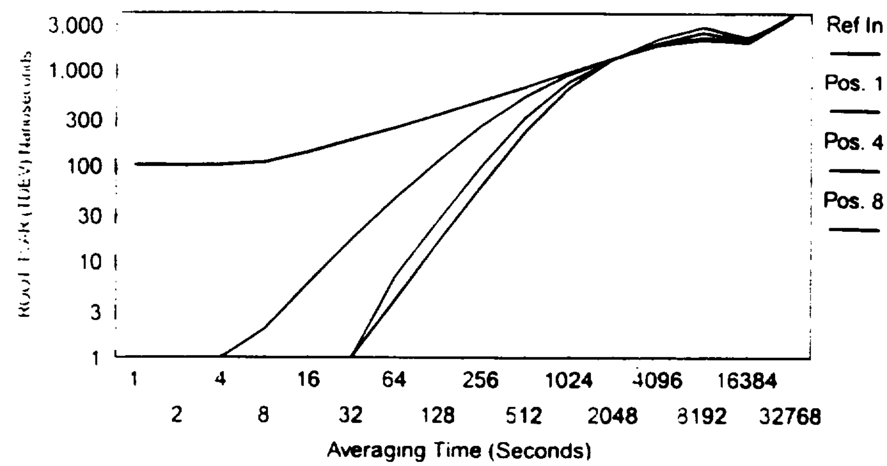

Figure 10a. Ref input noise ANSI T1.101 network noise mask linear simulation results

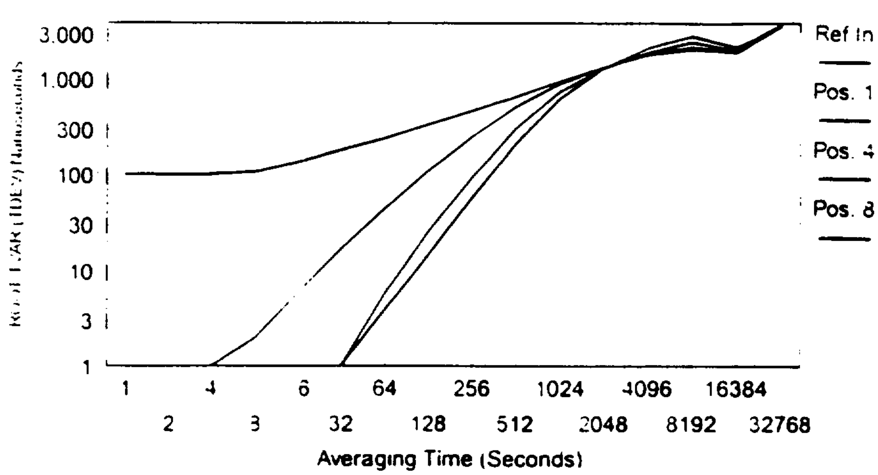

Figure 10b. Ref input noise ANSI T1.101network noise mask non-linear quant. simulation results

QUESTIONS AND ANSWERS

Marc Weiss, NIST: What would happen if we used the optical fibers? Optical fibers are extremely good for time transfer. What would happen if we bounced pulses back and forth between each network element to maintain synchronization throughout the network? How would that help some of these problems?

George Zampetti: Yes, the issue there is not technical. When I was at AT&T, we did experiments on commercial fiber; you basically have tens of ps per degree kelvin temperature variation, and that is about it. And for buried fiber, you get very good stability relative to what the network needs. The problem is that you don't have accessibility to the fiber; you have multiple vendors who are terminating that fiber. And they get paid for moving data and information, not for moving synchronization. And Japan has been pushed to try to utilize the fiber more directly. And I think that is going to have to iron itself out in standards; because, there really is sort of two camps: one camp says let's put more and more smarts and management right in the embedded network elements; others say that it can't happen, it's not manageable, let's take it out of that and make a separate overlay synch network. And so the use of the fiber is something where the issue is not technical; it is how do you get access to the pure fibers, or as close enough to it that you can achieve your goal.

David Allan, Allan's Time: I have two comments and one question. First of all, thank you for a very outstanding and very timely paper. I found it extremely interesting. One point of clarification, TVAR isn't a simple scaling from the modified two–sample variance because the multiplier tau is a variable. And when you do the Fourier transform, you see quite a different picture in Fourier space of these two functions. So it is a slightly different animal.

The question is that we are now seeing quite inexpensive GPS receivers which have claims of, even with SA one pps outputs which have RMSs in the vicinity of 40 or 50 ns, if is such inexpensive receivers could be located throughout networks, would this be useful? What is your perspective?

George Zampetti: My perspective is that that is happening for different administrations. They have already crossed some mental boundary which says GPS, with all its woes, is more stable (this may sound strange to this audience), more predictable and more manageable as a source of calibration traceability than trying to deal with its constantly changing network issues. So you are seeing GPS going in. Now what else you are seeing is acknowledgment that when we get done with this transition and we put down this GPS system, we take a step back and we ask the question, "Is this office better off for doing that?" And that is the big issue. Because, GPS is something that also has to be managed at the gate before it enters your whole central office. Like a virus gets in. And if something happens, if somebody opens up a hatch in the roof, then all of a sudden that moves over. What type of GPS do you really have? So there is an issue here that says yes, that basically it looks good. Let's look at it operationally and let's start looking at different vendors and look at what they are doing in terms of fault tolerance and sound length; how they manage the time scale; and oh by the way, it still has to be absolutely inexpensive. That is almost a given.

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Time and Position Accuracy using Codeless GPS

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Abstract

The Global Positioning System has allowed scientists and engineers to make measurements having accuracy far beyond the original 15 meter goal of the system. Using global networks of P-Code capable receivers and extensive post-processing, geodesists have achieved baseline precision of a few parts per billion, and clock offsets have been measured at the nanosecond level over intercontinental distances. A cloud hangs over this picture, however. The Department of Defense plans to encrypt the P-Code (called Anti-Spoofing, or AS) in the fall of 1993. After this event, geodetic and time measurements will have to be made using codeless GPS receivers.

There appears to a silver lining to the cloud, however. In response to the anticipated encryption of the P-Code, the geodetic and GPS receiver community has developed some remarkably effective means of coping with AS without classified information. We will discuss various codeless techniques currently available, and the data noise resulting from each. We will review some geodetic results obtained using only codeless data, and discuss the implications for time measurements. Finally, we will present the status of GPS research at JPL in relation to codeless clock measurements.

1. Introduction

The Global Positioning System (GPS) consists of a constellation of satellites (currently 27) which broadcast ranging signals. When four or more of these signals are tracked by a ground receiver, it is possible to solve for the position and clock of the ground receiver if the orbits and clocks of the satellites are known. If several receivers are tracking the satellite constellation simultaneously, the position and clock of each ground receiver, the orbit and clock of each satellite and some earth orientation and media parameters can all be solved for.

Using the International GPS Geodynamics Service (IGS), a global network including approximately 50 Rogue and TurboRogue GPS receivers, analysts at the Jet Propulsion Laboratory and several other GPS processing centers have demonstrated that it is possible to determine absolue geocentric receiver positions to a few parts in 10^9 (corresponding to 1 cm level coordinate accuracy anywhere in the world) [Heflin, *et. al.*, 1992; Blewitt *et al.*, 1992]. GPS satellite orbits are simultaneously adjusted in these global solutions to about 35 cm (RSS 3-D) accuracy and receiver clocks to about 0.3 ns, based on consistency tests carried out at JPL. With the addition of data from low earth orbiting receivers such as the one on the TOPEX/Poseidon spacecraft, solution accuracy improves still further, with GPS orbits improving to $\approx$ 25 cm [Bertiger, *et. al.*, 1993]. All of these results were obtained using the full P-Code precision. In the near future, the GPS P-Code will be encrypted. What impact will this have on GPS results?

2. Global Network GPS Solutions

The method used at JPL to produce GPS results involves using a network of globally distributed ground receivers which obtain radiometric observables from all satellites in view (up to eight) at each ground station. This is shown schematically in Figure 1. The primary observable obtained by the receivers is the carrier phase as a function of time. The pseudorange, smoothed over a track, is used to establish the *a priori* bias of the carrier phase. The carrier phase, shown in Figure 4, provides a much more precise measure of satellite range variation than the pseudorange, as can be seen in Figure 3.

Because each ground station sees several satellites and each satellite is viewed by several ground stations, enough data are available to estimate not only the ground station positions and clocks, but also to estimate the satellite orbits, the effects of the troposphere, earth orientation, and geocenter. By accurately estimating and modeling these parameters and error sources, solution error is approaching the limit imposed by long period multipath and unmodeled tropospheric signal delays. Multipath reduction and enhanced modeling of tropospheric path delays are ongoing efforts at JPL.

It is important to note that the strength of the clock solutions results from a combination of the carrier phase and pseudorange observables produced by the receivers. The carrier phase is less noisy than pseudorange by a factor of about 500. Thus, the carrier phase can be used to precisely track the variations of the receiver (and transmitter) clock. When these variations are removed from the pseudorange data, the noisy pseudorange can be averaged over an entire satellite pass to produce a single "phase bias" number. When this bias is added to the carrier phase observable, a measure of range results which tracks variation in range with extreme precision (better than 1 mm over 1 second) and has a constant offset that provides absolute range with high precision ($\approx$ 10 cm).

Further improvements in the estimates of satellite orbits and media effects have resulted from the addition of the P-Code GPS receiver on the TOPEX/Poseidon spacecraft. Because this satellite orbits the earth every 112 minutes, it provides much stronger dynamical and geometrical information about the location of the GPS satellites than the ground stations do. Similarly, the location of TOPEX/Poseidon can be determined very accurately due to the strong geometry. Currently, TOPEX/Poseidon orbits are believed to be accurate to 3 cm in the radial direction [Bertiger *et al.* 1993], and GPS orbits determined simultaneously in a global network solution which includes Topex GPS tracking data are accurate to approximately 25 cm RMS (RSS over all three components) [Bertiger *et al.* 1993].

The combination of these advances has enabled the results quoted in section 1.

3. Effects of Anti–Spoofing

The unencrypted GPS signal consists of a dual frequency carrier at frequencies L1 = 1.57542 GHz and L2 = 1.2276 GHz biphase modulated with ranging codes. The L1 carrier is modulated with a 1 MHz Gold code, known as the C/A code, and, in quadrature, a 10 MHz pseudo–random noise code (PN–code) known as the P1 code. The L2 carrier is modulated only with a 10 MHz code, P2. In order to track the ranging codes, the receiver's code generator must been matched to better than one code chip of the incoming code, or 1 microsecond for the C/A code and 0.1 microsecond for the P codes. This makes the C/A code easier to acquire than the P code, but a more significant factor is that the C/A code repeats every ms, while the P code does not repeat until a week has past. The L2 signal exists to reduce errors resulting from the ionosphere. The ionosphere introduces a dispersive signal delay, which can be used to determine the ionospheric delay from the difference in delay between the P1 and P2 ranging codes. There is no C/A code on the L2 carrier.

In order to control the accuracy with which users of the GPS are able to determine their position using a single GPS receiver and to protect against intentionally generated interference of the P–codes (spoofing), the defense department has implemented two security measures. These are selective availability or "SA", and anti–spoofing, or "AS".

Selective availability degrades user accuracy by introducing errors into the broadcast satellite ephemerides and by varying the satellite clock rate. Single station errors due to SA can be as large as 300 m. GPS users utilizing "double difference" processing suffer no measurable degradation in performance due to SA. Because different receivers view common satellites, the variations in the satellite clock can be solved for. Similarly, because GPS satellite orbits are estimated in the network solution, the solution is not sensitive to broadcast ephemeris errors. Anti–Spoofing degrades user accuracy in a more significant way. When AS is turned on, the P-Codes are encrypted so without classified information the receiver is unable to correlate its model code with the broadcast signal. The C/A code remains unencrypted, but due to its longer period, only 1/2 to 1/10 the pseudorange precision is available. Because there is no C/A code on the L2 carrier, it can not be tracked directly, which limits or eliminates the ionospheric information available to the user.

Commercial GPS receiver manufacturers have devised several strategies to recover some of the information which is obscured by AS. All of these designs use some aspect of the broadcast signal, determined by observing the encrypted broadcasts, to remove some of the encryption.

Squaring & Delay and Multiply:

The fact that the ranging codes are modulated onto the carrier using a bi–polar ($\pm$ 1) modulation can be used in truly codeless receivers by squaring the incoming signal. Because $(-1)^2 = (+1)^2 = 1$, the squared signal is free of code modulation, encrypted or otherwise. After squaring, the remaining carrier can be tracked to provide high precision Doppler information. However, all pseudorange data is lost, so squaring receivers are not very useful for clock synchronization. A variation on the squaring technique which produces a range observable is delay and multiply. By delaying the received signal by 1/2 chip and multiplying by the undelayed signal, the 10 MHz P–Code clock can be extracted from the sign changes in the P–Code. This produces a range to the satellite which is ambiguous to the 30 m period of the clock. This ambiguity can be resolved through knowledge of the satellite orbit. This technique has been used to demonstrate sub–nanosecond time transfer over short baselines [Buennagel *et. al.*, 1982], but no commercial receiver implementing this strategy exists. Note that in squaring and delay and multiply, the noise is squared as well as the signal, so SNR is degraded compared to code mode by approximately 30 dB for high satellites.

Cross Correlation:

Other codeless designs use the fact that the encrypted P–Code broadcast on L1 and L2 are the same. The simplest exploitation of this is to cross correlate the L1 and L2 signals. This is the codeless scheme implemented in Rogue and TurboRogue GPS receivers, designed at JPL. In the Rogue codeless scheme, L1 data is derived from the C/A code. The L2 carrier phase and pseudorange are determined by cross–correlating the L1 and L2 signals, and adjusting the relative delay and phase until the correlation amplitude is maximized. This results in a differential phase and delay measurement between L1 and L2. The L2 observables are recovered by adding the C/A measurement to the difference measurements for phase and delay, respectively. A schematic of the cross-correlation process is shown in Figure 2.

Figure 5 shows estimates of the of the errors expected in TurboRogue codeless processing when the data is processed as part of a global network with 24 hours of continuous tracking. Multipath, cable and filter instabilities are shared with code mode tracking, and were included in the code mode results quoted above.

Cross correlated data is "less good" than normal p–code tracking in four respects. Most significantly, when L1 is correlated against L2, the noise of both channels is multiplied together. This results in a loss in SNR of approximately 20 dB for strong satellite signals (greater than 50 degrees elevation), and more for weaker signals. Even with this loss, carrier phase noise is insignificant to clock synchronization. Using the carrier smoothing technique discussed above, the pseudorange data can be smoothed over an entire satellite pass ($\approx$ 6 Hr.) to result in the 0.07 ns error given in Figure 5.

Another error results because, in TurboRogue, the relative delay between the L1 and L2 signals can only be controlled in 50 ns steps (the "Lx Lags" shown in Figure 2). In code mode, the feedback can be used to exactly match the delays of the receiver's code generator and the received signal. In cross correlation mode, though, due to the 50 ns lag spacing, it is usually not possible to directly match the delays of the L1 and L2 signals, but, rather, it must be calculated from measurements made at other delays. This requires a detailed knowledge of the shape of the L1 x L2 cross correlation amplitude. Errors in this model contribute 0.25 ns, labeled "Amp. vs. Lag Modeling" in Figure 5.

A third error results because the C/A code is used for the L1 observables. This error results from two level sampling and is proportional to the cube of the single sample voltage SNR. This error is labeled "Two–Level Sampling" in Figure 5 and contributes approximately 0.1 ns. This error is insignificant in code mode, because the P–code SNR is lower by 3 dB, and the chip length is shorter.

Of less significance, because cross correlated data is processed differently than p–code data, the total measured delay will be different. This has the effect of introducing a bias between code and codeless data. The constant part of these biases should not affect clock synchronization, because they can be measured and recorded. This can be operationally troublesome, however. The magnitude of this bias is $\approx$ 2 ns in TurboRogue, and tens of nanoseconds in Rogue.

Enhanced Cross Correlation:

The cross correlation technique can be improved by determining properties of the encrypted signal from observation and then applying this knowledge to algorithms which reduce the bandwidth of the encrypted signal. By reducing the bandwidth, more noise can be excluded from the measurement, and a higher SNR obtained. In theory, enhanced codeless can result in SNR's 13 dB higher than cross correlation, or only 7 dB lower than code mode for strong signals. No receiver manufacturer has yet published results that we know of living up to this promise, however.

Enhanced cross correlation implementations will invariably suffer from some of the errors shown in Figure 5. The precise values of each error depend on proprietary details of the implementation, and may be available from the manufacturer.

PPS/SM:

Finally, it should be mentioned that users authorized by the DOD can recover the full precision of the p–code by using a (classified) PPS/SM module to decrypt the encrypted signals.

4. Experimental Test of Codeless Clock Synchronization

In order to test the error predictions given in Figure 5, we observed the clock estimates for three TurboRogue receivers whose frequency references were connected to hydrogen masers. By looking at the change in the receiver clocks when AS was turned on, we get a crude estimate of the accuracy of codeless time transfer as compared to code mode operation. We refer the reader to Dunn, *et. al.* [1991] for a discussion of external tests of code mode time transfer accuracy.

The data used in this analysis were taken from September 22, 1993 through September 25, 1993. GPS week 715 was chosen specifically because anti–spoofing was on during part of this week. The data contains carrier phase and pseudorange measurements from 24 available GPS satellites tracked by approximately 42 globally distributed JPL Rogue receivers. The data were processed in the JPL precise orbit determination and parameter estimation software, GIPSY/OASIS II (GPS Inferred Positioning SYstem, [Lichten & Border, 1987 and Sovers & Border, 1990]). All non–fiducial station locations were estimated, as well as earth orientation parameters, GPS carrier phase biases, random walk zenith troposphere delays for each tracking site, and all transmitter and receiver clocks, except the clock at North Liberty, which was used as the reference clock. The coordinates of five "fiducial" site's were held fixed (unadjusted) in order to define the reference frame. The clocks were estimated as white noise parameters for each measurement epoch (no a priori constraint was applied to tie clock estimates at one time to clock estimates at another time). This is essentially a standard filtering strategy commonly used in precise geodetic analysis of GPS data. X and Y polar motion, polar motion rates, and UT1–UTC rates were estimated as constant parameters (reset every 24 hours). On days when AS was not in effect the GPS orbits were estimated with 5 solar radiation pressure parameters, 2 parameters estimated as constants and the 3 remaining parameters estimated as stochastic corrections to the constant solar pressure parameters. When AS was in effect, only the constant parameters when estimated for solar radiation pressure.

Figures 6 and 7 show the clock estimates for GPS TurboRogue tracking sites at Pie Town, New Mexico and Westford, Massachusetts relative to North Liberty when AS was turned on at the end of the day (UTC) September 23. The code mode data was taken from the Sept. 23 solution, while the codeless data was taken from the solution of Sept. 24. This increases the effect of clock errors due to errors in satellite orbits, troposphere estimation, and earth orientation parameters which would difference out if taken from the same solution. This test is not sensitive to errors due to delay variations in receiver hardware. Accounting for the clock rates, the shift in the estimate was 0.22 ns for Pie Town, NM and 0.72 ns at Westford, MA, both measured relative to North Liberty, IA. By subtracting these estimates, we find the clock jump between North Liberty and Pie Town was 0.41 ns. These are consistent with the estimates in Figure 5.

5. Conclusions

The GPS system has the potential to produce sub–nanosecond clock offset measurements over intercontinental distances. Anti–Spoofing increases the noise in the radiometric observables, but by using carrier smoothed pseudorange, the system noise error can be reduced to a level well below that expected from multipath. While biases between code and codeless operation result in operational difficulties, sub–nanosecond clock synchronization should still be possible with AS turned on.

Acknowledgments

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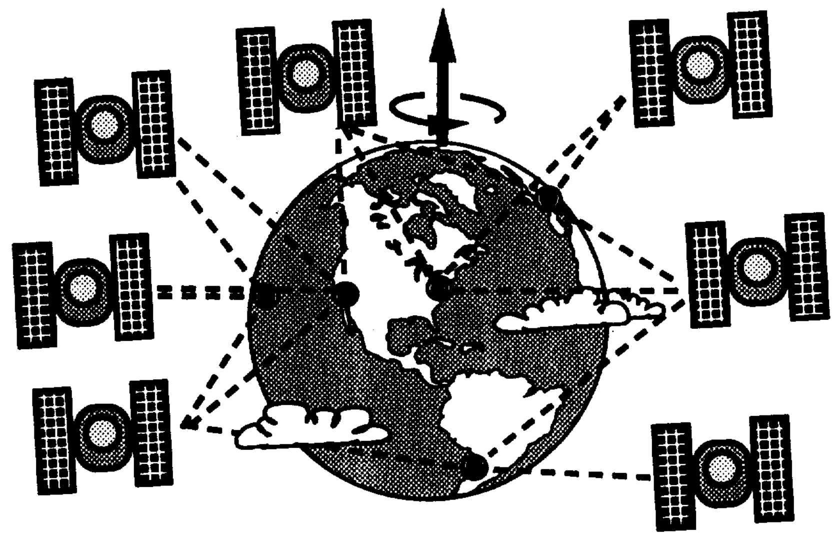

Figure 1: Global network solutions. Each satellite is observed by many receivers, and each receiver observes many satellites. Station positions, satellite orbits, troposphere and Earth rotation parameters are all estimated.

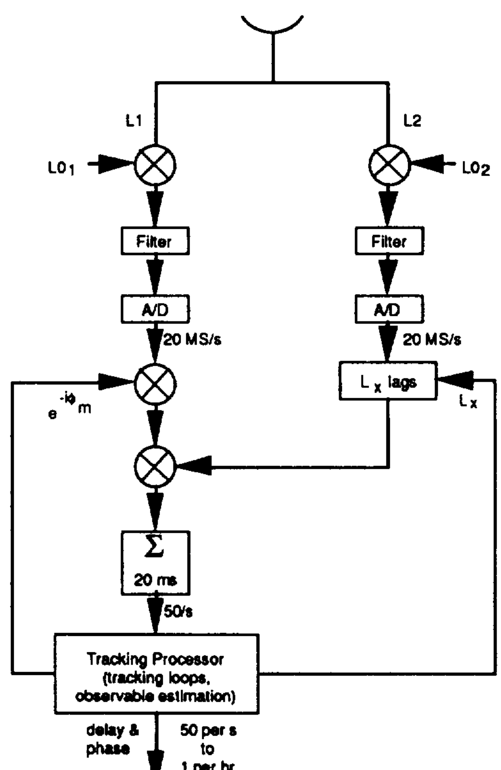

Figure 2: TurboRogue codeless Processing.

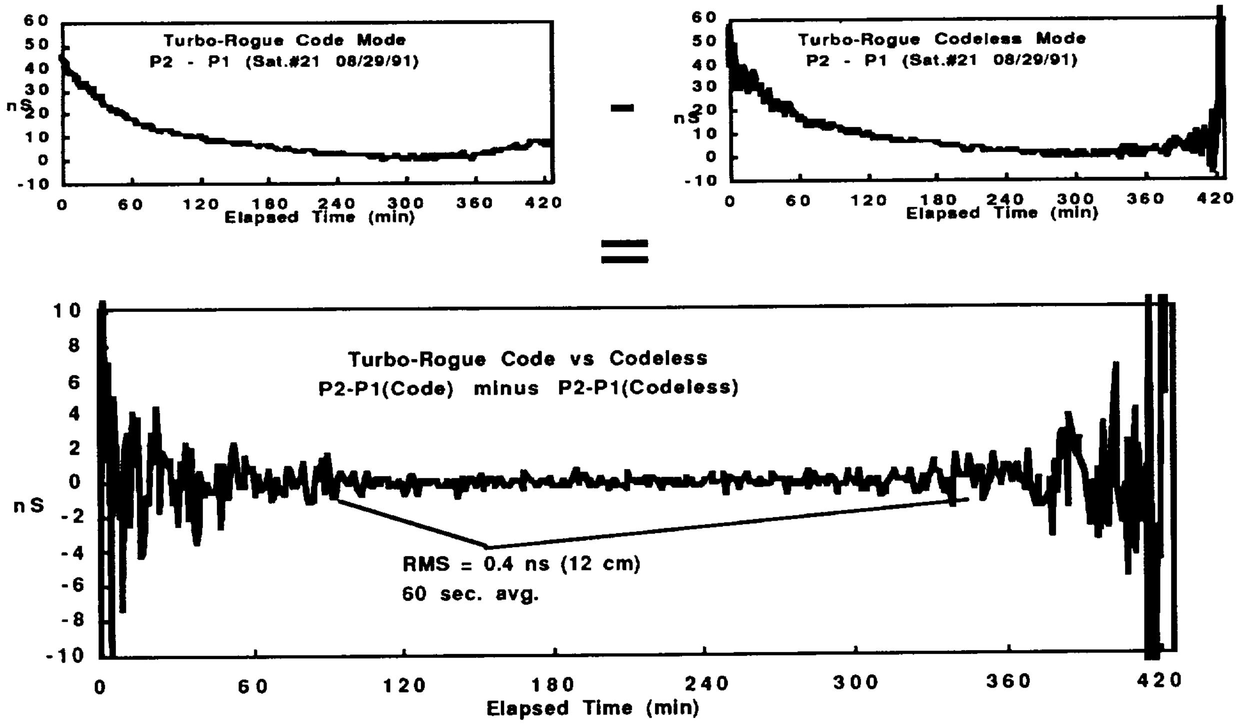

Figure 3: A comparison of TurboRogue code and codeless pseudorange. [Meehan, *et. al.*, 92].

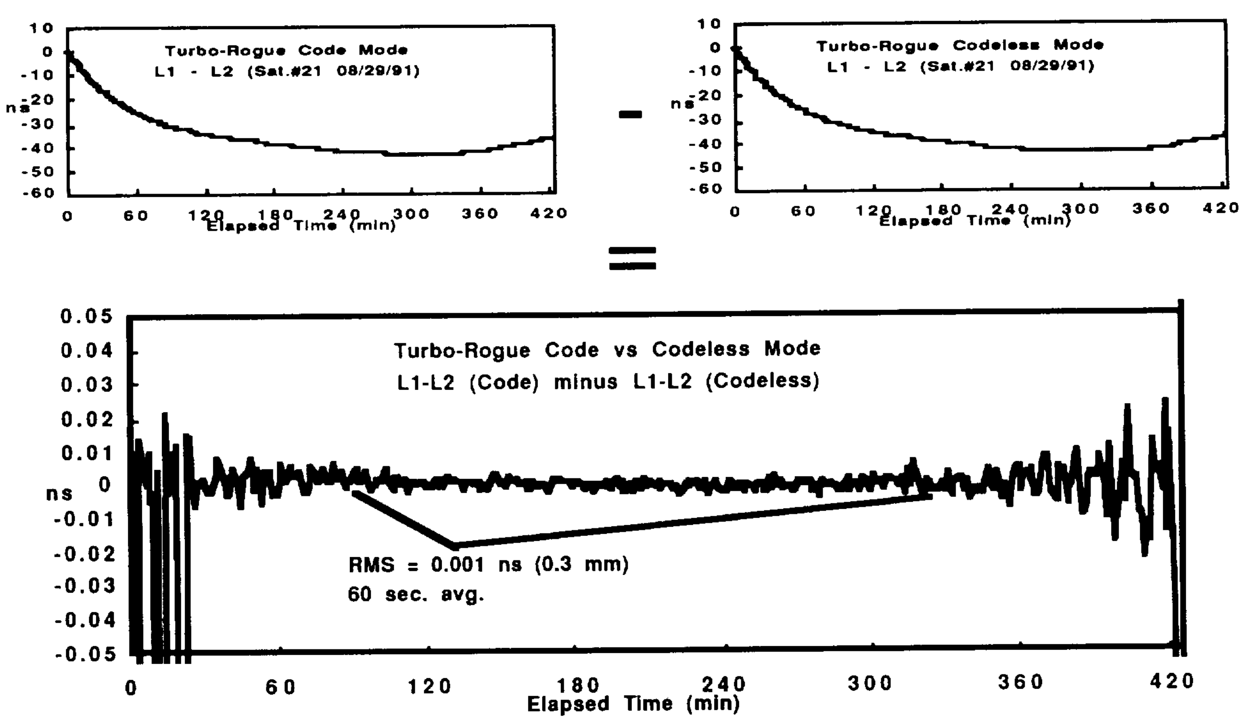

Figure 4: A comparison of TurboRogue code and codeless carrier phase. [Meehan, *et. al.*, 92].

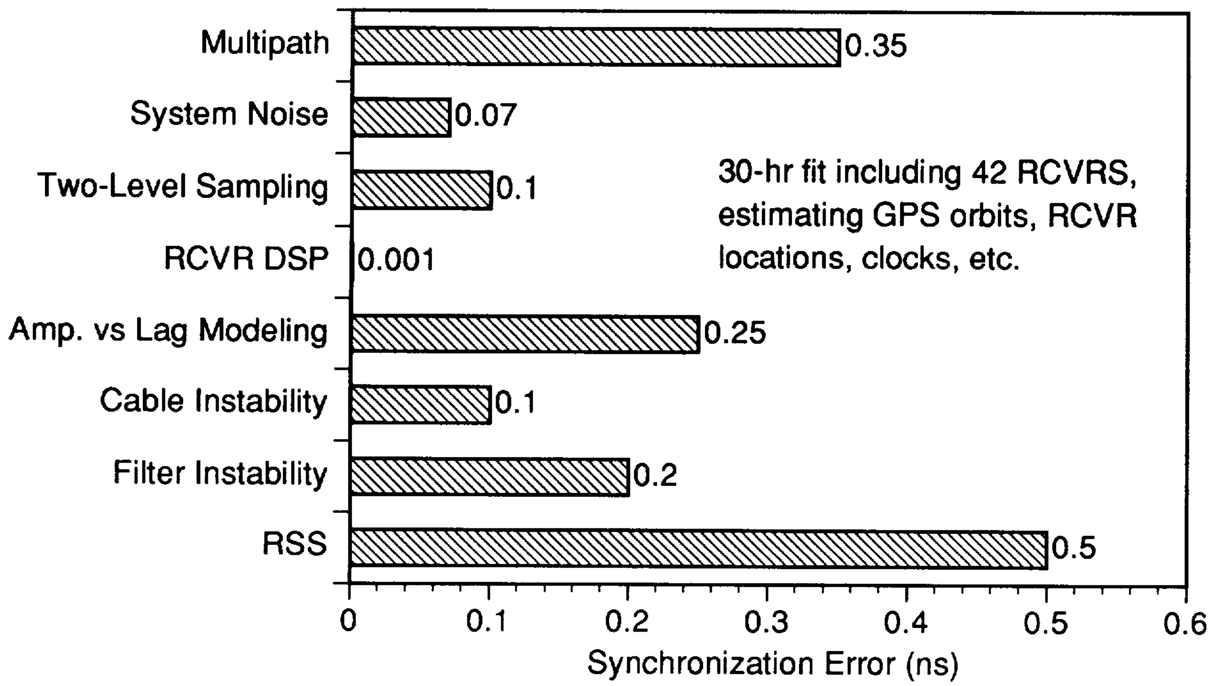

Figure5: Estimates of time-varying errors in clock synchronization between TurboRogue GPS receivers in the p-Codeless mode.

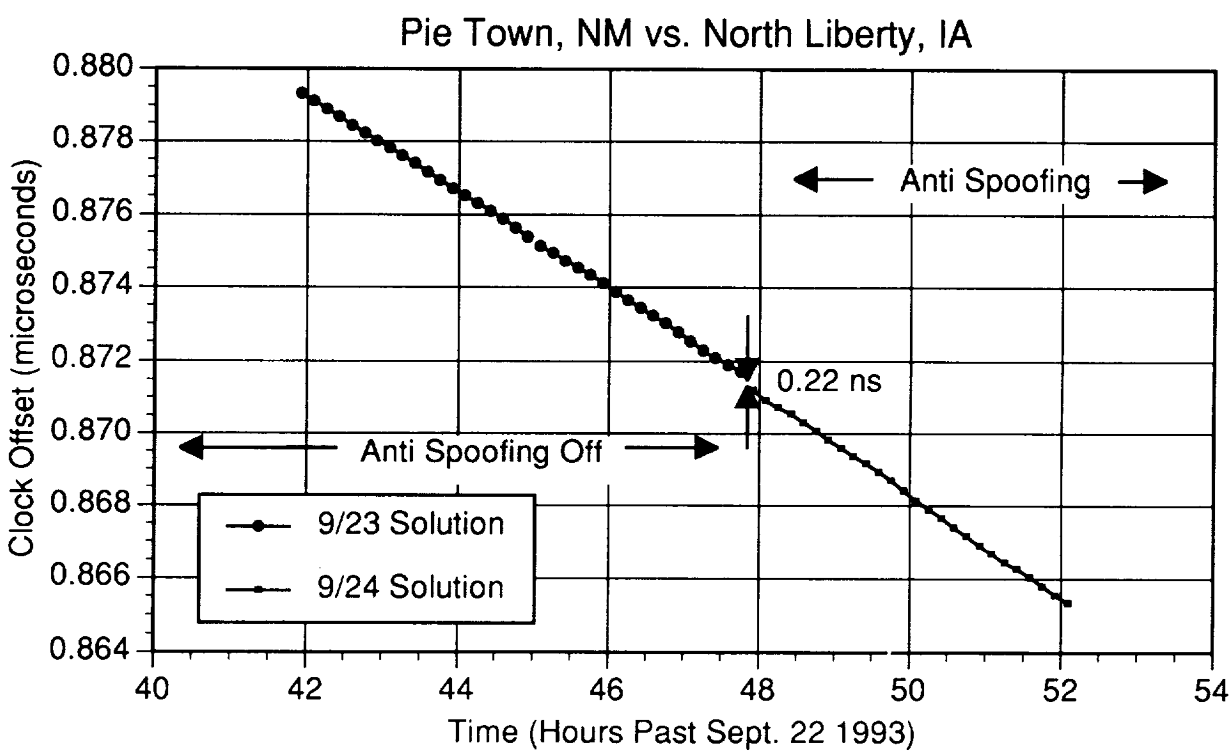

Figure 6: Receiver Clock Offset of Pie Town, NM.

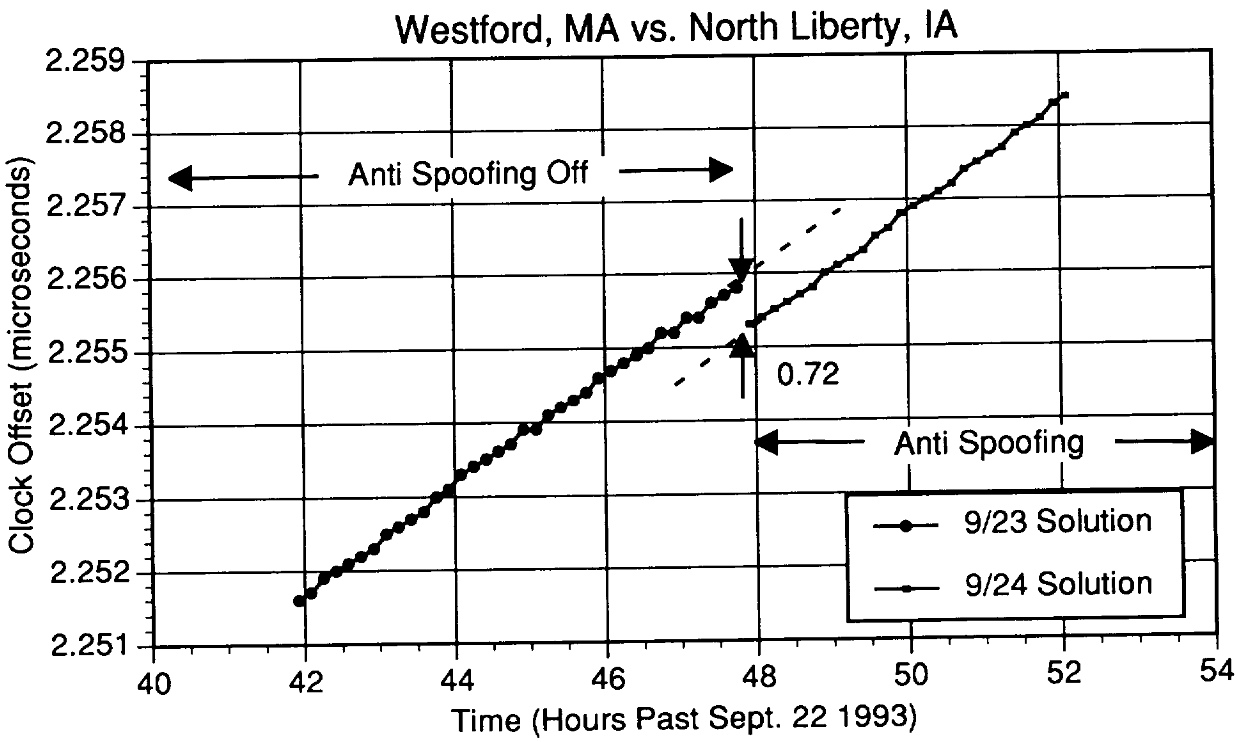

Figure 7: Receiver Clock Offset of Westford, MA.

QUESTIONS AND ANSWERS

Claudine Thomas, BIPM: I have one question. It might be a very naive question, but I'm not sure I have understood (or I missed something). You are speaking about clock synchronization using turbo–rogue receivers. But turbo–rogue receivers are geodetic receivers; we cannot do time with a turbo–rogue receiver.

Charles Dunn: Well the turbo–rogue receivers are geodetic receivers, but in fact they were designed with clocks synch in mind. We have a very wide-band front end and they can be run from an external frequency reference. So the frequency reference in the experiment was a hydrogen maser. The estimates that are produced by the software that are plotted here are of the receiver clocks. Now to connect the receiver clock to outside instruments – in other words, get an absolute offset between clocks – you have to look at the one pulse per second output of the receiver. We have looked at that and have shown that the delay of the one pps compared to the receiver clock is stable to two tenths of a ns over long periods of time, a month for instance.

Claudine Thomas: I mean your local hydrogen maser, for instance, is it put into the receiver with the 5 MHz?

Charles Dunn: That's right. The 5 MHz from the local clock is put into the receiver; the receiver phase locks an amount to generate a 20–MHz sample clock. And then that sample clock is used to take the GPS data. And so we are tied to the local frequency reference.

David Allan, Allan's Time: This is a question regarding maybe the accuracy of what you have done. It seems like from self–consistency you are really looking at stability of the system, time and stability and not accuracy. You have no independent check of the true time difference between the two hydrogen masers at these two locations for example, I believe. Is that correct?

Charles Dunn: Well it is true in this experiment that we do not have any independent tests. This was done fairly quickly for this conference. In the work that I presented two years ago, we used DSN sites and compared the clock offsets and rates generated by long baseline interferometric measures of quasars. So in other words, you correlate the signal from the quasars and you get the delay between the clocks very precisely. The offsets on those VLBI measurements are fairly imprecise, like 20 to 30 ns. And so that wasn't able to nail it down. The rates, however, are very precise; they are good to fractions of a ns per day. And our rates agree with their rates pretty well within our errors. And so all of that is still consistent with doing two or three tenths of a ns clock synch. To really nail it down, I agree you have to have some other way of doing it. And the spacecraft tracking demonstrations that we have been working on last summer and this December with TDRSS and Mars Observer should be the final nail in that. But they are not complete. And so I cannot talk about them yet.

Christine Hackman, NIST: You mentioned that you got your orbits from 40 stations around the world. I just wondered what happened when anti–spoofing came on. Were all these stations somehow able to – how did they keep tracking?

Charles Dunn: The receivers are able to tell when anti–spoofing comes on. They lose the P–code, they lose lock. And then they automatically go into cross–correlation mode and start looking for the encrypted signal. And then they are able to lock up usually in half a minute or so. And so there is more or less continuous data, although there is a phase break. The carrier phase will have a gap in here; and since it is not an absolute measurement of delay, that means that you have to reestablish what the carrier phase bias is. And then you have to use to the codeless pseudo range to level those carrier phase numbers and connect the phase across the gap.

Jack Klobuchar, AF Phillips Lab: This is kind of a complicated question. I gather that your biggest source of error is because you can't put that relative differential carrier phase to an absolute scale as precisely as you would like because of multi–path. Now if that is the case – and you mentioned you had some plans to improve the multi–path situation – can't you take advantage of the fact that multi–path is repeatable from day to day, because the satellites are repeatable with the 3 hour and 56 minute time difference, and basically subtract out the major parts of that multi–path from individual passes?

Charles Dunn: Well the number that I presented with multi–path being 50 centimeters comes from averaging the multi–path down over an entire track. It doesn't include trying to use daily repeatability to remove the multi–path. And that is one of the things that we are looking at, ways of determining the source of the multi–path so that you can model it and then remove it. And presumably the way that would work is that by using the daily repeatability of the multi–path, you could locate the primary sources and then subtract that from the data. Other things that we are doing are looking at the multi–path as a function of delay in order to estimate the multi–path in the receiver and then improve the observables. We are also looking into better antennas and a number of other things.

Bruce Penrod, TrueTime: Isn't the classic problem with using carrier phase for time transfer that you have to be able to have a pseudo–range code measurement accurate enough that you are within half of a cycle of the carrier phase? Isn't that the classic problem?

Charles Dunn: That's right. In fact, the pseudo range averages down to be less than a cycle. It is actually a false cycle, because in the codeless receiver mode we get full cycle measurements. If you average the pseudo range over an entire track of six hours, then you get down to where you can – well, the data I have shown doesn't have the integer cycles resolved. You can do better by doing that. The data I've shown just have the carrier phase leveled with the average pseudo range.

Bruce Penrod: I see your code data there and I can see that there is more than a few ns of noise from that data.

Charles Dunn: That's right, but if I average this down, it averages down to the number that is on the error plot. I think it was 10 or 15 centimeters, something like .07 ns. This is a nice zero mean kind of a thing.

Bruce Penrod: So you believe that you can resolve the carrier cycle ambiguity at these levels?

Charles Dunn: We definitely can resolve carrier cycle ambiguities. We do it in geodetic work when we need to do millimeter kind of stuff. The stuff I showed didn't have the cycle ambiguities removed; it was still limited by the uncertainty in the pseudo range.

Something I would like to point out is that even though the scatter on this is very small, the multi–path is more or less common to L–2 and L–1. So this plot does not show multi–path which is at 50 centimeters.

THE USE OF THE AOA TTR-4P GPS RECEIVER IN OPERATION AT THE BIPM FOR REAL-TIME RESTITUTION OF GPS TIME

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Abstract

The Global Positioning System is an outstanding tool for the dissemination of time. Using mono-channel C/A-code GPS time receivers, the restitution of GPS time through the satellite constellation presents a peak-to-peak discrepancy of several tens of nanoseconds without SA but may be as high as several hundreds of nanoseconds with SA. As a consequence, civil users are more and more interested in implementing hardware and software methods for efficient restitution of GPS time, especially in the framework of the project of a real-time prediction of UTC, UTCp, which could be available in the form of time differences [UTCp - GPS time].
Previous work, for improving the real-time restitution of GPS time with SA, to the level obtained without SA, focused on the implementation of a Kalman filtering based on past data and updated at each new observation. An alternative solution relies upon the statistical features of the noise brought about by SA: it has already been shown that the SA noise is efficiently reduced by averaging data from numerous satellites observed simultaneously over a sufficiently long time.
This method has been successfully applied to data from a GPS time receiver, model AOA TTR-4P, connected to the caesium clock kept at the BIPM. This device, a multi-channel, dual-frequency, P-code GPS time receiver, is one of the first TTR-4P units in operation in a civil laboratory. Preliminary comparative studies of this new equipment with conventional GPS time receivers are described in this paper. The results of an experimental restitution of GPS time, obtained in June 1993, are also detailed: 3 to 6 satellites were observed simultaneously with a sample interval of 15 s, a efficient smoothing of SA noise was realised by averaging data on all observed satellites over more than 1 hour. When the GPS system is complete in 1994, 8 satellites will be observable continuously from anywhere in the world and the same level of uncertainty will be obtained using a shorter averaging time.

INTRODUCTION

The NAVSTAR Global Positioning System, GPS, is a military satellite navigation system based on satellite ranging using on-board atomic clocks. It can also be used as a time distribution system for a user who has a known position and who tracks at least one satellite. The time scale, GPS time, distributed by the GPS satellites is a continuous time, maintained in agreement with UTC(USNO) to within 100 ns [1].

Observational data delivered by GPS time receivers represent time differences between the 1pps (1 pulse-per-second) of the user's local clock and GPS time, as deduced from the received signal of a given GPS satellite. Such timing-data may be used for time transfer purposes by the common-view method [2]. The principal feature of this method is that satellite clock error contributes nothing, as GPS time disappears in the difference. This is of utmost interest during implementation of Selective Availability (SA) [3]. The ultimate accuracy of the common-view mode is a few nanoseconds [4].
The GPS timing data may also be exploited for access to the time scale GPS time and hence to reference time scales such as UTC(USNO) or a even a real-time prediction of UTC [5]. The

precision of access to GPS time depends on local conditions of observation, mainly on the quality of the receiver antenna coordinates. Generally, the realization of GPS time through the constellation shows a peak-to-peak discrepancy, at a given instant, of up to 30 ns. However, this performance is largely degraded by implementation of Selective Availability. The real-time restitution of GPS time from Block II satellites then suffers peak-to-peak discrepancies up to several hundreds of nanoseconds as shown in Section 1 of this paper.

Previous studies have been carried out for real-time processing of local GPS timing data with the aim of improving the restitution of GPS time, in the case of SA, to a level comparable with that obtained without SA. One possible solution relies upon Kalman filter theory [6]. This method, which provides a real-time access to GPS time from filtered past data and from present observations, is efficient even if little data is available but is rather heavy to put in operation. A much simpler solution can be used when a greater amount of data is available. This relies upon the statistical features of the noise brought about by SA [7,8]: it is shown in Section 2 that, for an averaging time of a few hundreds of seconds, the SA noise is white and corresponds to an uncertainty (1σ) of about 85 ns. It follows that an average of data from numerous Block II satellites, observed simultaneously, greatly decreases the impact of SA. This method has been successfully applied to data from a GPS time receiver, model AOA TTR-4P, connected to the caesium clock kept at the BIPM. This device, a multi-channel, dual-frequency, P-Code GPS time receiver, is one of the first TTR-4P units in operation in a civil laboratory. Preliminary comparative studies of this new equipment with conventional GPS time receivers are given in Section 3, together with results of the test of restitution of GPS time.

1. REAL-TIME ACCESS TO GPS TIME FROM THE OBSERVATION OF ONE GPS SATELLITE

Data from a GPS time receiver take the form of time differences [Local Clock - GPS time (SV)](t) as obtained through observation of satellite SV over a time interval centred on date t. Quantitative information on the precision of real-time access to GPS time at date t, may be obtained by comparison of this raw observation with a deferred-time estimation of [Local Clock - GPS time](t), achieved through the application of a smoothing technique on a set of data from Block I satellites not affected by SA.

Such estimates are regularly made at the BIPM, which publishes values of [UTC - GPS time] in its monthly bulletin, *Circular T*. An example is shown in Fig. 1.a. for the two-month period February-March 1992, with data following the international GPS common-view schedule. The precision of GPS time restitution can be expressed in terms of the root mean square, r, of the residuals to the smoothed values; here r = 7,3 ns. This value, deduced from Block I satellite data only, reflects the impact of systematic errors due to conditions of observation:

- i. residual errors in local antenna coordinates, in general very small for national timing centres contributing to TAI [9],
- ii. errors in estimating the ionospheric delay of GPS signals, here negligible as measured ionospheric delays are used [10],
- iii. errors in ephemeride parameters broadcast by the satellite [11],
- iv. other minor error sources such as multipath effects and the sensitivity of the local receiver to external temperature [12]).

The r value can as large as 10 ns when measured ionospheric delays are not available [8].

In Fig. 1.b. are shown the smoothed values [UTC - GPS time] of Fig. 1.a., together with raw data obtained from a selection of Block II satellites. The impact of SA may be expressed quantitatively as r equal to 48 ns, which is much larger than the value 7,3 ns obtained from Block I. It follows that with reasonable conditions of observation, the real-time reading of the quantity [Local Clock - GPS time] presents discrepancies up to 30 ns from Block I satellites and up to 150 ns from Block II satellites. It is thus essential to design and implement hardware and software solutions for efficient real-time restitution of GPS time.

2. REAL-TIME ACCESS TO GPS TIME FROM THE SIMULTANEOUS OBSERVATION OF A NUMBER OF BLOCK II SATELLITES

If real-time access to GPS time is degraded to the level of 150 ns from the observation of one single Block II satellite, one could imagine that further information, from the simultaneous tracking of several Block II satellites, would permit a lower value to be obtained. To develop a procedure based on this idea, it is first necessary to have a good knowledge of the statistical properties of the SA noise.

For this purpose, timing data from different Block II satellites have been analysed at the BIPM. They correspond to 15 s data sequentially recorded with a one-channel C/A-code receiver at the BIPM on 10, 11 and 12 February 1993. Four different Block II satellites (SV 16, 19, 26, 27) and one Block I satellite (SV 12) were observed for several hours (from rising up to going down).

Figure 2.a. shows a plot of 15 s raw data recorded for satellite 26 over more than 4 consecutive hours. The Allan deviation computed with this timing data is reported in Fig. 2.b. together with the Allan deviation values obtained with 15 s data from SV 12. Timing data from SV 12 shows white phase noise, the level of which is about 15 s, for all averaging times. It corresponds to observational noise, as detailed in Section 1. The same noise is apparent on Block II data for the very short term, up to τ = 30 s. In the longer term, the SA degradation brings additional noise, characterized by the typical Allan deviation 'bump', which corresponds to sinusoidal variations of timing data with a half-period of order 150 s. For larger τ (240 s to about 2000 s), the predominant noise is white phase noise, corresponding to a level of about 85 ns. White phase noise can be reduced by using simple averages. Figure 2.c. shows the timing data from SV 26, after smoothing out of both of the short-term and long-term white phase noise. The corresponding Allan deviation values are added in Fig. 2.b.: they show the efficiency of the smoothing procedure. Figure 2.c. clearly indicates the presence of residual sinusoidal variations with periods of order some hundreds of seconds.

The same analysis has been performed with observational data from different Block II satellites. The corresponding Allan deviations are reported in Fig. 3. for four of them. This demonstrates that the SA noise has the same statistical features in each of the four examples, though the corresponding satellites were not tracked simultaneously. One can thus reasonably make the hypothesis that all Block II satellites are affected by white phase noise of comparable level, 85 ns (1σ), over averaging times longer than 240 s. For the usual 780 s tracks, the SA noise is thus reduced by a factor $\sqrt{780}/\sqrt{240}$. It gives a residual SA noise equal to 47 ns (1σ), a value which corresponds to what is reported in Section 1.

The statistical analysis of the noise brought about SA on timing data has very important consequences. With all Block II satellites affected by white phase noise of comparable level, 85 ns (1σ), over averaging times longer than 240 s, it is sufficient, to reduce SA effects, to observe simultaneously a number of Block II satellites over long averaging times and to compute a mean of the individual satellite results. For example, observation of 8 satellites with a multi-channel receiver for a 2000 s track-length reduces the level of the SA white noise to about 10 ns. This is comparable with the usual observational noise. In addition, the result of the mean may be obtained immediately after data recording, thus providing access to GPS time in near real-time. This method was tested using data from an AOA TTR-4P unit in operation at the BIPM.

3. USE OF THE AOA TTR-4P AT THE BIPM FOR REAL-TIME ACCESS TO GPS TIME

3.1. Brief Description of the AOA TTR-4P

The Allen-Osborne-Associates TTR-4P is a GPS receiver adapted to high accuracy time measurements. This device is issued from the largely digital Turbo-Rogue geodesic receiver. As is usual in GPS time receivers, it accepts the 1pps, delivered by a local caesium clock, as input together with a stable 5 MHz or 10 MHz signal. It operates with a multidirectional antenna mounted on a choke-ring plane in order to minimize the effects of multi-path propagation. The technical characteristics of the AOA TTR-4P can be obtained from the manufacturer. From our experience the device cannot yet be considered as fully operational but is has practical characteristics of utmost interest for civil users of the timing community. The principal advantages of the AOA TTR-4P are as follows.

- It decodes the P-code, so that it operates with a much higher precision than conventional C/A-code receivers.
- It receives both of the GPS frequencies, so that it delivers timing data directly corrected for measured ionospheric delays.
- In case of Anti-Spoofing (AS), it uses a special cross-correlation mode, so that results are still corrected for measured ionospheric delays. The precision of the results is not as good as that obtained by decoding the P-code but is much better than that obtained with conventional C/A code receivers.
- It has 8 physical channels which makes it possible to observe up to 8 satellite simultaneously.
- Theoretically it can operate with sample interval from 1 s to 30 s with 1 second increments, and from 30 s to 3600 s with 30 seconds increments. In its specific cross-correlation mode, 10 s is the minimum update rate.

The operation of one TTR-4P unit at the BIPM began in November 1992. To our knowledge, this was the sole unit, until late 1993, operating in a civil timing laboratory. Since November 1993, another unit has been installed at the NPL, Teddington, UK. The results of comparisons between two TTR-4P units, on the same site or through GPS strict common-views, are not yet available.

As is generally the case for C/A-code time receivers, our TTR-4P unit was delivered by the manufacturer without previous absolute calibration. In addition, no information is given on its long-term stability and in particular, on possible changes of its internal delay with the external temperature. We were thus very interested to compare this new device with receivers having well known characteristics. The results given here concern preliminary studies of comparisons between the TTR-4P unit and other multi- or mono-channel C/A-code receivers in operation at the BIPM. The TTR-4P unit is operated with a 1 s or 15 s sample interval according to the purpose of the experiments. Since our TTR-4P unit has no flash card for data storing, timing data is dumped directly into an outside microcomputer before treatment.
In case of a 1 s sample interval, the treatment is applied in real-time. This corresponds to short-term data processing as described in the Technical Directives for Standardization of GPS Time Receiver Software [13]: timing data are referenced to UTC, quadratic fits are applied on 1 s measurements over 15 s periods, and linear fits on the results of 52 successive quadratic fits. This makes it possible to recover timing data corresponding to the usual 780 s tracks, in particular those programmed in the international GPS tracking schedule as issued by the BIPM. We must add that we had many difficulties in making our TTR-4P unit operate correctly in the 1 s mode. The manufacturer delivered the appropriate software version only after 6 months of unsuccessful trials at the BIPM. In addition, because of the opacity of the

operator's manual, we discovered the mode for real-time dumping of 1 s data only on 18 October 1993.
Data obtained with 15 s sample interval have sometimes been saved with no immediate treatment and then used to test methods for GPS time restitution [Section 2.3.]. On an operational basis, the corresponding treatment would be implemented in real-time. The 15 s data can also be treated through linear fits in order to recover 780 s tracks. This data processing is in fact very close to the one suggested in [13] as the TTR-4P 15 s data are probably much less noisy than the 15 s data resulting from quadratic fits on 1 s measurements issued from a C/A- code receiver.

3.2. Preliminary results of comparison of the TTR-4P with other receivers in operation at the BIPM

The conditions of comparison are as follows.

- Two C/A code GPS time receivers are compared with our TTR-4P unit: one 4-channel SERCEL NRT2 unit and one single channel AOA TTR6 unit. Highly accurate antenna coordinates are entered in each receiver. The common local time reference is the clock installed at the BIPM.
- The comparison lasted 23 days, from 9 to 27 October 1993. From 7 to 18 October, the TTR-4P was operated with 15 s sample, and from 19 October with 1 s sample.
- About 190 tracks, each of them of 780 s duration, were recovered every day from the short-term TTR-4P data. About 40 of these correspond to the international GPS tracking schedule No 21, programmed in the TTR6 unit and in one channel of the SERCEL unit. The 150 tracks left were chosen from Block II satellites and were scheduled in the three remaining channels of the SERCEL unit. The 4 channels of the SERCEL unit were differentially calibrated before the experiment.
- The SERCEL and TTR6 units use modelled ionospheric delays while the TTR-4P unit uses measured delays. For an efficient comparison it is thus necessary to recover timing data which are not corrected for ionospheric delays. It is also necessary to correct the TTR-4P data using the L_1-L_2 correction [13]. After these diverse corrections are applied, one computes, for each track, the difference between the timing data, referenced to the same clock, obtained with two receivers:

$$\delta t = [\text{Local Clock - GPS time}]\text{Rec1} - [\text{Local Clock - GPS time}]\text{Rec2}.$$

Values given in Table 1 and reported in Figure 4 correspond to daily averages Δt of δt. All residual errors arising from the conditions of observation are smoothed out in the average and the values obtained correspond roughly to the differences of the internal delays of the two receivers. This comparison is thus denoted [Rec2 - Rec1].

A daily value Δt reported in Table 1, for a particular date, is characterized by the standard deviation, σ, of one measurement on that date, and by the number, n, of common tracks between two receivers also on that date. It may be seen that the σ values are always inferior to 4 ns: on average 3,0 ns for [TTR-4P - SERCEL] and slightly smaller, 2,5 ns, for [TTR-4P - TTR6]. These σ values can be considered as very good: they are of the same order of magnitude as that usually observed when comparing, for instance, one AOA TTR6 unit and one AOA TTR5A unit [14]. In addition, for the comparison [TTR-4P - SERCEL], the number of daily common tracks is much larger than usually done [14]. One can thus conclude that the comparison noise is mainly brought about by the C/A-code receivers, SERCEL and TTR6, and probably not by the TTR-4P. In addition, the change from 15 s to 1 s sample interval on 18 October for the TTR-4P unit was not followed by a decrease of σ values, which seems to indicate that, even with short-term data taken every 15 s, the TTR-4P is better than the C/A-code receivers.

In Figure 4, are plotted daily averages Δt for the comparisons [TTR-4P - SERCEL] and [TTR-4P - TTR6], together with the daily average of the outside temperature. One may see a strong variation with temperature of [TTR-4P - SERCEL], but not of [TTR-4P - TTR6]. The SERCEL unit has already been found sensitive with outside temperature [12], which is not the case for this particular TTR6 unit, so the observed phenomenon is probably not due to the TTR-4P unit. We are continuing comparison studies to confirm this result. For the period 15 October to 29 October, for which the outside temperature was stable, the average differences of internal delays are (-19,7 ± 0,5) ns for [TTR-4P - SERCEL] and (-24,7 ± 0,7) ns for [TTR-4P - TTR6].

To conclude, the preliminary results of comparison of our TTR-4P unit with two C/A-code receivers is satisfactory. For now, this device does not appear to be sensitive to outside temperature, and, in addition, it is convenient to operate it with 15 s sample interval, which facilitates the task. We continue to test this device in particular, through multi-channel common-views with a remote TTR-4P unit.

3.3. Experimental results of real-time restitution of GPS time

Data from the TTR-4P unit, which were taken over a 10 hour period on 15 June 1993, include 15 s observations of all available Block I and Block II satellites. Observations corresponding to very low satellite elevation were not retained in the data set. In addition, a hill close to the BIPM, and lying in a western direction from it, constitutes a mask, so that, for the period under study, data from only 3 to 6 satellites were observable simultaneously. Among them, data from 1 or 2 Block I satellites were available for some hours of the experiment. A deferred-time smoothing was applied to this Block I data and the corresponding values, reported in Figures 5.a. and 5.b., can be considered, to some extent, as reference values for [Local Clock - GPS time].

The 15 s data from all Block II satellites observed simultaneously are averaged and reported on Figure 5.a.: the SA noise is still evident. This Block II data is then treated through a moving average over a time interval chosen as a multiple of 240 s, the duration 240 s corresponding to the shortest time for which the SA noise is white (see Figure 3.). The result of the moving average is assigned to the mid-date of the averaging time interval and constitutes the restored value of [Local Clock - GPS time] at this date.

Results are reported on Figure 5.b. for a time interval of 3840 s (16 times 240 s). The SA noise can be treated as being white for this averaging time, as shown on Figure 3. Figure 5.b. indicates that the moving average performs a smoothing of Block II data. With, on average, 4 satellites observed simultaneously over a time period of 16x240 s, the SA noise, 85 ns (1σ), is reduced by a factor $\sqrt{16} \times \sqrt{4}$ and has an estimated value of 11 ns (1σ). This verifies approximately the value obtained from the computation of an Allan standard deviation on these values. A part from a residual noise, the restored values present biases relative to smoothed Block I data: the largest discrepancy is about 16 ns. Such biases may come from both Block I and Block II satellites:

- from Block I satellites, because they are at the end of their life and present biases of up to 20 ns between them [15],
- from Block II satellites, because it has already been shown that the SA noise can also cause long-term drift [8]. With 6 satellites observed simultaneously, a bias of 80 ns for one of them results in a bias of only 13 ns on the average.

To improve yet these results, it is necessary to observe more satellites, for preference 8 of them when the constellation is complete, and to control long-term drifts. In the above experiment, the restitution of GPS time is carried out with a delay less than half an hour. Observation of a greater number of satellites would reduce this delay further.

CONCLUSIONS

The precision of the real-time restitution of GPS time from the occasional observation of one single Block II satellite is degraded to the level of several hundreds of nanoseconds because of SA. In theory, this effect can be reduced if simultaneous observations of Block II satellites are continuously performed through the use of a multi-channel GPS time receiver.
This method was tested using data from a multi-channel, dual-frequency, GPS time receiver, model AOA TTR-4P, which decodes the P-code and is in operation at the BIPM. Some comparative studies between this newly designed device and conventional C/A-code GPS time receivers have been performed. Preliminary results confirm the stated performances of the TTR-4P model, though it cannot yet be considered as fully operational.
The experiment on the restitution of GPS time, performed at the BIPM, shows that the implementation of a moving average on a sufficient long period of simultaneous observations of Block II satellites helps to smooth out the SA noise. The delay of access to restored values can be of order half an hour. This is an important result, which must be still studied as part of the project of dissemination of a real-time prediction of UTC [5].

Acknowledgements
The author is grateful to her colleagues from the BIPM, especially to P. Moussay for his continuous effort in operating the TTR-4P unit. The experimental part of this work was done at the BIPM thanks to the loan of a caesium clock from the USNO (Washington DC, USA). The BIPM is grateful to USNO for its generosity.

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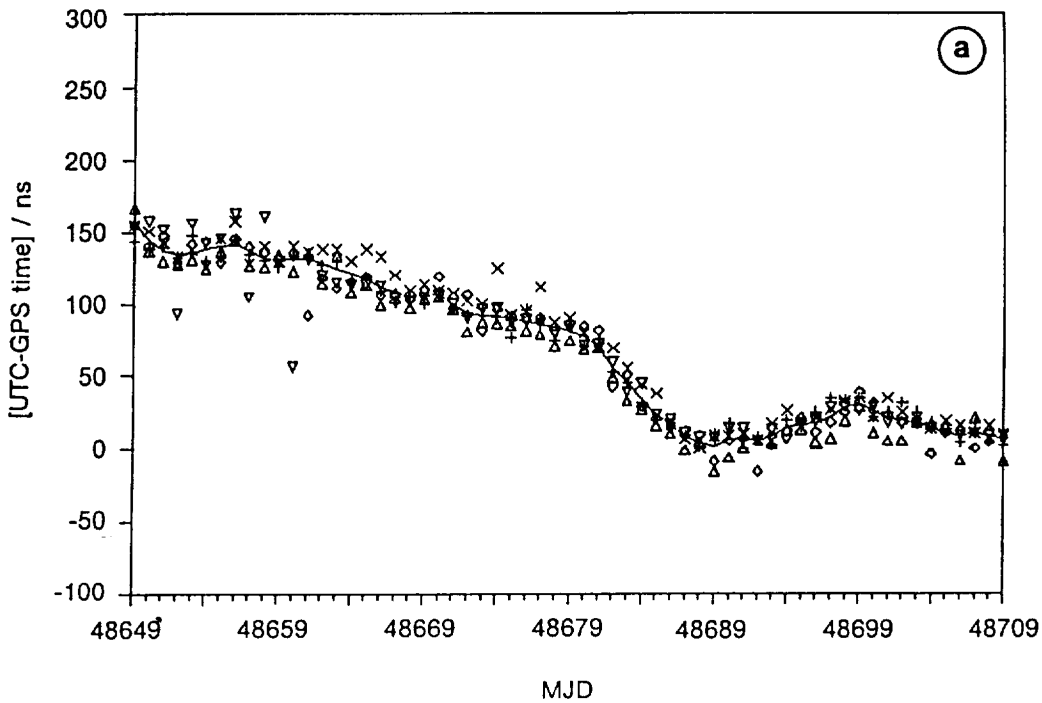

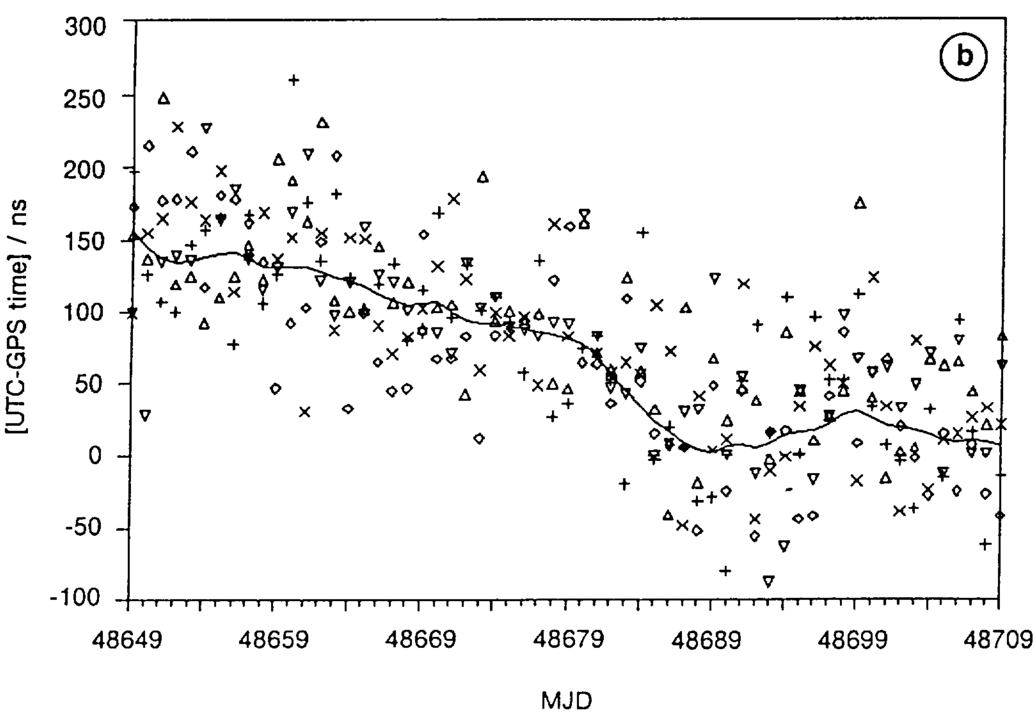

__Figure 1__. Restitution of [UTC - GPS time] in deferred-time.
Measured ionospheric delays are used to correct raw GPS data.
1.a. Data from Block I tracks and corresponding smoothed values (——).
1.b. Data from Block II tracks and smoothed values of Fig. 1.a.

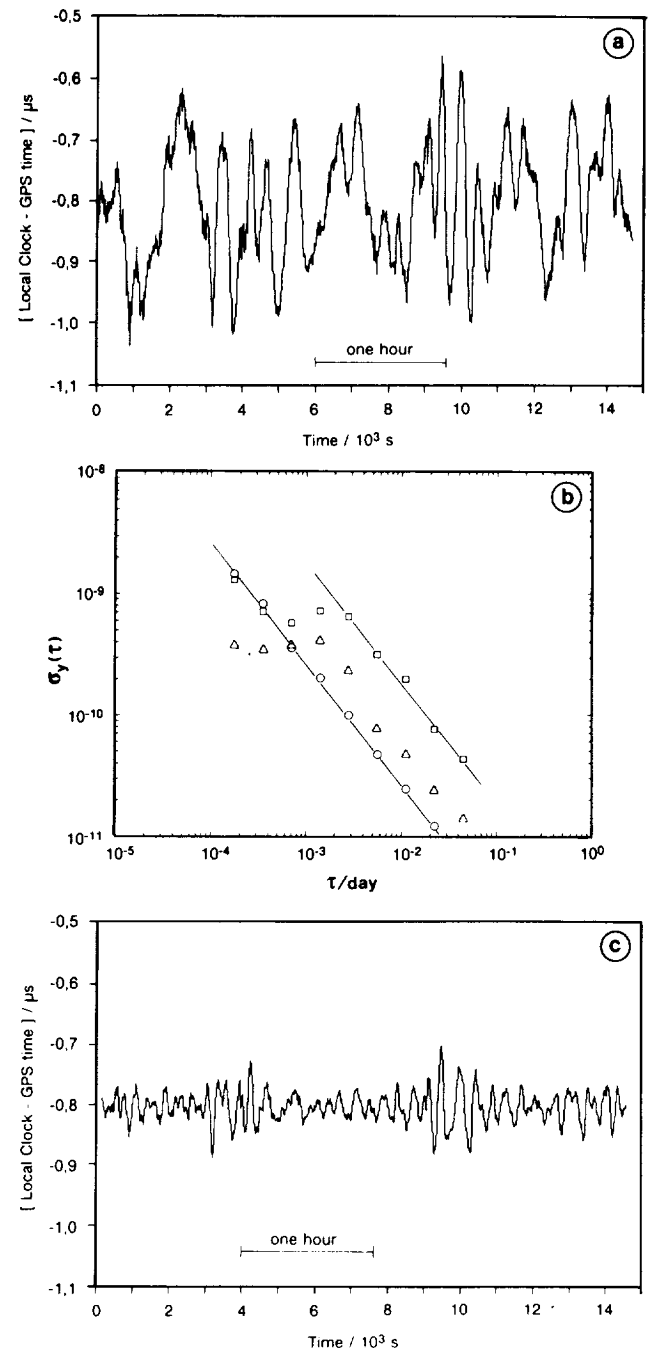

Figure 2. ***Study of data from satellite 26, taken for more than 4 consecutive hours.***

2.a. Raw 15 s measurements.

2.b. Allan deviation of:

□ ***15 s raw measurements from satellite 26.***

○ ***15 s raw measurements from satellite 12.***

△ ***15 s smoothed measurements from satellite 26.***

2.c. Data from satellite 26, smoothed for short-term and long-term white noise.

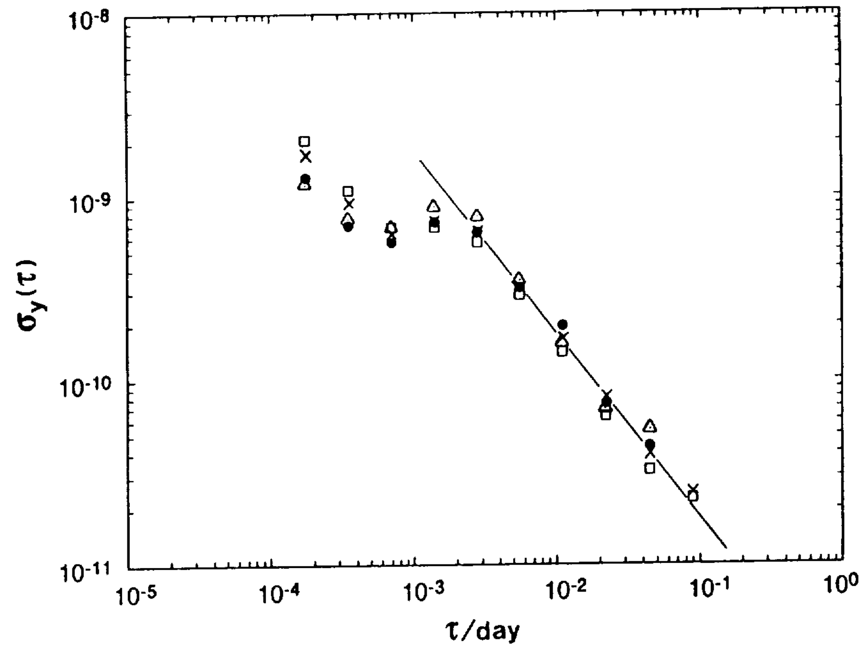

Figure 3. Allan deviation of 15 s data from 4 Block II satellites. Satellite 26,●, 19,□, 27,×, and 16,△.

date 1993	[TTR-4P - SERCEL]			[TTR-4P - TTR6]		
	Δt/ns	σ/ns	n	Δt/ns	σ/ns	n
07 Oct	-14,7	3,6	179	-25,1	4,7	34
08 Oct	-15,0	3,6	179	-25,5	3,6	32
09 Oct	-15,6	3,2	172	-26,0	2,9	33
10 Oct	-14,6	3,1	180	-24,8	2,8	35
11 Oct	-14,2	3,7	185	-24,7	3,4	35
12 Oct	-14,2	3,2	188	-25,0	2,8	34
13 Oct	-14,4	3,2	180	-23,3	3,5	35
14 Oct	-15,8	4,0	177	-24,2	3,3	33
15 Oct	-19,0	2,7	145	-23,5	1,7	32
16 Oct	-19,4	2,8	167	-24,1	3,9	35
17 Oct	-19,5	2,5	181	-24,5	2,6	35
18 Oct	-19,9	2,6	176	-24,7	2,4	34
19 Oct	-19,6	2,6	182	-25,0	2,1	36
20 Oct	-20,1	3,1	182	-25,3	2,4	35
21 Oct	-19,3	3,0	182	-24,1	2,3	34
22 Oct	-19,2	2,8	178	-24,2	1,8	33
23 Oct	-19,9	2,6	187	-25,0	2,6	35
24 Oct	-19,3	2,7	184	-24,1	2,0	35
25 Oct	-19,6	2,9	193	-24,9	1,8	34
26 Oct	-20,9	2,5	185	-26,3	2,4	35
27 Oct	-20,2	2,4	180	-25,0	1,6	33
28 Oct	-19,4	3,3	183	-25,0	2,4	34
29 Oct	-20,0	3,0	149	-25,5	2,3	27

Table 1. Comparison of three GPS time receivers at the BIPM for a 23-day period. The involved receivers are one AOA TTR-4P unit, one SERCEL NRT2 unit, and one AOA TTR6 unit. The different notations are defined in Section 3.2.

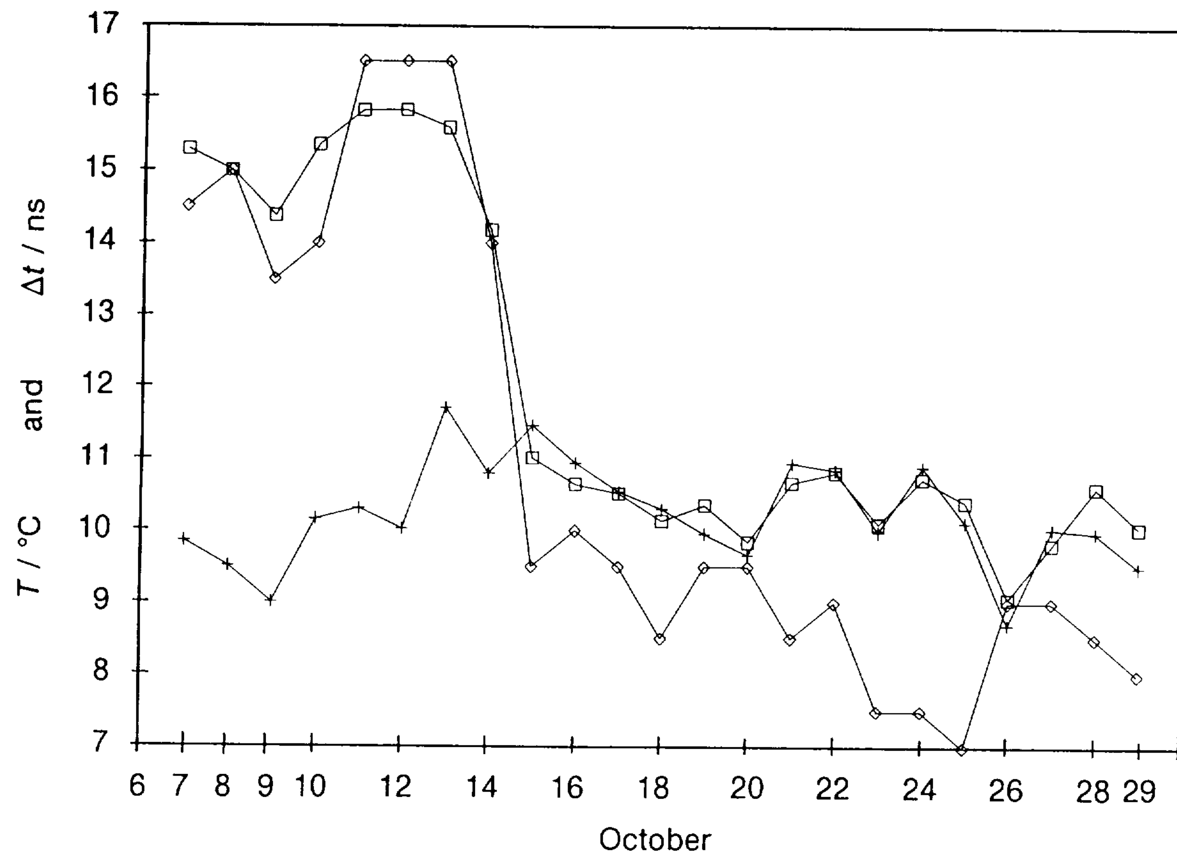

***Figure 4.** Comparison of three GPS time receivers at the BIPM for a 23-day period. The involved receivers are one AOA TTR-4P unit, one SERCEL NRT2 unit, and one AOA TTR6 unit. The notation Δt is explained in Section 3.2.*

◇ *Outside temperature T.*

□ *Δt for [TTR-4P - SERCEL], shifted by +30 ns.*

\+ *Δt for [TTR-4P - TTR6], shifted by +35 ns.*

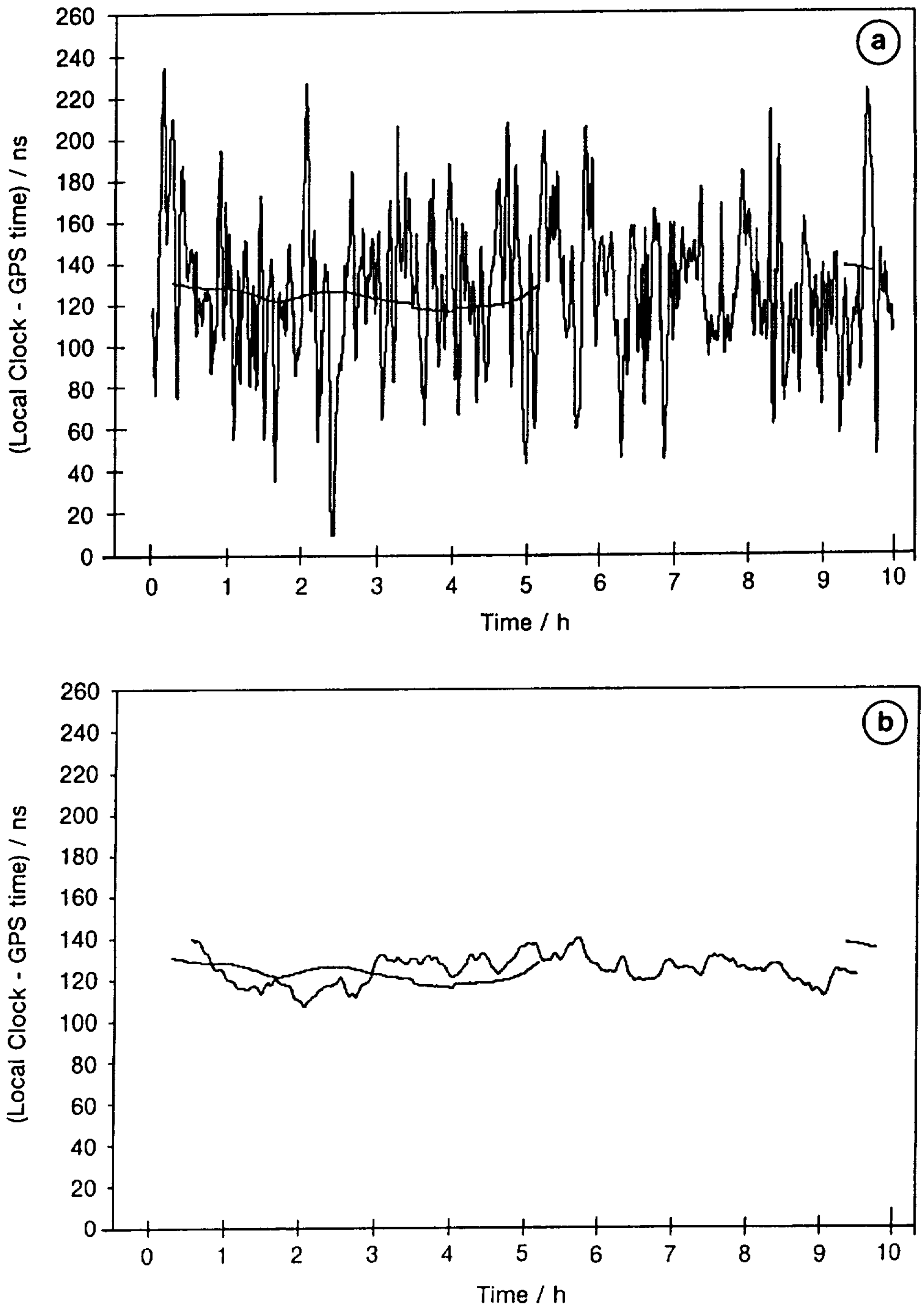

***Figure 5.* GPS data taken at the BIPM for 10 hours on 15 June 1993, from the AOA TTR-4P unit operating with a 15 s sample interval.**

5.a. Real-time average of data from all observable Block II satellites and smoothed Block I data.

5.b. Smoothed Block II data, through moving average over 3840s, and smoothed Block I data.

QUESTIONS AND ANSWERS

Phil Talley, Aerospace Corporation: If I understood correctly, your plot of the Allan deviation versus time in fractional days, it would appear to me that that is exactly what the clocks on orbit are doing, because that is the transition from the quartz operation with the control loop controlling from the atomic standard. The time interval, as I think I have interpreted it, is exactly what we see when we test the clocks on the ground.

David Allan, Allan's Time: You are very observant, Phil. Those curves are coincidentally about at the same point, around 250 seconds. The levels, however, are very significantly different. If you look at the values, the SA value is two orders of magnitude above where the clock noise is. So it is not clock noise, it is actually SA noise, even though it looks similar. So it is coincidental.

Dr. Winkler, USNO: I find it interesting to see that there is a change in doctrine from a strict common–view measurement to a robust method, which I have been advocating for years in my robust estimation seminars, where the principle is that you must collect as much data as you can from as many different satellites as you can get. Because if you do that, you obtain two things; you first obtain some kind of robustness; you are not sensitive to a single satellite and its problems. And secondly, you obtain an internal measure of precision on the deviations which you observed. And I am in complete agreement with that. I think that is the most promising one.

There is another side to that and that is that there are quite a few receivers which are coming out, some of them very inexpensive now. For instance, we have had several on test from Magnavox and Motorola, six–channel receivers. And if you just blindly use these receivers, let them select whatever satellites they see; then, in fact, the variance in time is somewhere slightly less than 40 ns if you have a stable reference. And that is not as good as you would expect from your estimates. So there some systematic effects still. But I think the principle which you have mentioned is absolutely correct. You have to make measurements of as many as you can get.

Claudine Thomas: I will say that the experiment that I reported here, we have cancelled all data corresponding to low elevation.

Dr. Winkler: You also have to remember that we cannot count on a continuing capability of the Block–1 satellites.

J. Levine, NIST: What I was going to do is commend you for what I think will be a very significant development in UTC. I think it will help all of us. One of the concerns and one of the points that will have to be watched very carefully is the transient response of your eight satellite average when something fails. Because, the system will crash in some funny way and will come back in some funny way. And you are then averaging this funny transient response of all these eight satellites together. And we will have to know what that step response is, "we" being the downstream users. And that is something that will need to be experimented with, I guess.

Claudine Thomas: Yes, that is why I never mentioned doing that as an operational service which will be provided by the BIPM. For now it is only an experiment. The results can be given informally to anyone who wants them, but it is impossible for now to stress about the installation of an operational service which is sure to deliver what is needed.

Dr. Winkler: There is one other point. And that is that I am kind of amazed that there are users who need that information in real time. Because, one of the things which I have observed is that the Observatory has provided that information for the last two years. And there are not more than three or four users who regularly call in. So I am just wondering who is going to need that.

6147 N94-30652

DEVELOPMENT OF AN ACCURATE TRANSMISSION LINE FAULT LOCATOR USING THE GLOBAL POSITIONING SYSTEM SATELLITES

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Abstract

A highly accurate transmission line fault locator based on the traveling-wave principle has been developed and successfully operated within B.C. Hydro. A transmission line fault produces a fast-risetime traveling wave at the fault point which propagates along the transmission line. This fault locator system consists of traveling wave detectors located at key substations which detect and time tag the leading edge of the fault-generated traveling wave as it passes through. A master station gathers the time-tagged information from the remote detectors and determines the location of the fault. Precise time is a key element to the success of this system. This fault locator system derives its timing from the Global Positioning System (GPS) satellites. System tests confirmed the accuracy of locating faults to within the design objective of ± 300 meters.

INTRODUCTION

Operating an electric system that includes long transmission lines passing through rugged terrain poses difficult challenges for operations personnel. The B.C. Hydro system is characterized by major hydroelectric generation sites that are separated by large distances from load centers. Confirming the location of transmission line faults typically involve a combination of helicopter and ground patrols both of which may be difficult or impossible to execute due to adverse weather conditions – which is usually the time when transmission line faults occur. A method for quickly and accurately locating transmission line faults has been a much desired tool for control center operators who must act quickly to determine locations of system disturbances in order to direct the work of search and repair crews.

Use of commercially available fault location tools such as fault–locating digital relays and digital fault recorders on the B.C. Hydro 500 kV system have produced limited successful results. Factors such as high ground resistance, series capacitor banks, etc. reduce the effectiveness of these fault location systems. To address the problem of accurate fault location under these conditions, a traveling wave based fault location system has been developed and successfully operated on the B.C. Hydro 500 kV system.

FAULT LOCATION METHODS

Time Domain Reflectometers

Early fault locators were based on pulse radar techniques. These devices known as time domain reflectometers (TDRs), are commonly used for locating faults in buried cables where visual inspection is not possible without excavation. This technique makes use of a "probe" pulse that is launched into one end of the cable and relies on the pulse being reflected back to the source due to an electrical discontinuity at the faulted location. The fault location is determined by measuring the time delay from launching the pulse and receiving its reflection. There is, however, little interest in applying this method to overhead transmission lines. Several factors make this technique impracticable:

Unlike cables which are physically and electrically uniform throughout its length, overhead lines have inherent discontinuities such as tower structures, conductor variations, etc. that cause unwanted secondary reflections which interfere with detecting the reflected "probe" pulse.

The faulted line must be taken out of service to conduct testing and special precautions must be taken to ensure mutual inductance effects from healthy adjacent lines and nearby energized equipment does not pose a safety hazard.

The fault must be permanent (e.g.. solid short or open conductors) to ensure a strong reflected signal. Difficult to find faults such as ice build–up, galloping conductors, etc., conveniently disappear by the time the fault location equipment can be mobilized and put into service.

B.C. Hydro has used time domain reflectors on transmission lines for many years before largely abandoning this technique due to its complexity and small gains.

Impedance–Based Fault Location Methods

The largest area of development on fault location methods are those based on the measurement of system frequency (60Hz) signals. These methods make use of information from the transmission lines that are already available for protective relaying purposes (i.e. line voltage and current). In the most general sense, these techniques analyze the impedance characteristics of the line to determine the fault location.

Early fault locators were based on the reactance method where fault location is determined by measuring the ratio of the reactance of the faulted line at the source end to the unfaulted line reactance, the assumption being that the fault impedance is purely resistive. More complex algorithms make use of pre– and post–fault conditions to reduce the effects of sources (except for the virtual source at the fault) and loads. The development of digital fault recorders and digital protective relays has made it possible to implement better and computationally more complex algorithms. Many of these methods involve simultaneous solutions of non–linear equations which can easily be implemented using iterative techniques.

A number of protective relaying manufacturers have incorporated fault location functions as part of their protective relays. B.C. Hydro has made extensive use of these devices on lower voltage lines (230 kV and below). Experience with these fault locating relays have shown some very good results, but occasionally some poor results.

On the 500 kV system where accurate fault location is of much greater importance, the use of series compensation precludes the use of these relays for fault location. In long transmission lines, reactive compensation in the form of a series capacitor is typically inserted at the midpoint of the line to compensate for the line inductance and increase the load carrying capacity of the line.

A fault on a series compensated line produces transient frequencies below the power system frequency that are the result of the natural resonance of the series capacitance and system inductance. The frequency of these oscillations depends largely on the source impedance and can lie close to the power system frequency. These transient frequencies can produce spurious outputs, causing inaccurate fault location.

Traveling Wave Fault Location

Traveling wave fault locators make use of the transient signals generated by the fault. When a line fault occurs, such as an insulator flashover or fallen conductor, the abrupt change in voltage at the point of the fault generates a high frequency electromagnetic impulse called the traveling wave which propagates along the line in both directions away from the fault point at speeds close to that of light. The fault location is determined by accurately time–tagging the arrival of the traveling wave at each end of the line and comparing the time difference to the total propagation time of the line. Refer to Figure 1.0

Unlike impedance–based fault location systems, the traveling wave fault locator is unaffected by load conditions, high ground resistance and most notably, series capacitor banks. This fault locating technique relies on precisely synchronized clocks at the line terminals which can accurately time–tag the arrival of the traveling wave. The performance goal selected by B.C. Hydro is a fault location accuracy of ± one tower span or approximately 300 meters. The propagation velocity of the traveling wave is roughly 300 meters per microsecond which in turn requires the clocks to be synchronized with respect to each other by less than one microsecond.

Precisely synchronized clocks is the key element in the implementation of this fault location technique. The required level of clock accuracy has only recently been available at reasonable cost with the introduction of the Global Positioning System.

IMPLEMENTATION AND TESTING

Evaluation of the fault locator involved the installation of GPS timing receivers at four 500 kV substations, see Figure 2.0. A especially developed Fault Transient Interface Unit (FTIU) connects to the transmission lines and discriminates for a valid traveling wave. The FTIU produces a TTL–level trigger pulse that is coincident with the leading edge of the traveling wave.

A time–tagging input function was provided under special request to the GPS receiver manufacturer. This input accepts the TTL level logic pulse from the FTIU and time tags the arrival of the fault–generated traveling wave. The time tag function is accurate to within 300 nanoseconds of UTC – well within the overall performance requirement of timing to within

1 microsecond.

The fault locator was tested by placing B–phase to ground faults on line 5L82 using a high speed ground switch. Twelve faults were applied to the line and the fault locator successfully located all twelve faults to well within the design goal of plus or minus one tower span (300 meters) accuracy. The results are summarized in Table 1.0.

ADDITIONAL SOURCES OF VERIFICATION

The fault locator responds to any traveling wave impulse with sufficient energy in the 35 kHz to 350 kHz range. These impulses are not limited to those generated by actual transmission line faults. Routine switching of substation equipment also produces similar fast risetime impulses which are also detected and time tagged by the fault locator. These station–generated traveling waves provide an opportunity to test (and calibrate) the fault locator by comparing the measured results against the total propagation time of the line – a known quantity. Traveling waves generated by routine operation of 500 kV equipment at NIC, KLY and ING substations over a period of one year indicated repeatability of fault location measurements to within the one microsecond or 300 meter performance accuracy goal. See table 2.0.

EFFECTS OF SERIES CAPACITOR BANKS

A prime consideration leading to the development a traveling wave fault locator was the use of series capacitor banks has made it very difficult if not impossible for the system frequency (60Hz) or impedance–based fault location techniques to operate properly i.e. fault location using digital relays and digital fault recorders. The high frequency fault-generated traveling waves on the other hand, are not affected by series capacitor banks. There are series capacitor banks installed on lines 5L81, 5L82 and 5L42. Testing using traveling waves generated by reactor switching at NIC and KLY showed the capacitor banks did not have any noticeable effects on the propagation of the traveling waves.

DISTORTION AND ATTENUATION OF TRAVELING WAVES

The accuracy of fault location depends on the ability to accurately time tagging the arrival of the traveling wave at each line terminal. The traveling wave once generated, is subject to attenuation and distortion as it propagates along the transmission line. Attenuation occurs due to resistive and radiated losses. Distortion of the waveform occurs due to a variety of factors including bandwidth limitations of the transmission line, dispersion from different propagation constants of phase–to–phase and phase–to–ground components, etc. These effects combine to degrade the quality of the "leading edge" of he traveling wave at large distances from the fault inception point. The accuracy of time tagging the traveling wave diminishes for the substations far away from the fault. Experience with the evaluation system has shown that the traveling wave is relatively "undistorted" for distances less than 350 km. To effectively reduce the effects of attenuation and distortion requires traveling wave detector installations spaced at regular intervals. For B.C. Hydro, this translates to installing fault location equipment at fourteen out of nineteen 500 kV substations.

EFFECTS OF SELECTIVE AVAILABILITY

Selective Availability (SA) is the intentional degradation in accuracy of the GPS signal which is applied at the discretion of the U.S. Department of Defense. The result is a pseudo-random wander of the navigation and timing data. To overcome this effect requires the use of a special military–authorized GPS receiver. Selective availability when "switched on" reduces the accuracy of civilian GPS timing receivers from ± 100 nanoseconds to ± 300 nanoseconds, which is still within the allowable tolerance for the accuracy of the fault locator. Selective availability is not considered to be a problem for the purposes of fault location.

CONCLUSION

Testing of the fault location system has produced results meeting the design goal of plus or minus 300 meter accuracy. Based on successful experience with the evaluation system, B.C. Hydro has allocated funding for implementing this fault locator throughout the 500 kV system. This project, which is currently underway, involves the installation of GPS-based timing units and traveling wave detectors at fourteen 500 kV substations and a master polling station and console at the System Control Center.

ACKNOWLEDGEMENTS

The author wishes to thank the Bonneville Power Administration for supplying the design of the traveling wave detector (the Fault Transient Interface Unit) and whose pioneering work on traveling wave fault location provided inspiration for this project.

Table 1.0

Fault Locator System Test

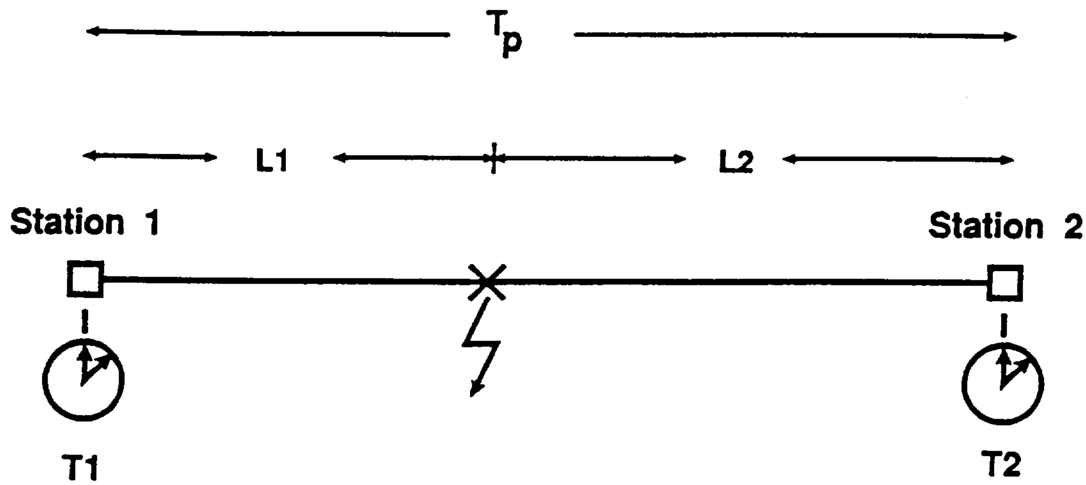
Calculated cumulative arc length from NIC substation to the fault = 131,694.5 meters.

Test	Fault Locator Output (meters)	Difference from Est. Value (meters)
1	131,725	30
2	131,819	124
3	131,721	26
4	131,803	108
5	131,800	105
6	131,834	139
7	131,730	35
8	131,697	2
9	131,829	134
10	131,806	111
11	131,810	115
12	131,814	119

Table 2.0

Fault Locator Response to Travelling Waves Generated by Routine Switching of Substation Equipment

Line	Estimated T_p (μsec)	Measured T_p (μsec)
5L87	501	499
5L44	66	67
5L82	850	851
5L81	900	896
5L45/42	901	901



The distance to the fault from the line terminals is given by:

$$L_2 = \frac{T_p + \Delta T}{2} \times V_p \quad \text{and} \quad L_1 = \frac{T_p - \Delta T}{2} \times V_p$$

Where V_p is the velocity of propagation for the line and $\Delta T = T_2 - T_1$.

Figure 1.0 Principle of Operation

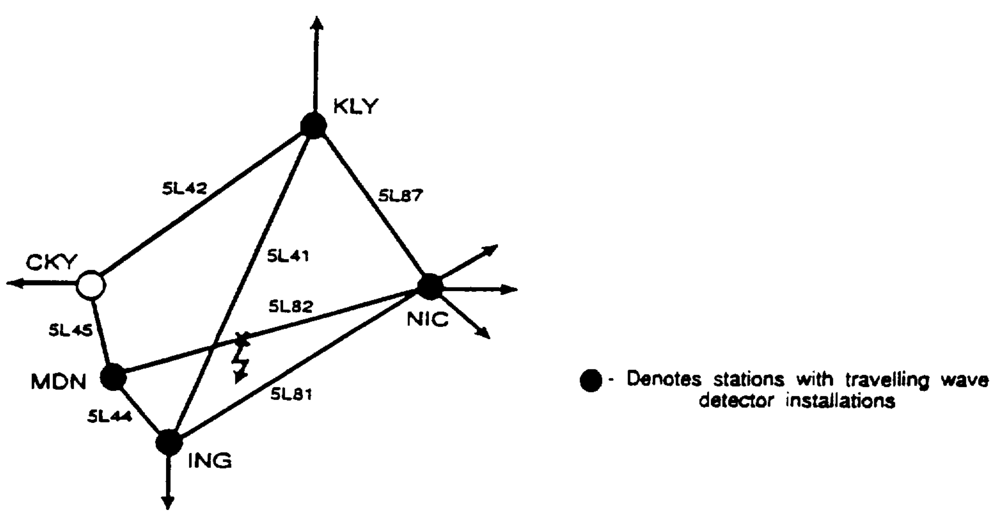


Figure 2.0 Fault Locator Installations and Testing

QUESTIONS AND ANSWERS

Thomas Becker, Air System Technology, Inc.: Have you found any naturally occurring phenomena that produce signals on the line that would appear to be a failure?

Harry Lee: Lightening is one thing that we are really interested in locating. That is something that we have never been able to do in the past. Other than that, there hasn't been much else naturally occurring, if you may mean the effects of solar radiation.

Thomas Becker: No, lightening is probably a great example.

Harry Lee: Lightening is what we do want to locate. It is not too much of a problem for us, these other extraneous sources of travelling waves, because we do have our regular instrumentation that tell us when the line is tripped out. And using that, coupled with this fault locator system, it can effectively field throughout.

Thomas Becker: Is the line switching done automatically based on these fault locators? Or is it then suggested to an operator to actually unload that line and transfer something?

Harry Lee: The two systems operate independently. As I said, we do have our protection systems which monitor faulted conditions, basically short circuits, overloads, high current, low voltage, that type of detection scheme. And that automatically trips the line out of operating circuit breakers. At that point, the operator will then look through the fault locator system to try to pinpoint where the fault occurred. So the two operate independently. The fault locator doesn't initiate corrective tripping.

Thomas Becker: It would seem fairly easy for a cascade of events to occur if you were not prepared for that sort of thing.

Harry Lee: That's right. And those things do happen unfortunately.

6148 N94-30653

Relativistic theory for picosecond time transfer in the vicinity of the Earth

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Abstract. *The problem of light propagation is treated in a geocentric reference system with the goal of ensuring picosecond accuracy for time transfer techniques using electromagnetic signals in the vicinity of the Earth. We give an explicit formula for a one way time transfer, to be applied when the spatial coordinates of the time transfer stations are known in a geocentric reference system rotating with the Earth. This expression is extended, at the same accuracy level of one picosecond, to the special cases of two way and LASSO time transfers via geostationary satellites.*

1. Introduction

It is well known that in relativity the notion of simultaneity is not defined a priori so that a conventional choice of a definition has to be made. This choice will then lead to a corresponding definition of clock synchronization as synchronised clocks must simultaneously produce the same time markers. A widely used definition is that of coordinate simultaneity and corresponding coordinate synchronization, as given, for example, by Klioner (1992):

"Two events fixed in some reference system by the values of their coordinates (t_1,x_1,y_1,z_1) and (t_2,x_2,y_2,z_2) are considered to be simultaneous with respect to this reference system, if the values of time coordinate corresponding to them are equal: $t_1 = t_2$. In the following this definition of simultaneity (and corresponding definition of synchronization) we shall call coordinate simultaneity (and coordinate synchronization)."

Clearly, the synchronization of two clocks by this definition is entirely dependent on the chosen reference system and is thus relative in nature, rather than absolute.

In practice, coordinate synchronization between two distant clocks can be achieved by the exchange of an electromagnetic signal. From the knowledge of the positions of the clocks at emission and reception of the signal in the reference system of synchronization and the laws of light propagation in the same reference system, the coordinate time elapsed during transmission T_t can be calculated.

For the construction and dissemination of international reference time scales, coordinate synchronization in a geocentric, non-rotating (oriented with respect to fixed celestial objects) reference system is required. We choose the geocentric non-rotating reference system as defined by the resolution A4 of the IAU (1992), with asymptotically flat spatial coordinates, but with Terrestial Time TT being the coordinate time. TT is an ideal form of the International Atomic Time TAI, which is the basis of the measurement of time on the Earth. By its definition, TT differs from the coordinate time of the IAU by a constant rate.

The clocks that are to be synchronized are usually fixed on the Earth, and have their spatial positions given in a rotating reference frame. Using the metric equation of the non-rotating system and taking into account the displacement of the clocks (in the non-rotating system) resulting from the relative movement of the two systems during signal propagation, the transmission coordinate time T_t can be calculated.

Recently, the precision of clock synchronization between remote clocks on the surface of the earth has reached the sub-nanosecond level (Hetzel & Soring 1993; Veillet et al. 1992; Veillet & Fridelance 1993) with further improvements expected in the near future. For these applications it seems sensible to develop the theory to the picosecond accuracy level. Recent theoretical studies in this field claim an accuracy of 0.1 nanosecond (Klioner 1992), and in some cases (CCIR 1990, CCDS 1980) the provided formulae are expressed in terms of path-integrals making them more difficult to use than explicit expressions. In this article we provide explicit equations for synchronization in a geocentric non-rotating system of two clocks that have their positions given in the rotating system. All terms that in the vicinity of the Earth (within a geocentric sphere of 200000 km radius) are greater than one picosecond are included. Outside this sphere terms due to the potential of the Moon may amount to more than 1 ps and need to be accounted for separately. We also present formulae (to the same accuracy) for the special cases of two way time transfer (section 3) and LASSO (LAser Synchronization from Stationary Orbit, section 4) time transfers via a geostationary satellite. Here a possible small residual velocity of the satellite (< 1 m/s) results in further terms contributing some tens of picoseconds for two way- and LASSO time transfers.

We will assume that all clocks are rate corrected for the gravitational potential at their positions, and their velocities in the reference system of synchronization, and hence run at the rate of TT.

2. Formula for a one way transfer

We consider a rotating frame $(t,\bar{x}_r)$ which rotates at a constant angular velocity ω with respect to a fixed star oriented one $(t,\bar{x})$ with two clocks a and b, at $\bar{x}_{ra}$ and $\bar{x}_{rb}$ at time t_0 when the two frames coincide. The two clocks are to be coordinate synchronized by the transmission of an electromagnetic signal from a (emission at t_0) to b (reception at t_1).

To this end the coordinate time interval $T_t = t_1 - t_0$ elapsed between emission and reception of the signal needs to be calculated.

The metric of a geocentric non-rotating system in the first post-Newtonian approximation with TT as coordinate time and asymptotically flat spatial coordinates (for $r \rightarrow \infty$ the components of the spatial metric $g_{ij} = \delta_{ij}$) is:

$$ds^2 = -(1 - 2U/c^2)(1 + L_g)^2c^2dt^2 \\ +(1 + 2U/c^2)(dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\phi^2) \qquad (1)$$

where:
ds is the relativistic line element.
t is the coordinate time TT.
r, θ (colatitude), ϕ (longitude) are spherical coordinates in a non-rotating geocentric coordinate system.
U is the gravitational potential of the Earth (positive sign).
$L_g = 6.969291 \times 10^{-10}$.

The scaling factor $(1 + L_g)$ results from the choice of TT as coordinate time. L_g is equal to U_g/c^2, where U_g is the value of the gravitational potential on the geoid including the centrifugal potential due to the rotation of the Earth.

Introduction of post-post-Newtonian terms and terms due to the tidal potentials of the moon, sun and planets into the metric leads to a correction to the propagation time of a light signal in the vicinity of the Earth of less than one picosecond. Hence (1) is sufficient for our purposes.

Transforming to the rotating frame by

$$d\phi = \omega dt + d\phi_r \qquad (2)$$

then setting $ds^2 = 0$ for a light signal and solving the resulting quadratic for dt provides an expression for the transmission coordinate time T_t:

$$T_t = \int \{du/c - U_g du/c^3 + \omega r^2 \sin^2\theta d\phi_r/c^2 + [1+r^2\sin^2\theta(d\phi_r/du)^2]\omega^2 r^2 \sin^2\theta du/2c^3 + 2U du/c^3\} + O(c^{-4}), \quad (3)$$

where du is the increment of coordinate length along the transmission path and the integral is to be taken from a to b along the transmission path in the rotating frame.

Evaluating the above expression (for a detailed derivation see Petit & Wolf (1993)) gives an explicit formula for the transmission time:

$$T_t = R_0/c + \delta$$

$$= R_0/c - U_g R_0/c^3 + \bar{R}_0.\bar{v}_b/c^2 + (v_b^2 + \bar{R}_0.\bar{a}_b + (\bar{R}_0.\bar{v}_b)^2/R_0^2)R_0/2c^3 + 2GM_E \ln\{[x_{rb} + n.\bar{x}_{rb}]/[x_{ra} + n.\bar{x}_{ra}]\}/c^3 \quad (4)$$

where:

δ is the total relativistic correction.
$\bar{R}_0 = \bar{x}_{rb} - \bar{x}_{ra}$
$\bar{v}_b = \bar{\omega} \times \bar{x}_{rb} + \bar{v}_{rb}$
$\bar{a}_b = \bar{\omega} \times (\bar{\omega} \times \bar{x}_{rb}) + \bar{\omega} \times \bar{v}_{rb} + \bar{a}_{rb}$
$n = \bar{R}_0/R_0$ is the unit vector along the transmission path
$\bar{v}_{rb}$ is the satellite velocity in the rotating frame
$\bar{a}_{rb}$ is the satellite acceleration in the rotating frame
and the two frames coincide at $t = t_0$.

The above expression provides the coordinate transmission time for a light signal travelling from station a to station b in the vicinity of the Earth (within a geocentric sphere of 200000 km radius) with the coordinates of the two stations given in an Earth fixed rotating frame. All terms that are greater than one picosecond are included. Note however, that atmospheric delays which can amount to several tens of nanoseconds are not considered and need to be taken into account separately.

3. Two way time transfer

We consider a two way time transfer between two stations c and d, fixed on the surface of the Earth, via a geostationary satellite s (as shown in Fig. 1).

Two signals are transmitted in opposite directions leaving c and d at t_0 and $t_0+\Delta t$ respectively. They reach the satellite at t_1 and t_3, where they are immediately retransmitted, and arrive at the opposite stations at t_2 and t_4. From the clocks two coordinate time intervals are obtained (assuming that the clocks are rate corrected as mentioned in section 1):

$$t_c = t_4 - t_0$$
$$t_d = t_2 - t_0 - \Delta t \qquad (5)$$

For synchronization the interval Δt is required. We shall assume that the clocks have been synchronized previously to within 0.1 s, a typical station to satellite transmission time (which can be achieved without difficulty in practice), and that the satellite has a residual velocity v_r smaller than 1 m/s and a residual acceleration in the rotating frame of less than 10^{-5} m/s^2. These values have been chosen as typical after consultation of the EUTELSAT satellite control centre.

The defining equations for the transmission times are:

$$T_1 = t_1 - t_0$$
$$T_2 = t_2 - t_1$$
$$T_3 = t_3 - t_0 - \Delta t$$
$$T_4 = t_4 - t_3 \qquad (6)$$

and solving for Δt yields:

$$\Delta t = (t_c - t_d)/2 + \delta$$

$$\delta = (T_1 + T_2 - T_3 - T_4)/2 \qquad (7)$$

The relativistic correction δ arises from the motion of the stations and the satellite in the frame of synchronization and the gravitational delays for the individual transmissions T_1 to T_4.

Using equation (4) to calculate T_1 to T_4 and substituting the results into (7) gives an expression for the relativistic correction (Petit & Wolf (1993)):

$$\delta = \{\bar{R}_{cd}.(\bar{\omega} \times \bar{x}_{rs}) + [(R_{cs} - R_{ds} - c\Delta t)(R_{ds}\bar{R}_{cs} + R_{cs}\bar{R}_{ds}).\bar{v}_r] / (2R_{cs}R_{ds})\}/c^2 + O((v/c)(v_r/c)\Delta t) \qquad (8)$$

where:

$$\bar{R}_{cs} = \bar{x}_{rs} - \bar{x}_{rc}$$
$$\bar{R}_{ds} = \bar{x}_{rs} - \bar{x}_{rd}$$
$$\bar{R}_{cd} = \bar{x}_{rd} - \bar{x}_{rc}$$

The first term is equivalent to $2\omega A_E/c^2$ with A_E being the equatorial projection of the area of the quadrangle whose vertices are the centre of the Earth and the positions of the satellite and the stations in the rotating frame.

The second term of (8) varies with v_r and Δt, and can amount to several hundred picoseconds. If $\Delta t \sim 0$, it can amount to several tens of picoseconds, depending on the residual velocity which is in general not well known. However, one can compensate for it by intentionally introducing a desynchronisation in order to drive this term towards zero, which is the case when the two signals arrive at S at about the same time (ie. $t_1 \approx t_3$).

4. LASSO

In this method laser pulses emitted from the stations c and d at t_0 and $t_0+\Delta t$ respectively are reflected by the geostationary satellite and return to the stations (as shown in fig. 2).

The satellite is equipped with a clock which measures the time interval between arrival of the signals. Hence three coordinate time intervals (after rate correction of the clocks) are obtained:

$$\begin{aligned} t_c &= t_2 - t_0 \\ t_d &= t_4 - t_0 - \Delta t \\ t_s &= t_3 - t_1 \end{aligned} \qquad (9)$$

For synchronization Δt is required. Similarly to the two way case, the defining equations (6) for T_1 to T_4 yield:

$$\Delta t = (t_c - t_d)/2 + t_s + \delta$$

$$\delta = (T_1 - T_2 - T_3 + T_4)/2 \qquad (10)$$

Using (4) to calculate the individual transmission times T_1 to T_4 gives for the relativistic correction (Petit & Wolf (1993)):

$$\begin{aligned} \delta = \; & [\bar{R}_{cd}.(\bar{\omega} \times \bar{x}_{rs}) + \Delta t(\bar{\omega} \times \bar{v}_r).\bar{x}_{rd}]/c^2 \\ & + O((v/c)(vr/c)(R_0/c)) \end{aligned} \qquad (11)$$

As in (8) the first term is equivalent to $2\omega A_E/c^2$.

The second term varies with $\bar{v}_r$ and Δt. This term is smaller than 10^{-2} ps for $\bar{v}_r \sim 1$ m/s and $\Delta t \sim 0.1$ s, which is the case for a two way transfer and hence it does not appear in (8). However, for LASSO Δt can amount to several minutes in practice (Veillet et al. 1992; Veillet & Fridelance 1993) and therefore the second term in (11) can contribute up to 10 ps.

Note also that while the second term of (8) can be minimised by an appropriate choice of Δt, this is not the case in (11).

5. Constraints for practical applications

For picosecond accuracy, the relativistic correction δ contains terms in c^{-2} and in c^{-3} in the case of one-way time transfers (4), and terms in c^{-2} only in the case of two-way (8) and LASSO (11) transfers.

The term in c^{-2} can amount to a few hundred nanoseconds, depending on the relative positions of the transmission and reception points. For example, between the Earth and a geostationary orbit, the maximum value is about 200 ns for the one way- and 400 ns for the two way case. In order to compute this term with picosecond accuracy, it is sufficient for all quantities in the term in c^{-2} to be known with a relative uncertainty of one or two parts in 10^6. This requires coordinates known to within 6-12 m for the Earth stations, including uncertainties in the realization of the reference frame which are below ~ 1 m for e.g. WGS84 and ITRF. This is generally the case for time laboratories. The satellite position should be known to within some tens of metres, depending on its orbit, and this is generally not the case a priori for a satellite without geodesic objectives. In addition the velocity of the satellite should be known to the same relative uncertainty of one or two parts in 10^6, which is also not the case in general. Typically the position of a geostationary satellite is known to an accuracy of ~ 1 km which results in an error in the computation of the c^{-2} term of ~ 10 ps. Similar arguments can be made to set constraints in the case of higher orbits or satellite to satellite time transfers.

In the real case of a non-perfect geostationary orbit, the constraint on the knowledge of the velocity of the satellite is transferred to the residual velocity v_r. For the one way and two way techniques, this constraint is about 1 cm/s for picosecond accuracy but in the two way technique it can be completely relaxed by an intentional desynchronisation of the emission of the signals at the two stations, as mentioned in section 3. For LASSO, the constraint on v_r is about 10 cm/s if one wishes to use laser pulses from the two stations separated by Δt of several minutes. The constraint on v_r can be relaxed by severing that on Δt.

When one of the stations is on the Earth, propagation through the atmosphere is the major problem for one way time transfer. It leads to delays that can reach several tens of nanoseconds and can certainly not be calibrated to picosecond accuracy. This problem is not considered in this study. However the effects cancel to the picosecond level in the two way (provided the up and down frequencies are close enough) and LASSO techniques.

6. Conclusion

We have derived the relativistic correction for a one way time transfer between two stations that have their position given in a geocentric reference frame rotating with the Earth (equation (4)) including all terms in c^{-3} and larger. For time transfer with a geostationary satellite the terms in c^{-3} can amount to around 10 ps for the Sagnac correction and 80 ps for the gravitational delay. At present, one way time transfers are not accurate enough to necessitate the consideration of these terms. However, with accuracy expected to increase in the near future, and in view of possible satellite to satellite transfers (which would eliminate uncertainties due to atmospheric delays) these terms might well become significant.

We also provided expressions for the relativistic corrections that need to be applied to two way and LASSO techniques. We have shown that the main errors in computing these corrections are due to the uncertainties in the position and the residual velocity of the satellite. The uncertainty in the position leads to an error in the computation of $2\omega A_E/c^2$ of the order of 10 ps for both techniques. The uncertainty in the residual velocity affects the two techniques differently. For LASSO the second term in (11) is typically of the order of 10 ps, hence reducing the overall uncertainty for LASSO requires better knowledge of the satellite position as well as consideration of the additional term. For two way time transfers, on the other hand, the second term in (8) can reach 80 ps (for $\Delta t = 0$). Hence reducing this term by an appropriate choice of Δt will improve the overall accuracy of the two way time transfer even in the case where $\bar{v}_r$ is unknown.

In both techniques, the precision of experiments repeated over periods of several weeks could be affected by the variation of the residual velocity of the satellite, if the corresponding terms are not accounted for.

This shows that the time community is rapidly approaching levels of precision and accuracy that will necessitate a more exact development of the theory. We consider the present paper a step in that direction.

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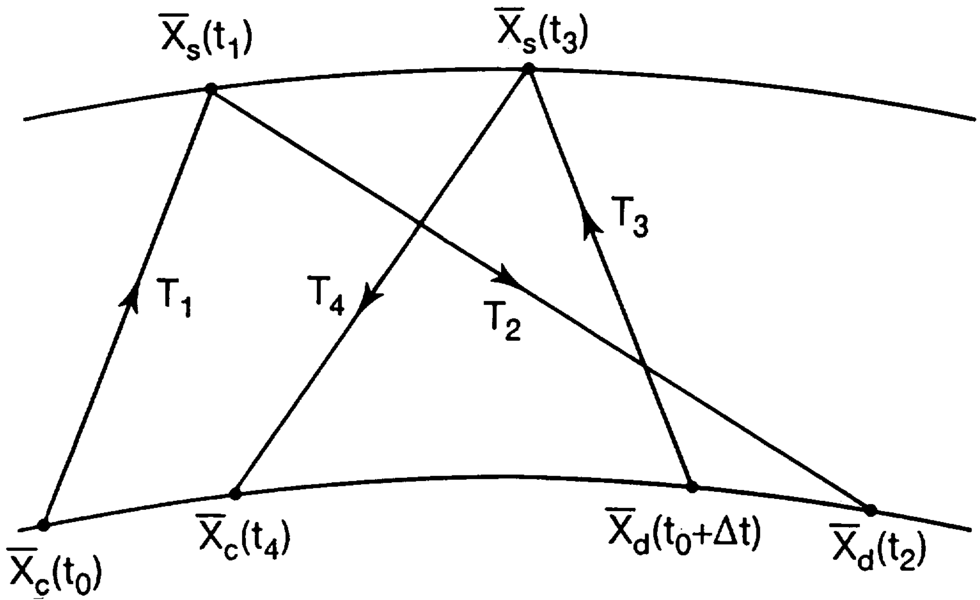

Fig. 1. Two way time transfer in the non-rotating frame. Two signals are transmitted in opposite directions leaving c and d at t_0 and $t_0+\Delta t$ respectively. They reach the satellite at t_1 and t_3, where they are immediately retransmitted, and arrive at the opposite stations at t_2 and t_4.

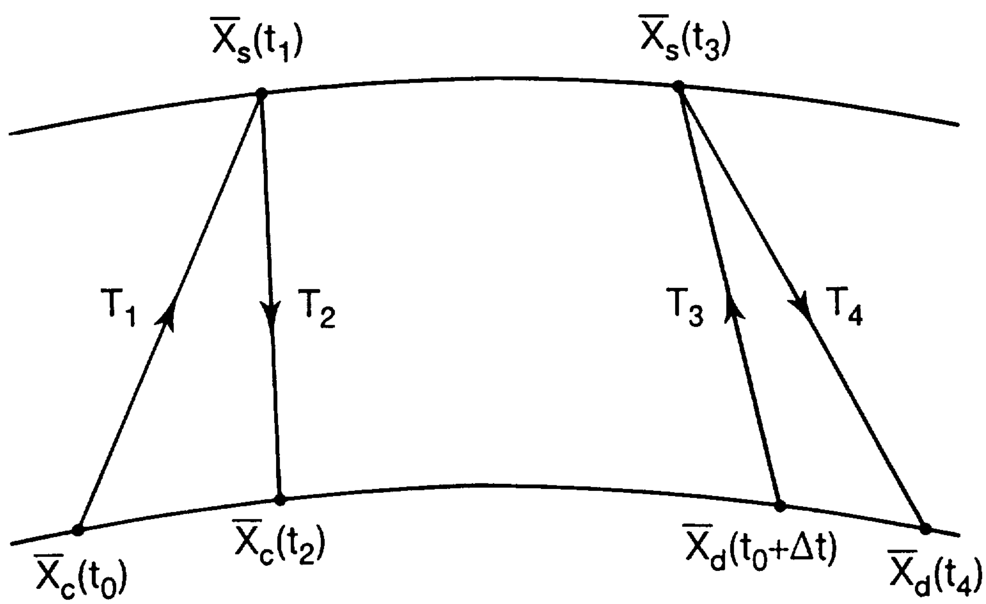

Fig. 2. LASSO time transfer in the non-rotating frame. Laser pulses emitted from the stations c and d at t_0 and $t_0+\Delta t$ respectively are reflected by the geostationary satellite and return to the stations. A clock on board the satellite measures the time interval between arrival of the pulses.

QUESTIONS AND ANSWERS

Dieter Kirchner, TUG: One comment to the microsecond issue, from the practical point of view it is not easy to hold this 10 microseconds. Because a well kept geostationary satellite has a range rate of many tens of microseconds. So you would have to change your offset for each measurement. And this is not very convenient to do.

Peter Wolf: What was that first bit? What varies several microseconds per day?

Dieter Kirchner: The range of a geostationary satellite with respect to a station. If you measure the range to a geostationary satellite, this range changes.

Peter Wolf: That is quite right. That is the problem that you don't know its position exactly all the time. It kind of moves, which simply changes the distance.

Dieter Kirchner: If you measure the range to the satellite, you have a figure which changes and may be 100 to 150 microseconds.

Peter Wolf: It is a trade–off. You have to do it one way or the other if you want to be more precise. Either you manage to change your offset for every measurement so you can get rid of the additional term, or you get some knowledge on the velocity of the satellite; and then you can calculate the additional things. However the velocity of the satellite – as far as I know, what they do with geostationary satellites, they have them sort of wandering about a kind of observation window; as soon as it approaches the edge, they give it a boost to go back where it belongs. So it sort of varies quite a bit. I'm not sure. If you know the velocity, you are fine. If you don't, you have to get around it.

David Allan, Allan's Time: Regarding GPS time with the laser retro–reflectors, then we can also calibrate that path which should help in the uncertainty, at the sub–ns level I believe.

Peter Wolf: Of course, yes.

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A REAL-TIME PREDICTION OF UTC

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Abstract

The reference time scale for all scientific and technologic applications on the Earth, the Universal Coordinated Time UTC, must be as stable, reliable and accurate as possible. With this in view the BIPM and before it the BIH, have always calculated and then disseminated UTC with a delay of about 80 days. There are three fundamental reasons for doing this.

i) It takes some weeks for data, gathered from some 200 clocks spread world-wide, to be collected and for errors to be eliminated.

ii) Changes in clock rates can only be measured with high precision well after the fact.

iii) The measurement noise originating in time links, in particular using Loran-C, is smoothed out only when averaging over an extended period.

Until mid-1992, the ultimate stability of UTC was reached at averaging times of about 100 days and corresponded to an Allan deviation $\sigma_y(\tau)$ of about $1{,}5\times10^{-14}$ when compared to the best primary clock in the world, the PTB CS2.

For several years now, a predicted UTC has been computed by the USNO (Washington D.C., USA) through an extrapolation of the values [UTC - UTC(USNO)] as published in deferred time by the BIPM. This is made available through the USNO Series 4, through the USNO Automated Data Service, and through GPS signals. Due to the instability of UTC, the poor predictability of the available clocks, and the intentional SA degradation of GPS signals, the real-time access to this extrapolated UTC has represented the true deferred-time UTC only to within several hundreds of nanoseconds.

Recently, there have been dramatic improvements in several domains.

i) New commercial Hewlett-Packard caesium clocks and active auto-tuned hydrogen-masers, both presenting a remarkable frequency predictability, are now available in timing centres.

ii) The widespread use of GPS in common-views, combined with improved performances of contributing clocks, has improved the stability of UTC, namely $\sigma_y(\tau)$

to the order of 8×10^{-15} for averaging times of 40 days, and this could also help to decrease the delay of access to UTC.

iii) The SA is now overcome both for GPS common-views and for real-time access to GPS time. In addition, other time dissemination methods, which are not intentionally degraded, are now very promising.

iv) Modern computer capability and improvements in data communication capability allow quicker and more efficient automatic data transmission.

By taking advantage of these advances, it may soon be possible to obtain a real-time estimate of UTC, provisionally entitled UTCp, from the 1pps output of a commercial clock maintained at the BIPM. In this project the BIPM clock is steered to a software time scale computed by combining present data with extrapolated frequencies, relative to UTC, from a small ensemble of highly predictable clocks maintained in several timing centres. In this way and with definitive computation of UTC performed every month, it seems feasible to maintain a representation of UTC to within ± 60 ns (20 ns standard deviation).

The physical clock which delivers UTCp will be used to measure timing signals, such as those from GPS, GLONASS, INMARSAT and a hydrogen-maser on board the Russian satellite Meteor 3M. Anyone measuring those timing signals could then link local time scales to the estimated UTC, in near real-time, by simple data communication with the BIPM where time corrections between timing signals and UTCp would be continuously available.

We are now studying in detail how all this might be done with a view to carrying out some pilot experiments.

INTRODUCTION

It is anticipated that rapid advances in telecommunications will yield very high rates of data transport. The advent of the Synchronous Digital Hierarchy (SDH) and the Synchronous Optical Network (SONET) requires the best of clock technology and transmission systems. This growing need for synchronism within the telecommunication community was expressed recently by Dr Ghani Abbas, System Design/International Standard Manager of a major telecommunications company in the UK, who said:

> "New technologies, such as SDH, SONET, ..., are being introduced into the telecom transport networks. These technologies require good quality synchronization as well as better short term clock stability. In order to meet the synchronization needs of these new emerging technologies, a convenient tie to UTC to better than 100 ns is required. In the long term this requirement will be a global one."

The fundamental role of UTC is to be the ultimate reference time scale for any application on the Earth. Thus UTC must be as stable, reliable and accurate as possible. This can be accomplished correctly only if UTC is computed in deferred-time [1].

To be reliable, UTC is based on a weighted average of the readings of about 200 clocks spread world-wide in national timing centres. To compute this average the BIPM needs several weeks for data collection and verification. In addition, the need for long-term stability calls for the observation of each participating clock for a time sufficient to detect any frequency change with high precision and to treat it correctly. Since the beginning of the UTC computation, the length of the period of observation has always been two months. This averaging time is sufficient to average the measurement noise to be less than the clock noise. The measurement noise is dependant upon the time link. In particular, it is essential to average data using Loran-C as the time comparison method, for at least two months in order to reach the stability of some atomic clocks.

Until mid-1992, the ultimate stability of UTC was reached for averaging times of about 100 days and corresponded to an Allan deviation $\sigma_y(\tau)$ of about $1{,}5\times10^{-14}$ when compared to the best primary clock in the world, the PTB CS2.

Conformity of the UTC scale unit with the SI second on the rotating geoid is obtained through frequency steering after comparisons with the best primary frequency standards, the PTB CS1 and CS2. Twelve such corrections, each of order $0{,}5\times10^{-14}$, were applied between 1989 and mid-1992 in order to ensure a UTC accuracy of 2×10^{-14} [2].

The deferred-time access to UTC described above does not satisfy the needs of the telecommunication community. The sole possibility is to provide a prediction of UTC in real-time and to make it readily available.

For several years now, a predicted UTC has been computed by the USNO (Washington D.C., USA) through an extrapolation of the values [UTC - UTC(USNO)] as published in deferred time by the BIPM [3]. This is made available through the USNO Series 4, the USNO Automated Data Service, and GPS signals. Due to the instability of UTC and mainly to the intentional SA degradation of GPS signals, real-time access to this extrapolated UTC represents the true deferred-time UTC only to within several hundred of nanoseconds.

The aim of this paper is to show that it may be soon possible to provide a better real-time prediction of UTC thanks to recent significant advances in timing technology. It also explains the actions already taken, and shortly to be taken by the BIPM with the help of several national timing laboratories.

The first section of this paper shows the improvement of UTC stability during 1993. Further steps, in particular a reduction in the time of access, will be taken from the beginning of 1994. In the second section, we show how associating the improved qualities of UTC, which remains a deferred-time scale, with the improvement in available clocks and data transfer systems makes it possible to obtain a good real-time prediction of UTC. It is based on present data and extrapolated frequencies, relative to UTC, from a subset of the clocks contributing to UTC with a very good time predictability and with long-term frequency stability of less than 1×10^{-14}. This prediction of UTC, computed every few days, is used to steer a physical clock, maintained at the BIPM, the output of which can be measured, in real-time, against other time scales. The time scale corresponding to the physical 1pps output from this BIPM clock is named UTCp. We anticipate that UTCp will represent UTC within ±60 ns (20 ns standard deviation). In the third section we explain how UTCp could be made available to users.

1. IMPROVEMENT OF UTC STABILITY

The important changes which have occurred in time metrology since 1992 are the widespread use of GPS in strict common views and the maintenance in timing centres of clocks with high predictability such as auto-tuned active hydrogen-masers and the new caesium clocks from Hewlett-Packard.

1.1. GPS time comparisons

In September 1993, 38 of the 45 timing centres keeping a local representation of UTC, UTC(k), were equipped with GPS timing receivers. Most of them follow the international tracking schedule published by the BIPM and regularly send their GPS observations to the BIPM. This means that nearly all time links involved in the TAI computation are now obtained by one of the most accurate time transfer methods available and undergo a unified treatment. The international GPS network is organized as shown in Figure 1: it features local stars on a continental scale and two long-distances links, OP-NAOT and OP-NIST, chosen because of the excellence of the GPS antenna coordinates of these three laboratories and also because measured ionospheric delays are routinely available at locations close to these sites.

The current computation of GPS time comparisons incorporates a number of refinements. For most links the BIPM uses strict common views (synchronization within 1 s) in order to remove the clock-dither noise brought about by SA [4]. There is then no impediment to wide use of Block II satellites. In addition, a major source of error is reduced thanks to the accurate knowledge of GPS antenna coordinates and their world-wide homogenization in the ITRF [5]. Since October 1993, results obtained for both of the long-distance links have been corrected in deferred time for precise satellite ephemerides.

It appears that the precision of one single measurement [UTC(k_1) - UTC(k_2)] is now about 2 ns for short distances and 8 ns for long distances [6]. An important consequence is the improvement of the short-term stability of the resulting time scale. This can be seen in Figure 2 which compares the Allan deviations $\sigma_y(\tau)$ of the free atomic time scale EAL, relative to the PTB CS2, for two different periods, mid 1986-mid 1988 and 1992-1993 (UTC is deduced from EAL by frequency steering and addition of an integer number of seconds, UTC stability is thus very close to EAL stability except for very long averaging times). For the data covering the period 1992-1993, the measurement noise brought about by time comparison methods is already completely smoothed out for averaging intervals of 10 days, where formerly 40 days were required. The real qualities of the contributing clocks thus appear for short averaging intervals, τ = 10 days, which should allow reduction of the basic interval of computation.

1.2. Hydrogen-masers and new commercial caesium clocks

A dramatic improvement in the stability of the clocks contributing to UTC has recently been observed. In particular, active hydrogen-masers with specific auto-tuning modes and caesium clocks of the new HP 5071A design have been introduced in the computation, nearly all of them with the maximum weight authorized by the BIPM algorithm [1]. Table 1 indicates the evolution of the composition of the UTC ensemble from the end of 1991 until mid-1993.

i) The percentage of clocks at upper limit of weight increased from 21% to 28%. This leads to a more efficient averaging of individual drifts and thus reduces the residual drift of the scale. It also helps to maintain its accuracy and avoid the need to apply steering corrections.

ii) Hydrogen-masers contribute about 12%. Their auto-tuning modes greatly reduce their natural tendency to drift and improve their long-term stability. For instance, the Russian hydrogen-masers kept by the PTB (CHI-75 from Kvarz) present frequency drifts of order 1×10^{-16}/day and the N5 unit (Sigma-Tau) from USNO has no significant drift.

iii) At mid-1993, data from 36 HP 5071A clocks were reported to the BIPM, nearly all of them entering with the maximum weight. This results from their excellent stability as shown in Figure 3 (data kindly transmitted by Dr G.M.R. Winkler from USNO). They present a flicker floor of order 6×10^{-15} for averaging intervals from 20 to 60 days. It is anticipated that about 50 HP 5071A will participate to UTC, each with maximum weight, in January 1994.

The widespread use of GPS and the introduction of clocks with remarkable predictability have already greatly improved the stability of UTC. Using data from the beginning of 1992, the best stability of EAL and UTC, compared to PTB CS2, is characterized by an Allan deviation $\sigma_y(\tau)$ of 8×10^{-15} and is reached for 40-day averaging intervals.

1.3. Further improvement of UTC stability and accuracy

The BIPM has already taken action to improve the stability of UTC still further. From *Circular T 72*, corresponding to January 1994, UTC will be computed on the basis of clock observations taken over 30 days rather than 60 days. This is now possible for the reasons described in sections 1.2. and 1.3.: wide use of GPS and good stability and predictability of contributing clocks.

The new algorithm to be implemented in 1994 for computation of UTC will be described elsewhere [7]. Tests carried out with real timing data for the years 1992 and 1993 show an improved stability of the 'one-month' time scale, when compared to PTB CS2, for all averaging times (see Figure 4). The best stability $\sigma_y(\tau)$ is reached for τ of order 30 days. Its value, of order $6x10^{-15}$, probably reflects the instabilities of both UTC and PTB CS2. The part of instability due to UTC alone can thus be estimated to be of order 4,5 10^{-15}.

Another important consequence is the reduction of the delay in access to UTC. Nowadays, with a basic sample duration of two months and the slow delivery of some data, still reaching the BIPM via conventional post, the definitive results of UTC for month (n-1) and (n) are given on the 28th of month (n+1). With the wide use of efficient electronic mail, it should become feasible for the BIPM to obtain timing data in the form of files with pre-determined format. This should save time, in particular it will allow automatic data sorting and checking. The BIPM is already working hard on this point, encouraging all contributing laboratories to use a uniform data file format and to respect the deadline for making them available. The present objective of the BIPM is to produce the definitive results for UTC for month (n-1) on the 20th of month (n), before the end of 1994.

In future, it is anticipated that UTC may become a simple average of commercial HP 5071A and hydrogen-maser units, with specific frequency prediction modes for each clock type. This should improve both UTC stability and accuracy. Indeed, one HP 5071A unit has a manufacturer stated accuracy of order $1x10^{-12}$, but the actual performance has been shown to be much better: an ensemble of 36 HP 5071A clocks kept at USNO presents an average frequency of $3x10^{-14}$ relative to UTC, with an error bar, on the average frequency, of $2,5x10^{-14}$ [results kindly transmitted to the BIPM by Dr G.M.R. Winkler, USNO]. This suggests that ensembles of a large number of HP 5071A units can provide absolute frequency information that is competitive with the performance of the best current laboratory standards.

2. REALIZATION OF A REAL-TIME PREDICTION OF UTC, UTCp

2.1. Principle of realization

The real-time prediction of UTC, provisionally entitled UTCp, is the time scale corresponding to the 1pps output issued from a physical clock which is maintained at the BIPM. This physical clock is steered on a software time scale, provisionally entitled UTCs, computed at the BIPM as the optimum prediction of UTC from past knowledge of UTC combined with a small amount of clock data available with a short delay. The block diagram for the realization of UTCp is given in Figure 5.

An atomic time scale, UTCs, is computed from a small ensemble of clocks as a simple average of their readings. To produce an optimum prediction of UTC with a short time of access, the UTCs algorithm requires an estimation of the current values of the clock frequencies relative to UTC. This can be extrapolated from past values obtained from last UTC computation. The clocks contributing to UTCs should then be highly predictable.

One can easily imagine the UTCs clock ensemble composed of HP 5071A caesium clocks, auto-tuned active hydrogen-masers, and primary frequency standards operating continuously as clocks. Such clocks reach their flicker floor for averaging times ranging from 20 days to 40 days. Their frequencies relative to UTC, for the current month, can thus be predicted to be equal to their known frequencies relative to UTC, computed over the previous month.

Clocks of the UTCs ensemble will be chosen from those maintained in national timing centres. The BIPM will thus need the help of a small number of laboratories willing to make their timing data available to the BIPM regularly and with a very short delay. Technically this can be done using anonymous File Transfer Protocol (FTP) accessible through the INTERNET network. The BIPM could then retrieve clock and time transfer data for immediate treatment. In addition it would be essential to use data from a number of laboratories in order to detect simultaneous frequency steps of several clocks, which might occur due to external changes in a given laboratory.

The combination of the readings and predicted frequencies from clocks of the UTCs ensemble allows updating UTCs when new data is available. However, as updating involves several laboratories, the exchange of current GPS timing data from these laboratories is also necessary. Filtering of data takes a time of order 12 hours for short-distance links and 1 or 2 days for long-distance links. UTCs may thus reasonably be expected with a delay of access of several days. The requirement of access in real-time can be realized by steering a physical clock to follow UTCs. The output of this clock is the real-time time scale UTCp. Between two consecutive updates of UTCs, the quality of UTCp is maintained by the intrinsic qualities of the physical clock. The temporary loan of a HP 5071A unit to the BIPM, officially agreed by Hewlett-Packard during summer 1993, is an important step of our project. This unit is expected to be in operation before the end of 1993.

2.2. Expected qualities of UTCp

The ultimate stability of UTC, $\sigma_y(\tau) = 4{,}5\times10^{-15}$, corresponds to flicker noise of frequency and is reached for τ of order 30 days. The time error (1σ) on the optimum prediction of UTC over a τ-long prediction interval is equal to $\tau\times\sigma_y(\tau)/\sqrt{\ln 2}$ [8]. The part of the time error on the optimum prediction UTCp, accumulated after 30 days and due to the instability of UTC itself, can be estimated of order 16 ns.

A simple average of clock readings is more stable than any of its contributing elements. With an ensemble of 10 clocks equally weighted in the average and presenting flicker floors of order 6×10^{-15} over 30-day intervals, the expected flicker floor of the simple average is of order 2×10^{-15} and is reached for averaging intervals of 30 days. This leads to an additional accumulated error (1σ) after 30 days of order 7 ns.

The total error on the optimum prediction UTCs of UTC would then be of order 18 ns (1σ). In the future, it is anticipated that the 16 ns originating from UTC instability will be greatly reduced.

With a daily update of UTCs, the error accumulated by the physical clock maintaining UTCp comes from its intrinsic noise over a 1-day averaging period. This is theoretically less than 1 ns and is thus negligible. However an eventual abrupt frequency step of the BIPM clock would give an additional error of several nanoseconds. With one single clock, such a step can be detected only when external data arrives at the BIPM. In the future, we anticipate having three clocks at the BIPM, thus greatly reducing the probability of an undetected frequency step.

From the preceding values, one can reasonably estimate that the real-time UTCp will represent the true deferred-time UTC within ±60 ns (20 ns standard deviation).

2.3. First tests for the realization of UTCp

At a first step, the BIPM intends to retrieve clock and GPS data through the INTERNET network, three times a week (on Mondays, Wednesdays and Fridays), from two laboratories, the PTB and the USNO.

The advantages of this arrangement are that only two time links are needed, one long-distance link between the USNO and the PTB, and one short-distance link between the PTB and the BIPM, while the available ensemble of clocks is quite interesting. An ensemble of about 15 highly predictable and independent clocks could comprise:

- one PTB primary frequency standard operating as a clock, PTB CS1 or PTB CS2,
- one PTB active hydrogen-maser from the tandem of auto-tuned Russian units maintained at the PTB,
- one or two HP 5071A kept at the PTB,
- the Sigma-Tau N5 active hydrogen-maser kept at the USNO, and
- several HP 5071A from USNO, kept in different locations with individual environmental control.

Formal steps to initiate this particular collaboration, which requires specific inputs from the USNO and the PTB, have not yet been taken. If such a collaboration is approved and if the obtained results are convincing, tests could be carried out on a daily basis and with the gradual involvement of other laboratories. Implicit in this proposal is the implementation of a completely automatic system of data retrieval, checking and treatment. Whatever procedure is agreed, the BIPM clock will not participate in the computation of UTCs, its sole role being to follow UTCs in order to provide a physical output, UTCp, in real-time.

3. ACCESS TO UTCp

The UTCp, being physically available in real-time, can be made available through measurements of the time differences between UTCp and other time scales, observable from user laboratories, using satellite systems like GPS, GLONASS, INMARSAT, the hydrogen-maser on Meteor 3M, ... *etc.*

This leads to two requirements:

- calibrated reception equipment, capable of receiving all available signals, is required at the BIPM and must operate under excellent metrological conditions (accurate local coordinates, ionospheric measurements, multi-channel receivers, temperature and humidity control of the clock room, ... *etc*),
- development and implementation of efficient methods for the extraction, from real-time measurements, of the best estimates of the requested time differences [UTC - GPS time], [UTC - GLONASS time] ... *etc*.

The UTCp will be available in real-time at the BIPM, but the extraction and delivery of usable time differences takes some time. For example, efficient averages for smoothing out SA noise from raw GPS data requires the use of simultaneous measurements on several satellites taken for about one hour [9]. Once the BIPM has obtained the average time difference [UTCp - GPS time], it can deliver it via its INTERNET anonymous FTP. This will be updated when new data is available: the periodicity could be as short as one hour. A given user who also accesses GPS time from his local time scale could obtain the BIPM information through a connection to the BIPM INTERNET anonymous FTP. The user can take full advantage of this value only if:

- the INTERNET connection is established shortly after the BIPM has delivered an updated time difference,
- the user receiving equipment is well calibrated and is used under excellent metrological conditions, and
- an efficient method is available for restitution of GPS time in the user laboratory.

In the case of GPS, the restitution of GPS time detailed in Ref. 9 adds an uncertainty of about 10 ns. In the best case, the user will then access UTCp within ±75 ns (25 ns standard deviation) and with a delay not less than one hour. This performance may be improved when timing equipment becomes commercially available for satellite systems which do not present intentional signal degradation.

CONCLUSIONS

The production and distribution in real-time of a predicted UTC calls for the computation in short deferred-time (of order several days) of a software time scale, UTCs, from a small ensemble of clocks with good predictability, and the steering on UTCs of a commercial clock maintained at the BIPM. Its real-time output is the time scale UTCp, which represents the true deferred-time UTC within 20 ns (1σ). Its availability is made through the delivery by the BIPM of time differences between UTCp and time scales distributed by global satellite systems, in near real-time (of order several hours) and with uncertainties of order 25 ns (1σ).

This BIPM project, suggested by Allan and Lepek [10], comes in response to current and anticipated needs within the telecommunications industry. It is also indirectly encouraged by Recommendation S 5 (1993) approved by the Comité Consultatif pour la Définition de la

Seconde (CCDS) during its 12th meeting (24-26 March 1993). In this, the Comité Consultatif pour la Définition de la Seconde, recommends [11]

> "... that time centres provide information to facilitate time coordination to UTC in real time with a goal of 100 ns, standard deviation, when this is feasible, and that the technical problems implicit in this goal be carefully studied".

The BIPM is already carrying out studies on the real-time prediction of UTC. However it is important to underline that, even after experimentation has validated the concepts of a real-time predicted UTC, its concrete implementation at the BIPM will take place only after discussion in the CCDS and consultation with interested bodies.

Acknowledgements

The authors are grateful to Dr G.M.R. Winkler, USNO, Washington D.C., USA, for his support in this project, and to Gérard Petit and Jacques Azoubib, Time Section, BIPM, Sèvres, France, for helpful discussions. The BIPM thanks Hewlett-Packard for the loan of a commercial caesium clock HP 5071A, without which the provision of a real-time predicted UTCp could not even be considered.

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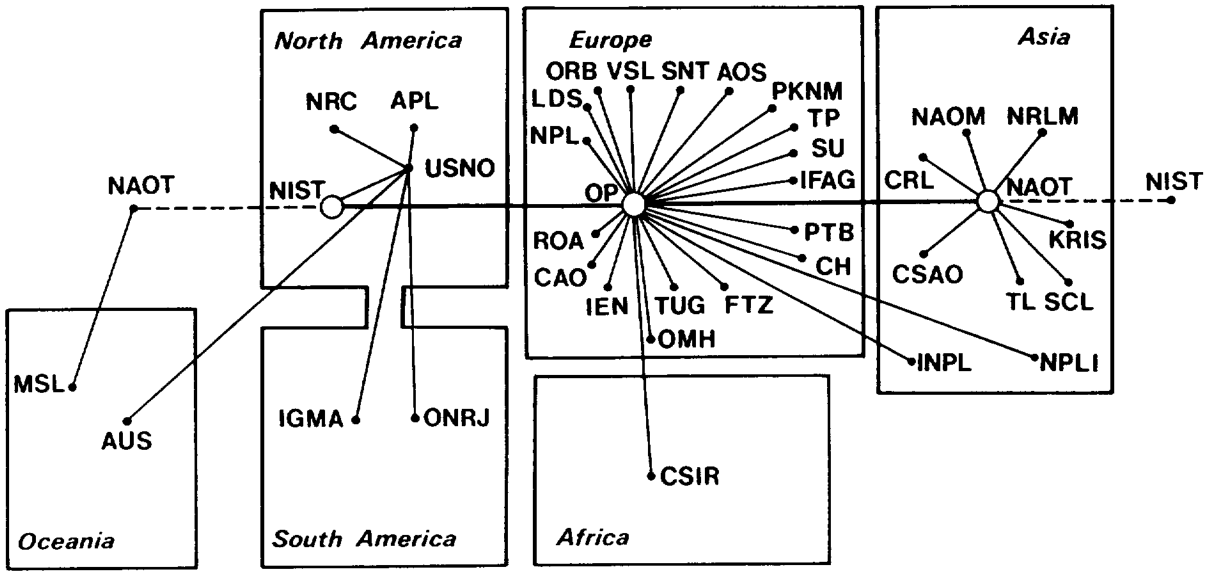

Figure 1. Organization of the international GPS network used in UTC computation (September 1993). Acronyms of laboratories can be found in Ref 2.

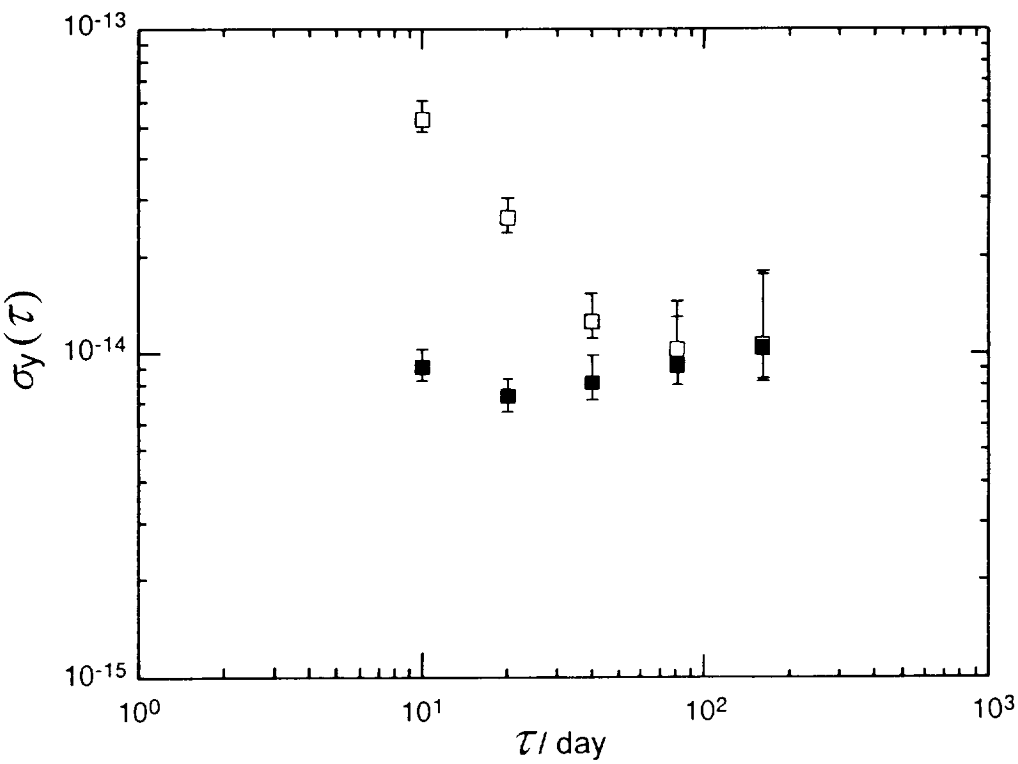

Figure 2. Allan standard deviation of the time difference [EAL - PTB CS2] computed with 10-day data covering a two-year period:

□ *mid 1986-mid 1988,*

■ *1992-1993.*

		Nov - Dec 1991	Nov - Dec 1992	May - Jun 1993
	Total number of clocks	194	194	215
	Max contribution	1,6%	1,4%	1,2%
	Number at max contribution	41	44	61
H-masers	Total number	20	23	27
	at max contr	8 (12,8%)	10 (14,0%)	11 (13,2%)
	under test	6	4	6
HP 5071A	Total number	0	8	36
	at max contr	0	1 (1,4%)	14 (16,8%)
	under test	0	4	20

***Table 1.* Contribution of hydrogen-masers and HP 5071A clocks in UTC computation.**

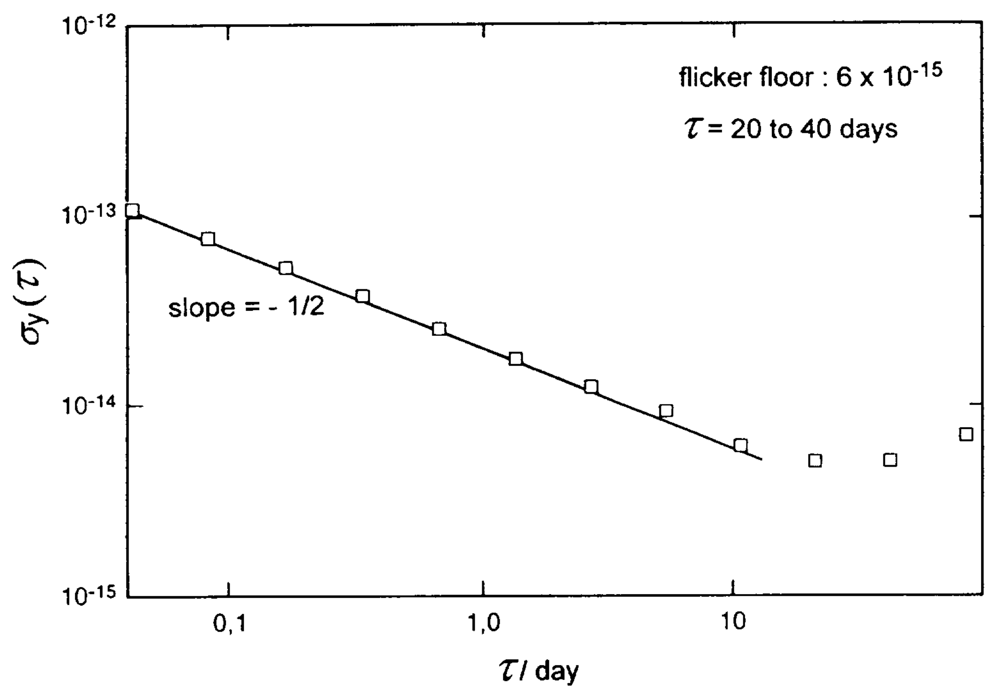

***Figure 3.* Allan standard deviation of the time difference between the HP 5071A clock serial number 114 and the Sigma-Tau hydrogen-maser N5, both kept by USNO. (Log-Log graph).**

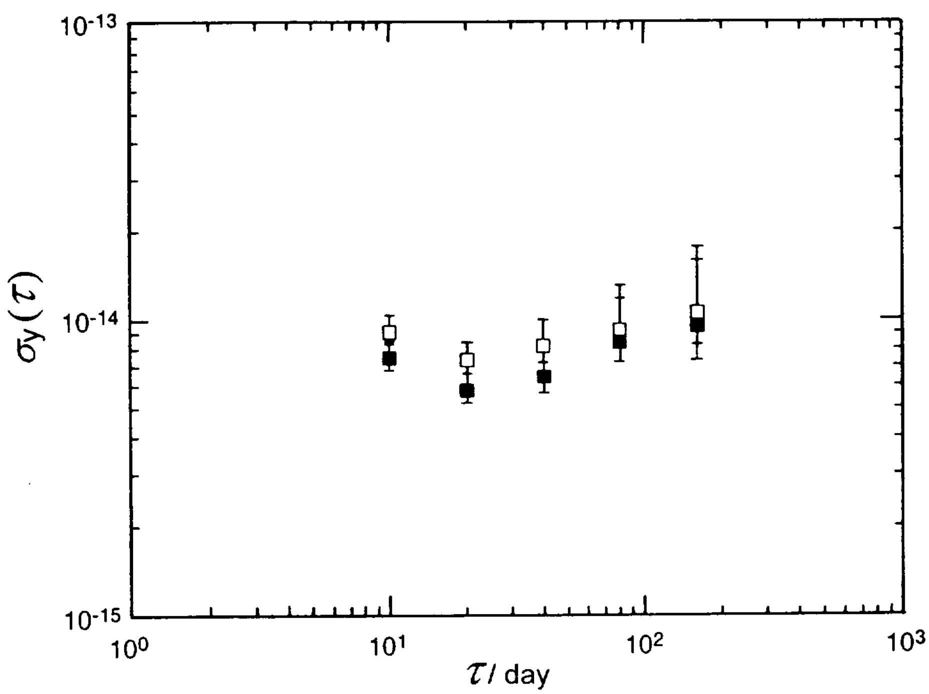

***Figure 4**. Allan standard deviation of the time difference [EAL - PTB CS2] computed with 10-day data covering years 1992 and 1993:*

□ *EAL computed with two-month basic intervals,*

■ *EAL computed with one-month basic intervals.*

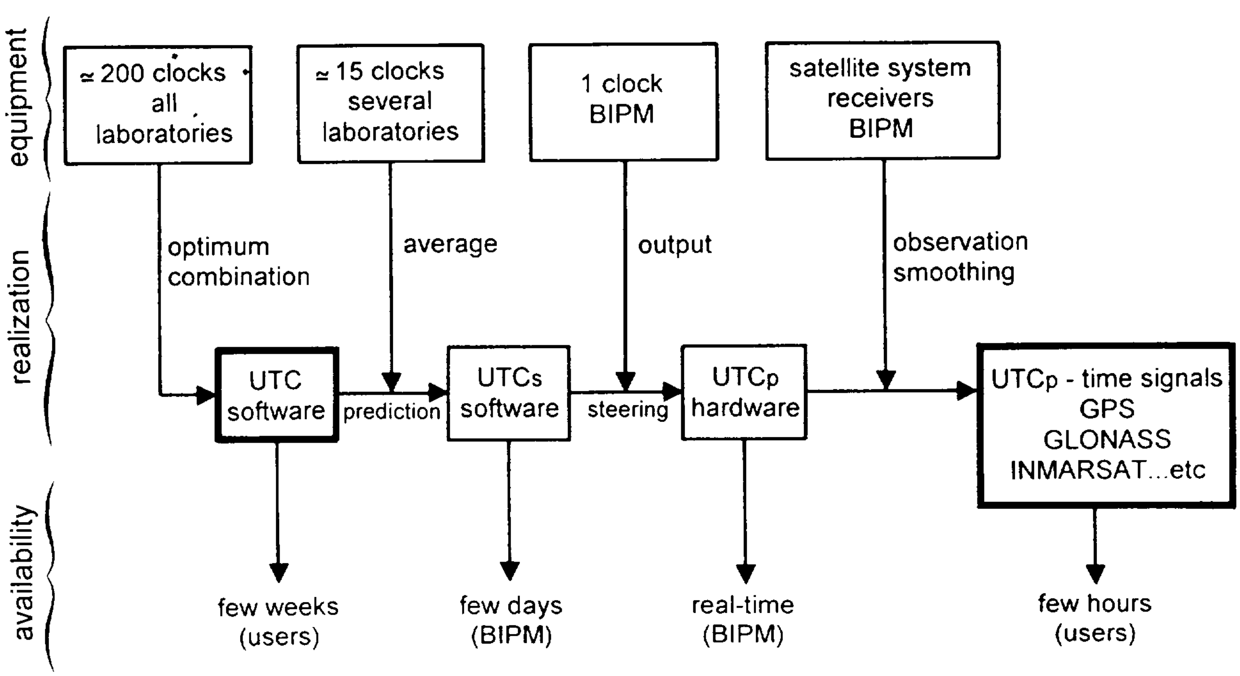

***Figure 5**. Block diagram of the realization of the real-time prediction of UTC, UTCp.*

QUESTIONS AND ANSWERS

David Allan, Allan's Time: I think the long–term hope is that this will be of great service to the user community, especially the telecommunication user community who has specified a need at the sub–100 ns level. And of course, the hope would be that other countries would have their UTC scales also synchronized, so that this would track the real time UTCP in any country at this very high level. NIST and USNO have both been very actively steering their clocks. The Observatory time unfortunately has been kept within something like less than 100 ns, maybe 50 ns. Is that true, Dr. Winkler?

Dr. Winkler: Yes.

David Allan: Of course, GPS broadcasts the UTC/USNO correction. So in addition to being able to have something of the order of tens of ns directly from BIPM on an operational basis, GPS will be broadcasting UTC BIPM. So I think with this cooperative as Dr. Thomas indicates we hope that it continues to go on. I think it has been excellent today. With international cooperation we can see UTC BIPM as represented by UTCP being a real time scale in every country at the hundred ns level, or certainly better.

Dr. Winkler: My comment is that indeed what I would like to see is an evaluation of the existing predictions which are available in real time. In fact, the correction between UTC at every moment is available on the computer. And I think that should be evaluated by you. You accessed that several times, I know that. Because, that prediction is based on a clock set which is much larger than the one which you will have.

The real problem is that until now we have only had the two months evaluation period. And if these corrections disappear, then of course the prediction will be immediately much more accurate and all of these values will converge to zero I hope.

Claudine Thomas: I hope so too.

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TROPOSPHERIC CORRECTIONS TO GPS MEASUREMENTS USING LOCALLY MEASURED METEOROLOGICAL PARAMETERS COMPARED WITH GENERAL TROPOSPHERIC CORRECTIONS

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Abstract

At the Technical University Graz (TUG), Austria, the Global Positioning System (GPS) has been used for time transfer purposes since the early 80's and from that time on local meteorological parameters are recorded together with each measurement (satellite track). The paper compares the tropospheric corrections (delays) obtained from models usually employed in GPS receivers and those using locally measured meteorological parameters.

INTRODUCTION

In order to calculate the path delay of the signals received from GPS satellites – as with any one–way system – one has to know the satellite and user positions with high accuracy and furthermore has to apply corrections for the propagation delays in the ionosphere and troposphere[1]. In the case of time laboratories the GPS antenna coordinates are usually known with high accuracy in a common reference frame and post–processed ephemerides are accessible within a few weeks from different agencies and the ionospheric delay can be measured using dual–frequency receivers[2,3]. The tropospheric delay is – for the frequencies used here – frequency–independent and can therefore not readily be established. Different models are employed in GPS timing receivers using general empirical atmospheric models which only take into account the station height and the elevation of the satellite. For increased accuracy models based on actually measured local surface temperature, atmospheric pressure and relative humidity may be used. At the Technical University Graz (TUG), Austria, the Global Positioning System (GPS) has been used for time transfer purposes since the early 80's and from that time on together with each measurement (satellite track) local meteorological parameters are recorded. The paper compares the tropospheric delays obtained from models usually employed in GPS receivers and those using locally measured meteorological parameters. Results are given for measurements done according to the GPS common-view tracking schedules issued by the Bureau International des Poids et Mesures (BIPM) during the years 1991 and 1992.

TROPOSPHERIC DELAY AND USED MODELS

The tropospheric excess delay D_T is given by

$$D_T = \frac{10^{-6}}{c} \int N(s) ds \tag{1}$$

where N is the refractivity given by $(n-1)10^6$ with n the index of refraction of air and c is the velocity of light in vacuo and the integral is evaluated along the signal path[4]. For frequencies below 30 GHz N is given by

$$N = 77.6(\frac{p}{T} + 4810\frac{e}{T^2}) \tag{2}$$

where T is the absolute temperature in Kelvin, p is the total atmospheric pressure and e is the partial pressure of water vapour both in millibars[4,5]. This form is widely used and accurate within 0.5% for the range of atmospheric parameters normally encountered[4]. The first term in Equation 2 is called the dry component N_d and the second term the wet component N_w and thus with

$$N = N_d + N_w \tag{3}$$

the tropospheric delay according to Equation 1 is composed of a dry component and a wet component due to dry air and water vapour effects, respectively, and can be written in the following form

$$D_T = D_{Td} + D_{Tw} = \frac{10^{-6}}{c} \int N_d(s) ds + \frac{10^{-6}}{c} \int N_w(s) ds \tag{4}$$

The main part of the total delay results from the dry component but the remaining part resulting from the wet component is highly variable due to the high variability both temporally and spatially of the water vapour concentration. Usually the integrals are evaluated in zenith direction and from the obtained zenith delay D_T^z the delay D_T for arbitrary elevation angles is computed by means of mapping functions MF[6,7]. Thus the tropospheric delay D_T is given by

$$D_T = D_{Td}^z \times \mathbf{MF}_d + D_{Tw}^z \times \mathbf{MF}_w \tag{5}$$

The accuracy of the calculated tropospheric delay depends upon the degree to which the atmospheric model used to determine the refractivity profile $N(s)$ reflects local atmospheric conditions[7]. Models are employed which either use a general empirical reference atmosphere only requiring the station height and the respective elevation angle to the satellite to calculate the tropospheric delay or which are based on surface measurements of the refractive index thus requiring the measurement of the local meteorological parameters i.e. temperature, atmospheric pressure and relative humidity. Models of the first type are usually implemented in GPS receivers. The model used in receivers of NBS type (NBS model)[3], the model used in STI TTS–502 receivers (STI model)[3] and the model recommended in the STANAG Doc. 4294 (STANAG model)[8] will be compared with models of the second type namely the ones by Hopfield[9], Saastamoinen[9] and Chao[10,11]. Of the latter models the first two are widely used within the geodetic community[12] and the last one was developed by the Jet Propulsion Laboratory (JPL) and is employed in the original Master Control Stations (MCS)[11]. In the following the Hopfield model will be used as reference. Apart from the tropospheric models investigated in this paper there exist many other models. The main reason for that is the difficulty in the modelling of the water vapour content[9].

DATA AND RESULTS

Table 1 gives the tropospheric delays in zenith direction for the above mentioned models at Graz (h = 540 m) whereby for the Hopfield, Saastamoinen and Chao models average meteorological conditions (T=11°C, p = 955 mbar, RH = 70%) computed from the data of 1991 and 1992 (see Figs. 5 → 10) are used.

Table 1 Tropospheric delays in zenith direction for average meteorological conditions (T=°C, p = 955 mbar, RH = 70%) at Graz (h = 540 m)

Tropospheric Delay in ns			
Model	Dry Comp.	Wet Comp.	Dry Comp. + Wet Comp.
NBS			6.73
STI			7.33
STANAG			7.66
Hopfield	7.27	0.31	7.58
Saastamoinen			7.56
Chao	7.12	0.36	7.48

The dependence of the dry component on temperature and atmospheric pressure and the dependence of the wet component on temperature and relative humidity of the tropospheric zenith delay computed by means of the Hopfield model are shown in Fig. 1 and Fig. 2, respectively. Indicated are the values for average conditions at Graz. The high variability of the wet component leading to large contributions in hot and wet climates can clearly be seen from Fig. 2. The mapping functions for the dry and wet components for this model are depicted in Fig. 3. The differences between the tropospheric delays given by the Hopfield model and the other models as function of the elevation angle – thus showing the influence of the different mapping functions used by the different models – based on the values given in Table 1 is plotted in Fig. 4. The large differences for low elevation angles caused by the different mapping functions are usually not relevant for the GPS common-view time transfer because in practice also for common-view time transfers over long distances the elevation angles usually employed are greater than 15 degrees (see Fig. 11). Because an elevation angle of about 15 degrees is the limit for some receivers using a type of choke ring groundplane for the antenna to reduce multipath effects this elevation angle was chosen as limit in the comparisons. The temperature, atmospheric pressure and relative humidity for the GPS measurement times (satellite tracks) according to the BIPM common-view schedules are plotted in Figs. 5 → 10 whereby the single measurements and daily means are given for each meteorological parameter. Fig. 11 shows the elevation angles at which the common-view time transfer measurements according to the different BIPM common-view schedules were performed in 1991 and 1992. The tropospheric delays computed by means of the Hopfield model and NBS model for this period are plotted in Figs. 12 and 13. For low elevation angles a change by 1 degree – this is the resolution of the old format for GPS data exchange which in the new format has been changed to 0.1 degree[14] – already causes large variations in the tropospheric delays. For the same period means over seven days of the differences between the Hopfield model and the other models are shown in Fig. 14 revealing model dependent offsets and seasonal patterns. To explain the differences between 1991 and 1992 one has to look at the meteorological parameters and the elevation angles for this period (see Figs. 6 and 8 and Fig. 11). The differences for 1991 between the Hopfield model and the ones by Saastamoinen, Chao, NBS, STI and STANAG for each satellite track are plotted in Figs. 15 → 19 and daily means of the same differences are shown in Fig. 20 and Fig. 21, respectively.

CONCLUSION

Models simply using the station height and the elevation angles to the satellites observed are easy to implement and therefore widely used. The three models investigated i.e. the NBS model, the STI model and the STANAG model give different tropospheric corrections for the zenith direction and use different mapping functions causing differences of up to several nanoseconds. Therefore employing models of this type the use of the same model in all timing receivers is recommended[14,15]. Tropospheric corrections obtained by these models and models using locally measured meteorological parameters differ by up to several nanoseconds. By averaging – for example the use of daily means – as usually done in GPS time transfer practice these differences are greatly reduced (see Fig. 21). Employing models which use locally measured meteorological data spatial and temporal variations of the refractive index are taken into account, but there are still differences for the single measurements of up to about one nanosecond between the models investigated (see Fig. 16). For daily means these differences are below one nanosecond, but one has to consider that these are still differences between models. A problem with the use of the latter models is that data are needed for the calculation of the tropospheric delay which are not provided by the GPS receivers itself and that the uncertainty of estimating the refractive index from local surface measurements may cause additional measurement noise due to measurement uncertainties and model deficiencies. Delay stabilities of GPS time transfer receivers now in use are in general of the order of some nanoseconds. Assuming the use of receivers of highest delay stability and asking for accuracies of one nanosecond or even better for GPS time transfers over long distances one has to use models based on actual meteorological parameters. To estimate the accuracy of tropospheric corrections obtained by models using surface measurements these models and those employing more refined techniques such as the use of data provided by water vapour radiometers should be compared.

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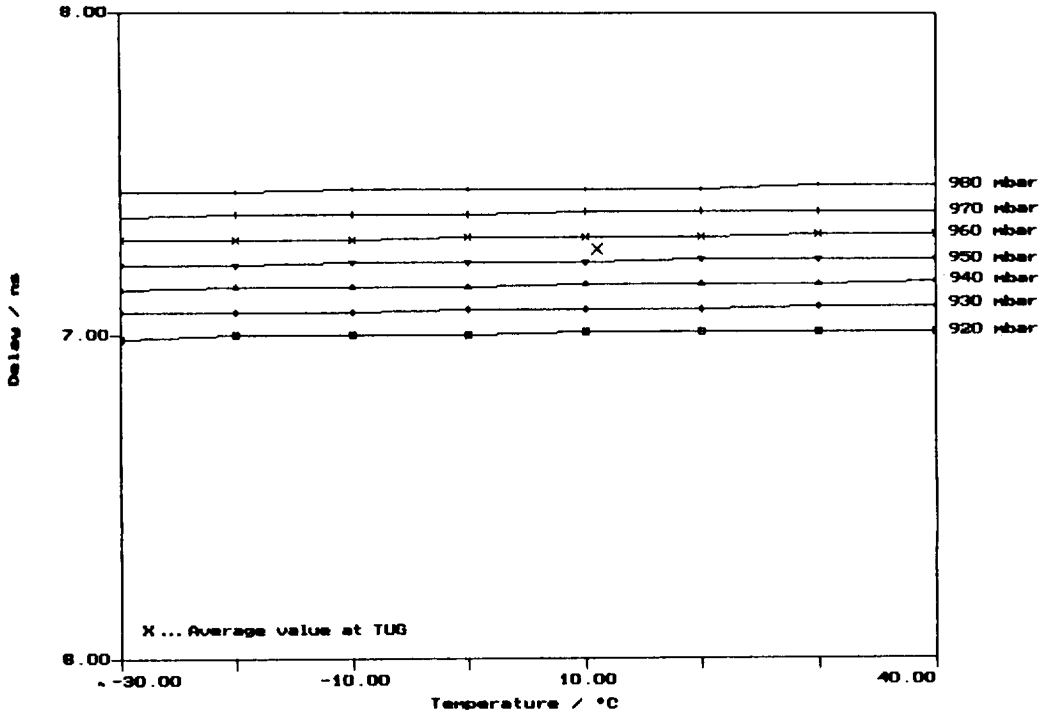

Fig. 1 Hopfield model: tropospheric zenith delay, dry component.

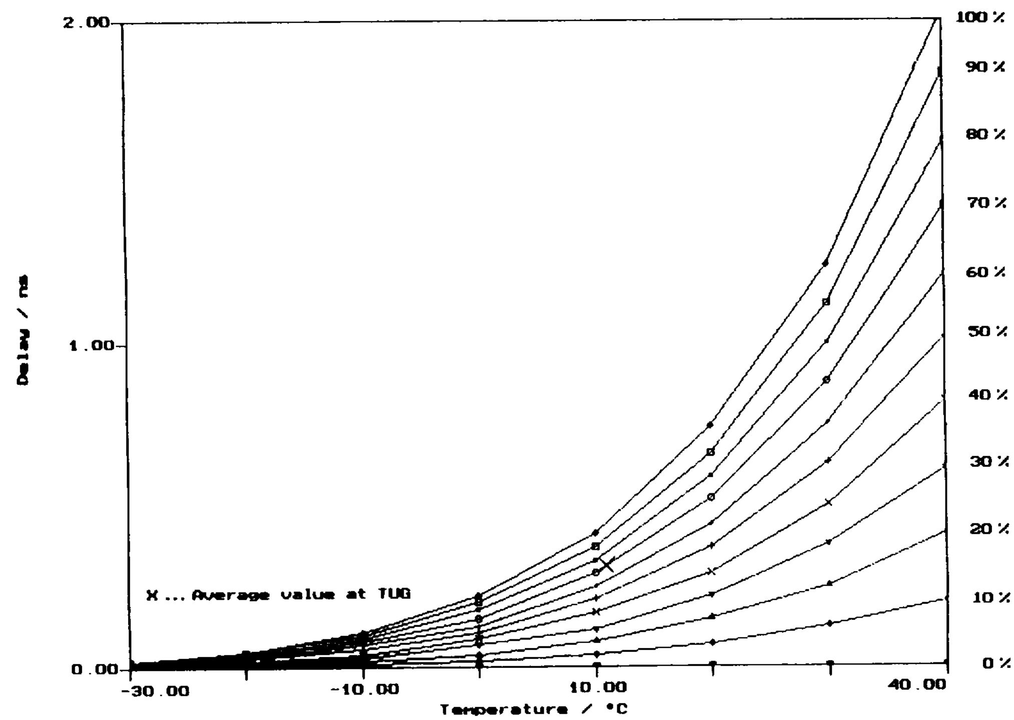

Fig. 2 Hopfield model: tropospheric zenith delay, wet component.

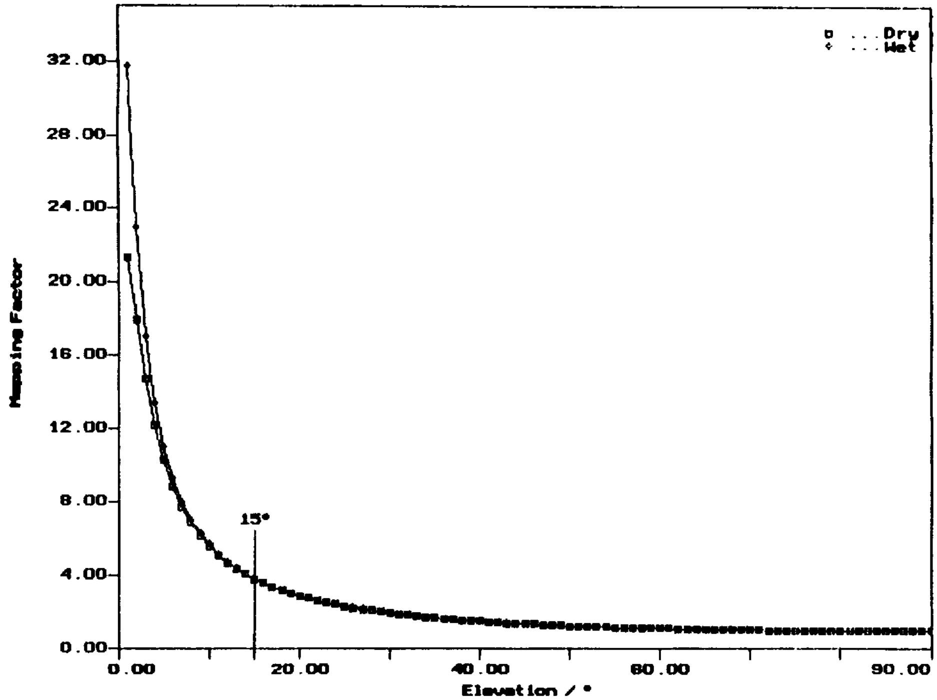

Fig. 3 Hopfield model: mapping functions for dry component and wet component.

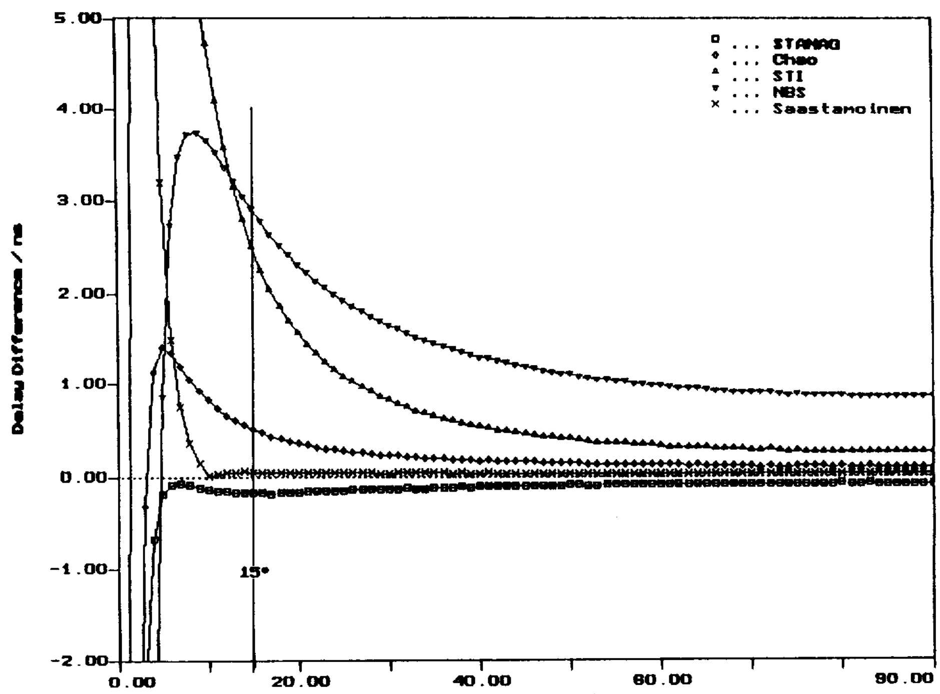

Fig. 4 Differences between the tropospheric delays given by the Hopfield model and the Saastamoinen, Chao, NBS, STI and STANAG models for average meteorological conditions at TUG.

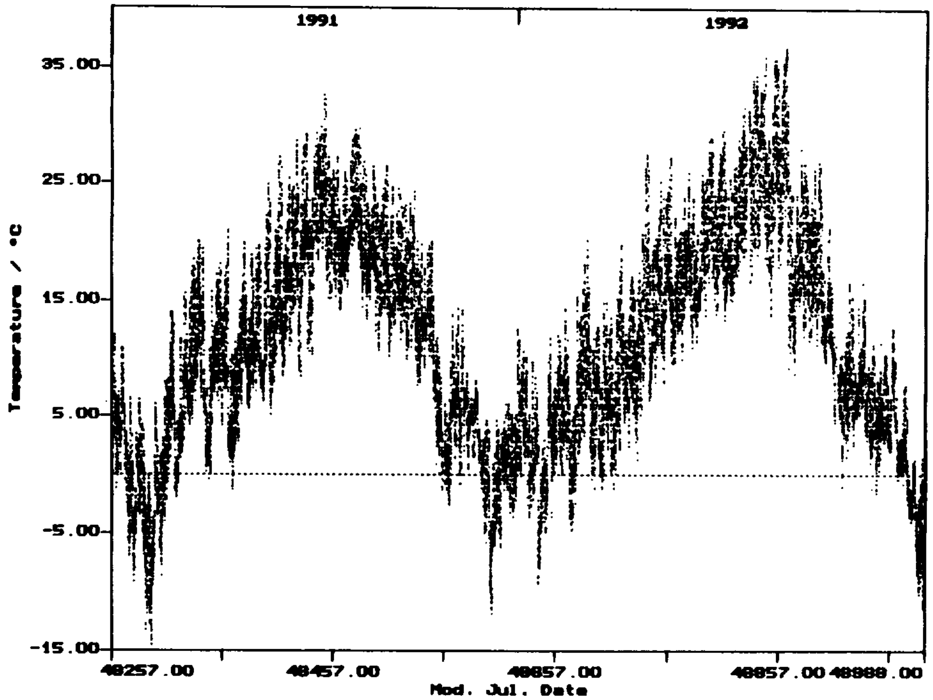

Fig. 5   Temperature at TUG for each satellite track.

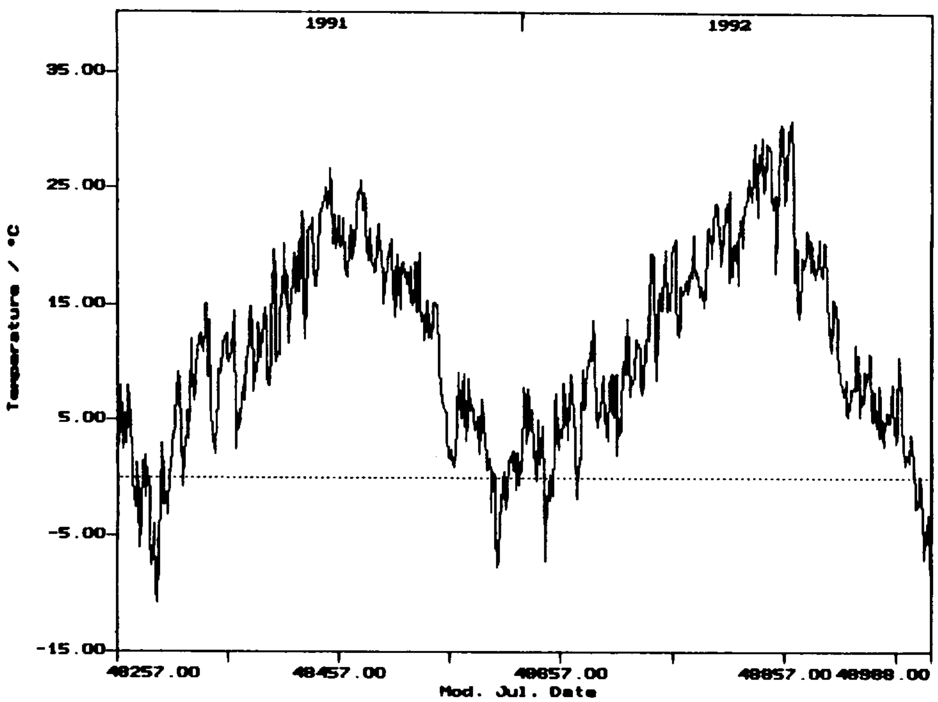

Fig. 6   Temperature at TUG (daily mean).

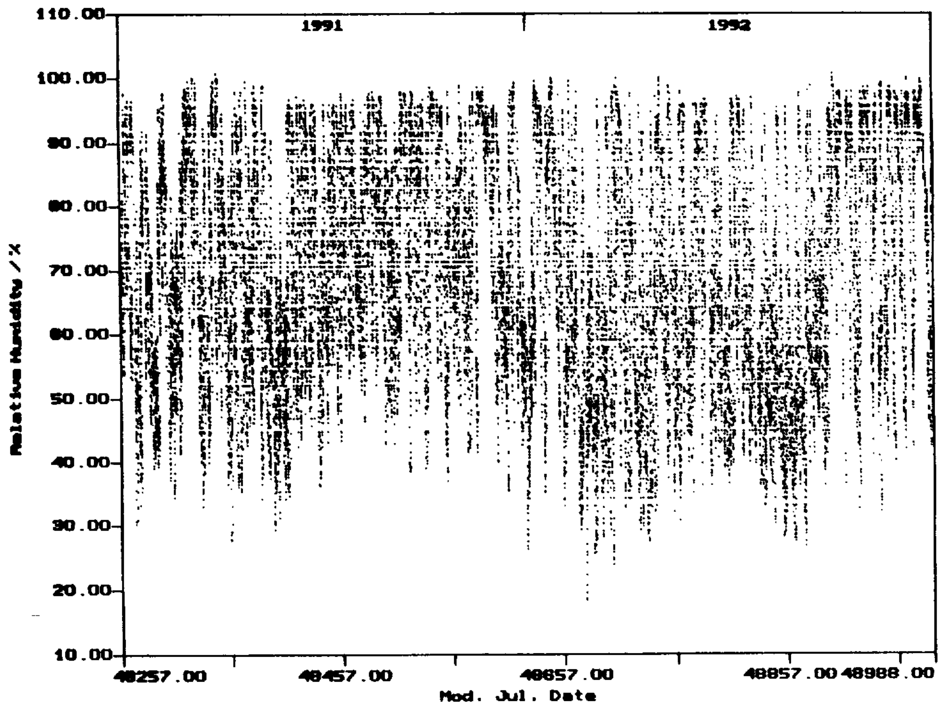

Fig. 7 Relative humidity at TUG for each satellite track.

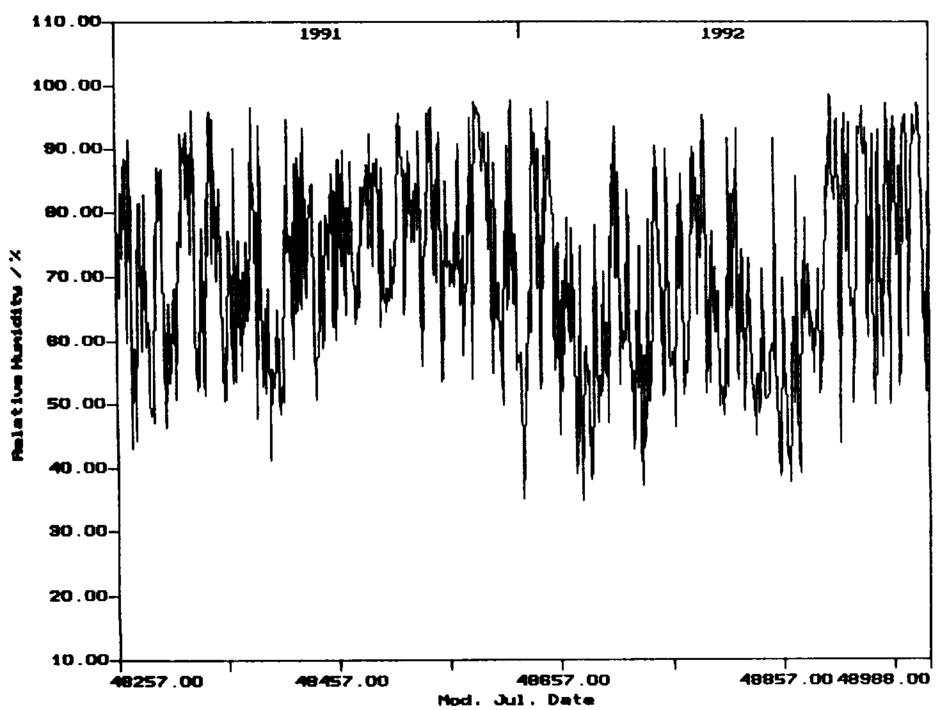

Fig. 8 Relative humidity at TUG (daily mean)

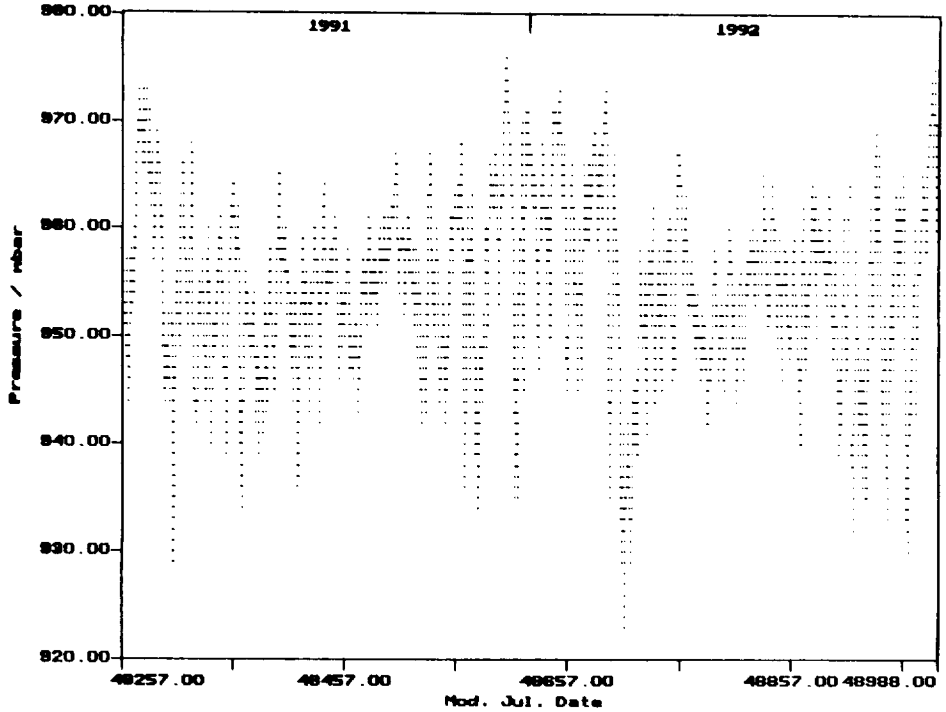

Fig. 9 Atmospheric pressure at TUG for each satellite track.

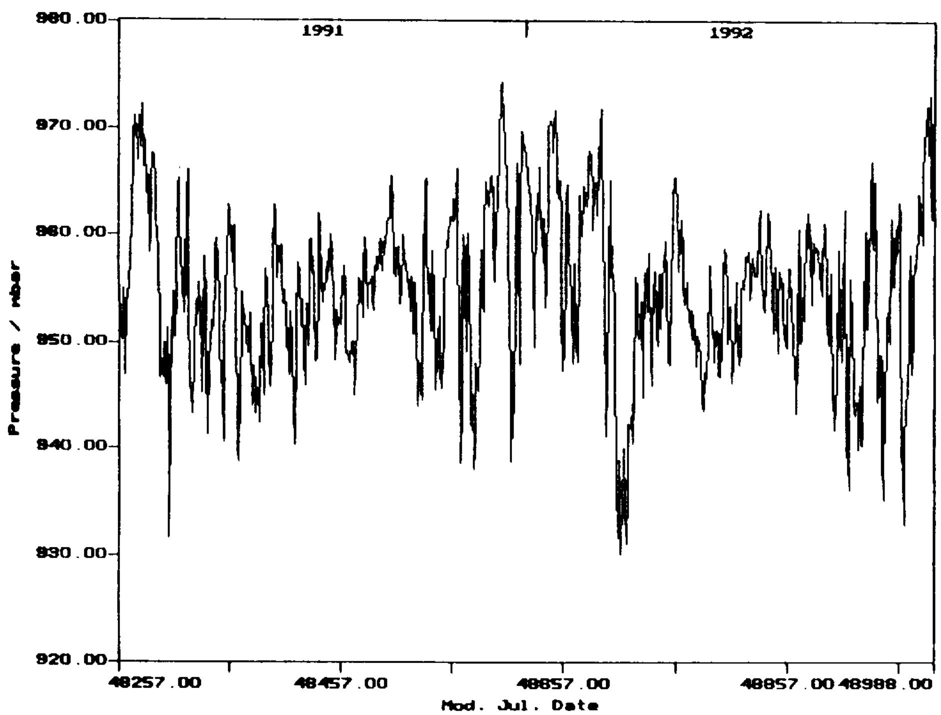

Fig. 10 Atmospheric pressure at TUG (daily mean).

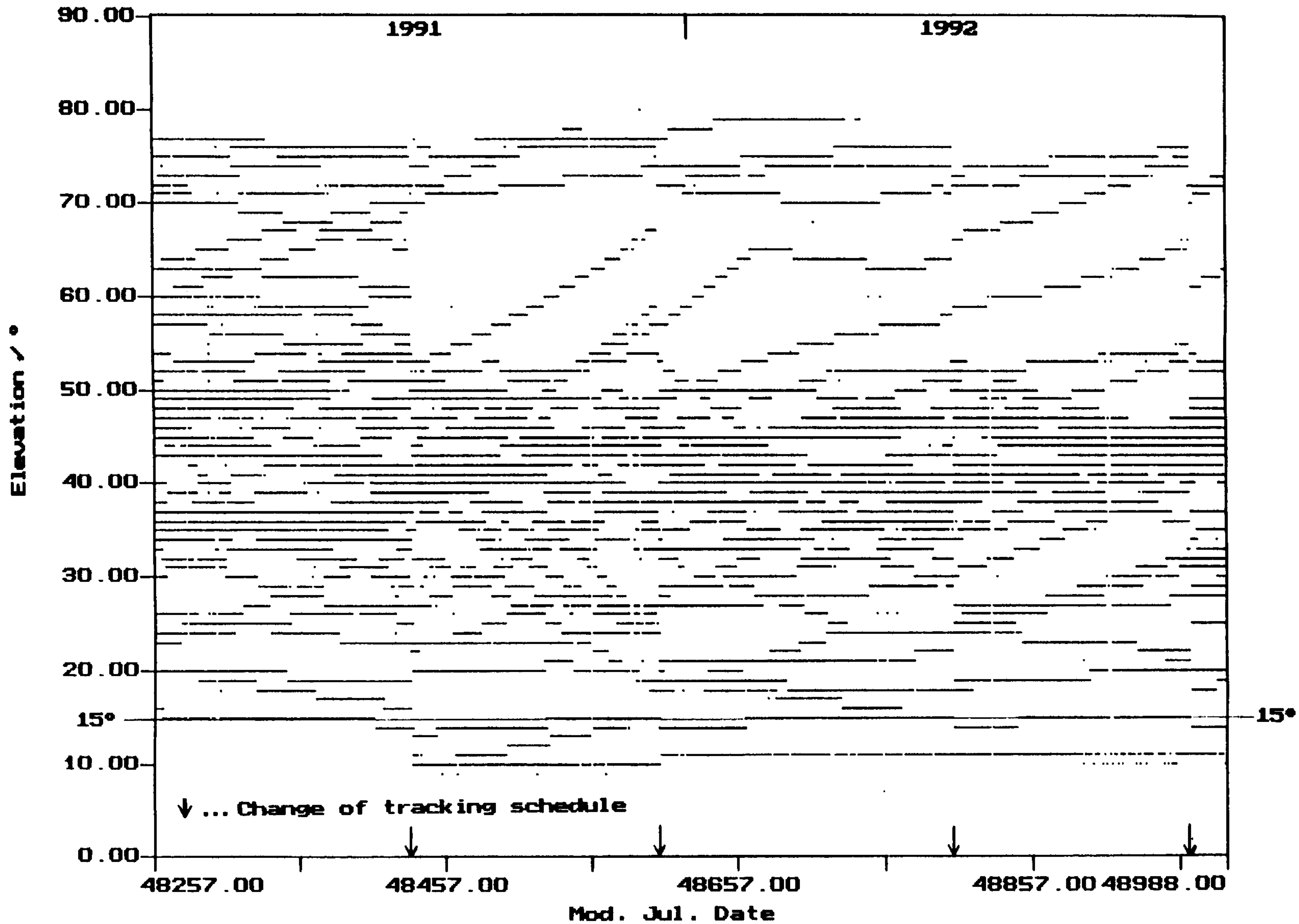

Fig. 11 Elevation angles at TUG for the satellite tracks observed according to the respective BIPM common-view schedule.

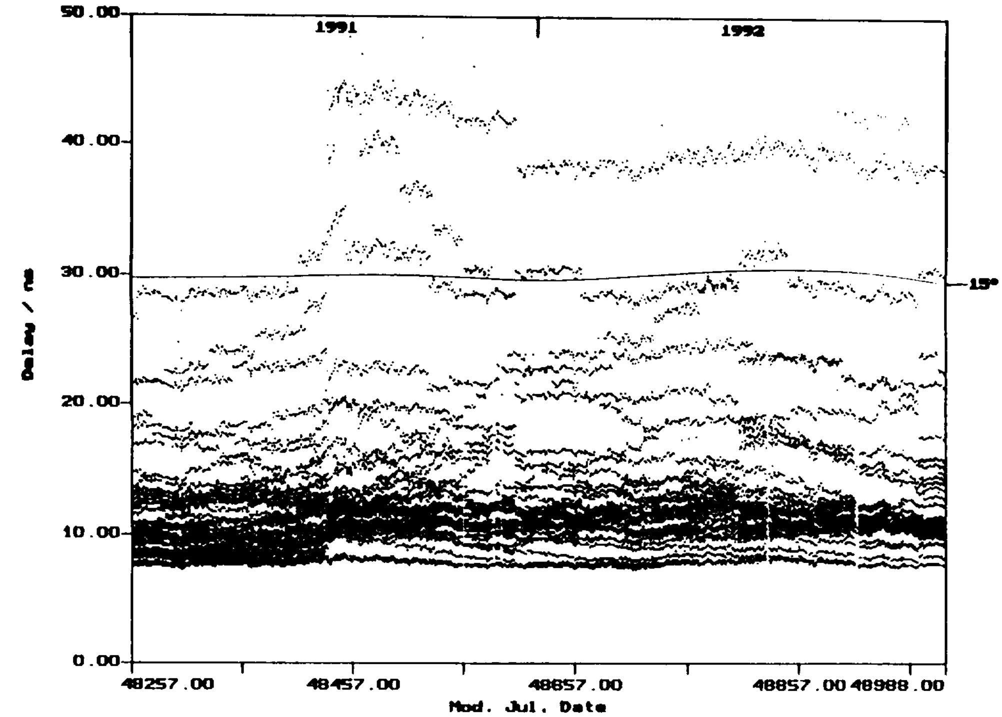

Fig. 12 Hopfield model: Tropospheric delay for each satellite track .

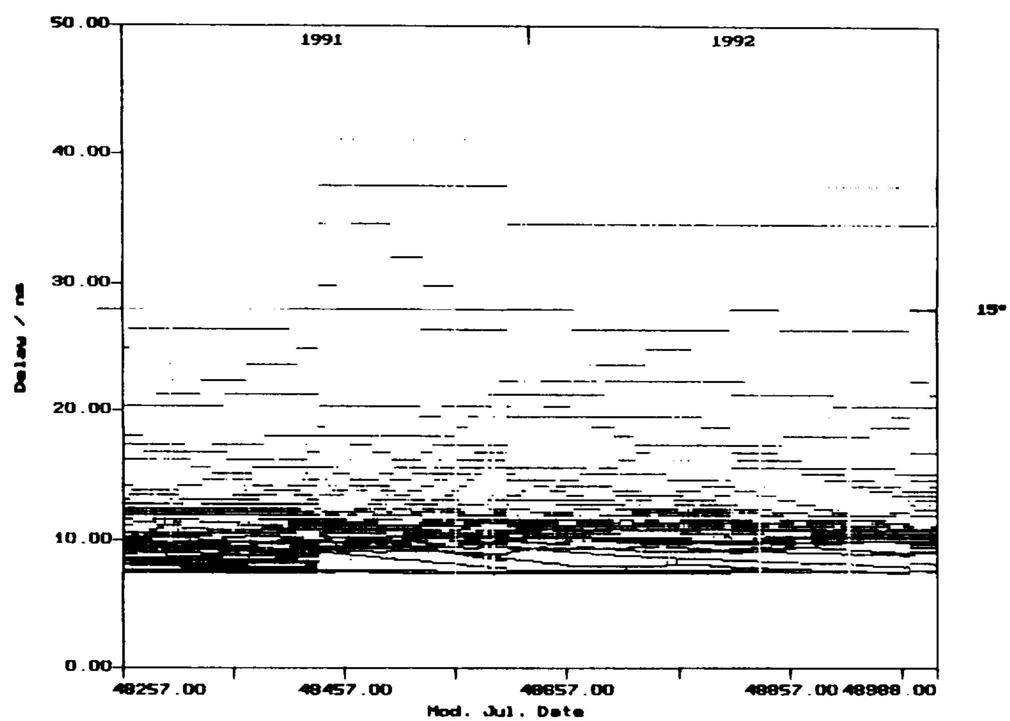

Fig. 13 NBS model: Tropospheric delay for each satellite track.

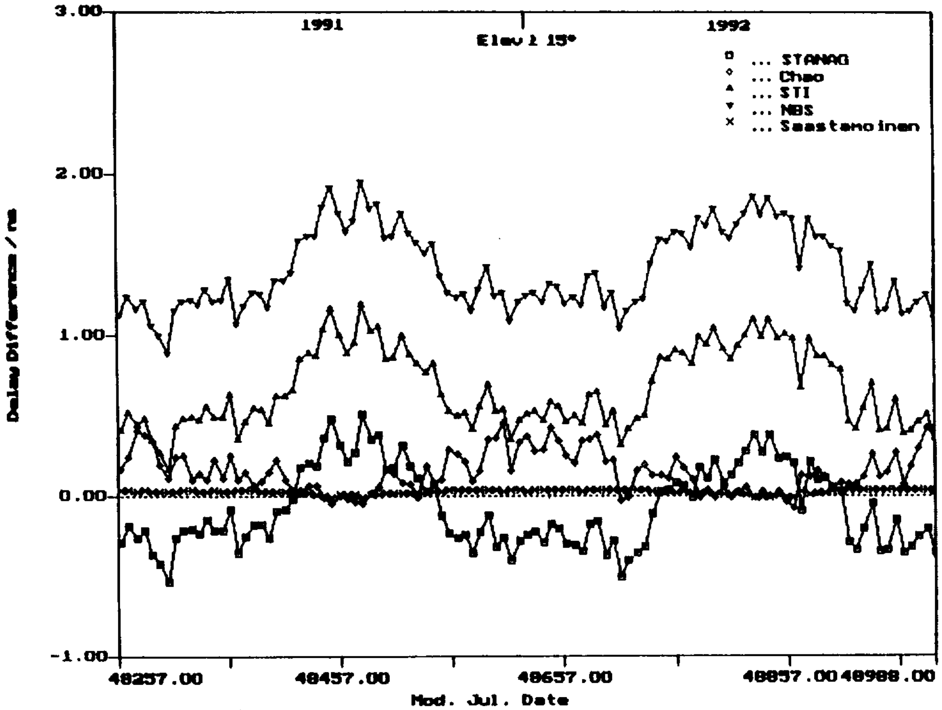

Fig. 14 Delay differences between the Hopfield model and the other models (seven day mean).

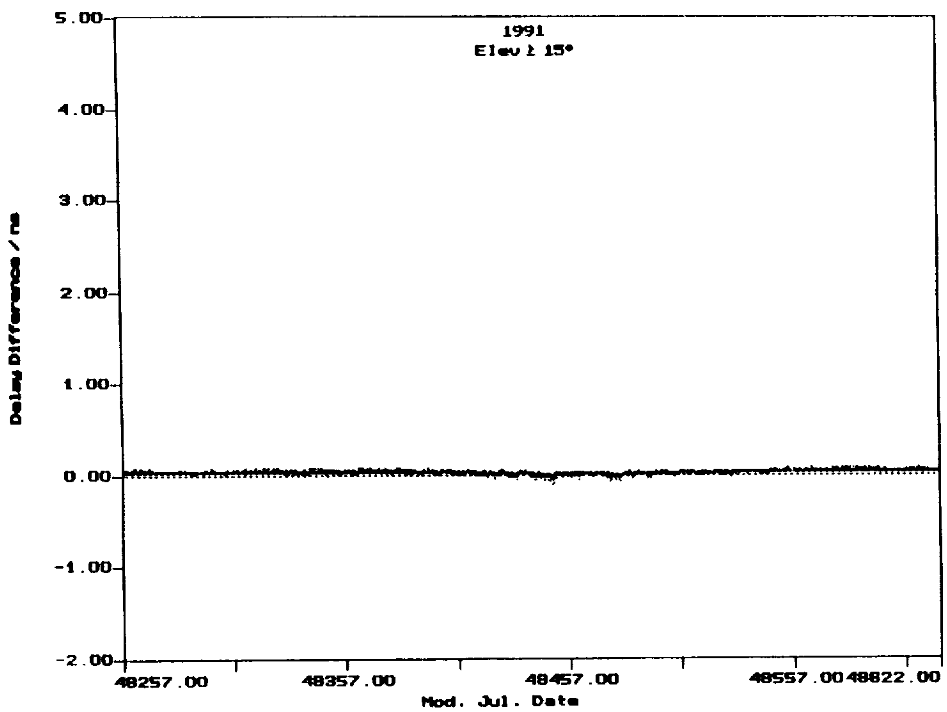

Fig. 15 Delay difference between the Hopfield model and the Saastamoinen model (each satellite track).

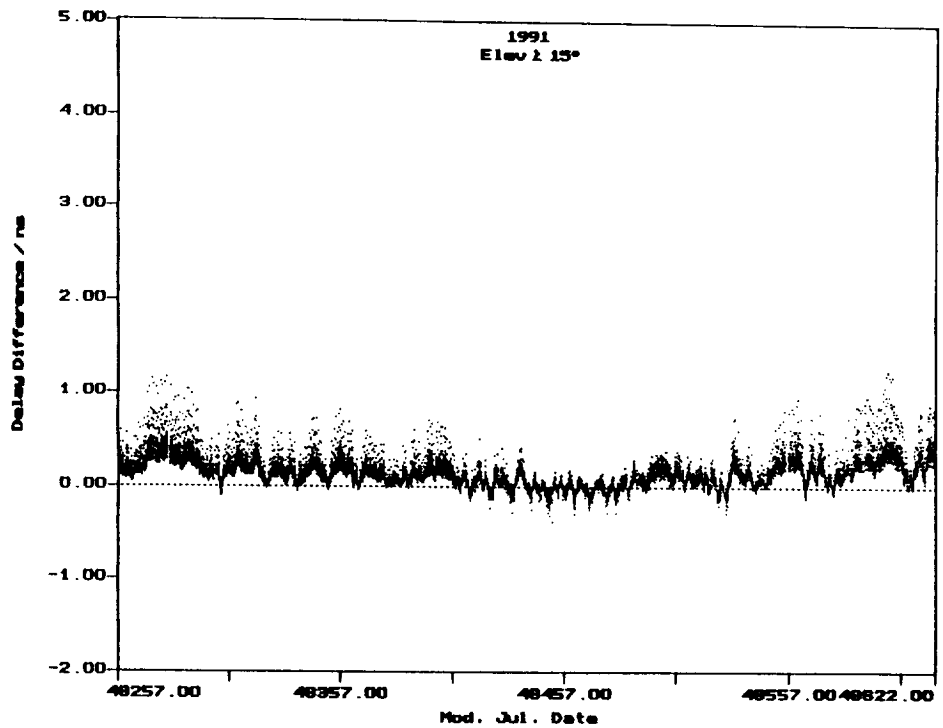

Fig. 16 Delay difference between the Hopfield model and the Chao model (each satellite track).

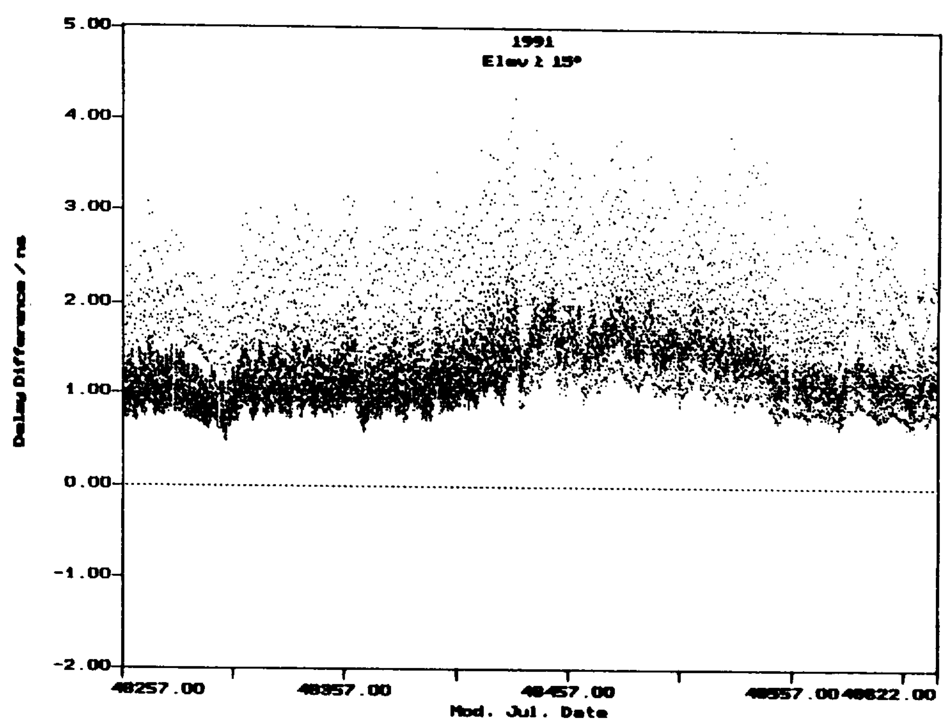

Fig. 17 Delay difference between the Hopfield model and the NBS model (each satellite track).

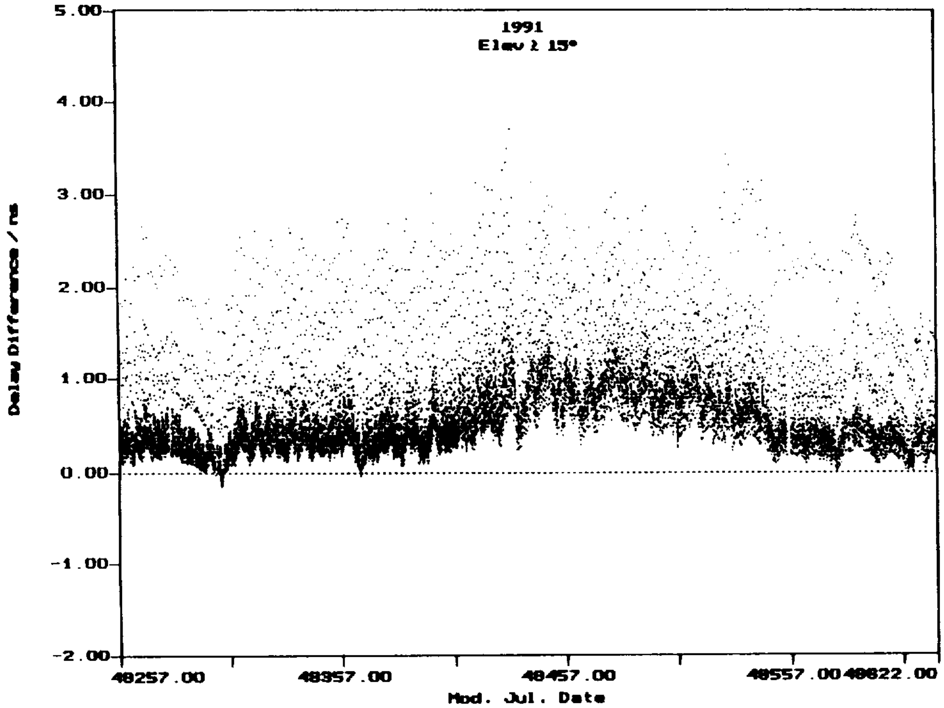

Fig. 18 Delay difference between the Hopfield model and the STI model (each satellite track).

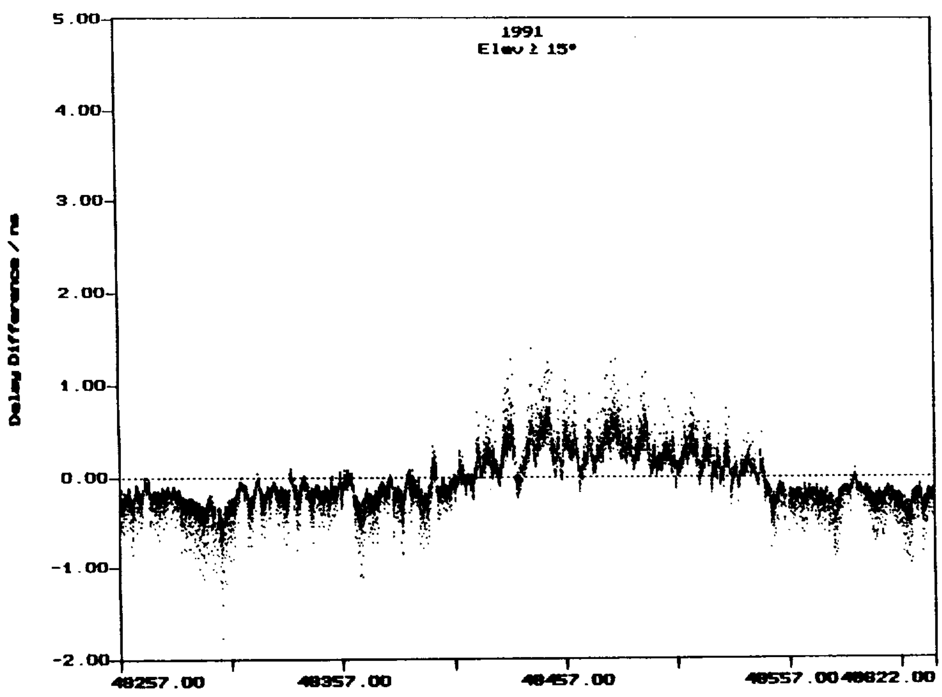

Fig. 19 Delay difference between the Hopfield model and the STANAG model (each satellite track).

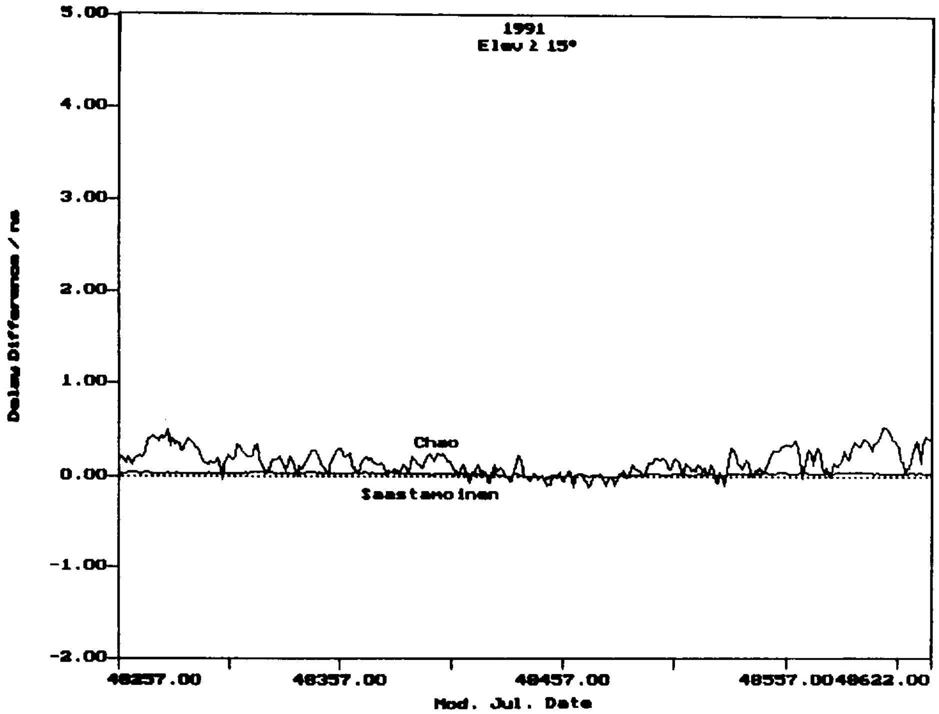

Fig. 20 Delay differences between the Hopfield model and the Saastamoinen and Chao models (one day mean).

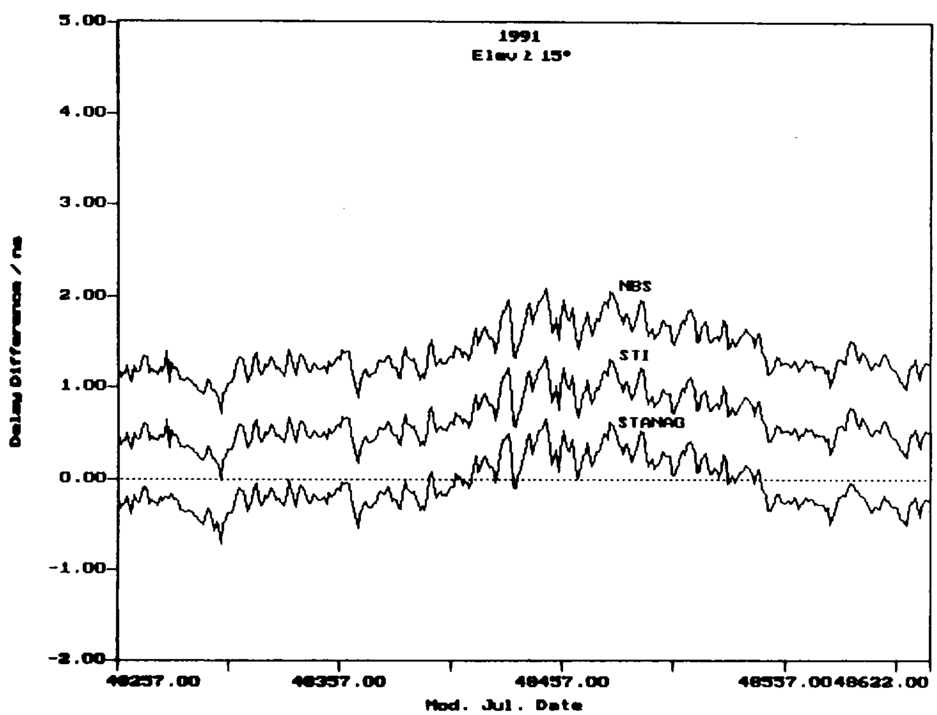

Fig. 21 Delay differences between the Hopfield model and the NBS, STI and STANAG models (one day mean).

QUESTIONS AND ANSWERS

Tony Liu, The Aerospace Corporation: I have a question as to whether you have considered using water vapor radiometers in your analysis. If you have, what success or problems have you encountered?

Dieter Kirchner: No, and the reason is very simple. The cost for a water vapor radiometer is several times the cost of a GPS receiver. And this would cause a problem for the general use. Of course for evaluation, it would be of interest. But we only compared models with each other and not models with *in situ* measurements.

Pat Romanowski, Allen Osborne Associates: I just have a question as to the distribution that you showed when you were comparing the different models and the differences. And I notice that they were skewed to one side. And I was wondering if you could comment on that. In most cases; I believe there was only one case that was an exception.

Dieter Kirchner: It is very easy to comment. This is a very general model which makes general assumptions for the refractivity; it uses a reference atmosphere. And the offset here is simply given by the figure with which you start at mean sea level. So it is simply which model do you use for your general model.

Pat Romanowski: Well, the point I want to make was the skewness of the data. For instance, it doesn't seem to be –

Dieter Kirchner: Okay, this is simply a yearly effect. This difference here between our reference model which takes into account the measured values at the surface and this model which takes global average and a time average cannot take into account the unit change of humidity and air pressure; and therefore, you see the different seasons; you see the winter, spring, summer and fall, and winter again.

Pat Romanowski: Are there actually two models represented in the graph?

Dieter Kirchner: In the graph is the difference between the Hopfield(?) Model and the NBS Model.

Pat Romanowski: And my question is why is the difference so terribly one sided?

Dieter Kirchner: Now I understand, I am sorry. You are thinking of this density distribution; and this is because most of the elevation angles are around here; and we have only a few elevations which are low elevations. And the differences are of course larger for the low elevations. And therefore most of the measurements are done here.

Pat Romanowski: The elevation of satellites? Okay, thank you.

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Accuracy Metrics for Judging Time Scale Algorithms

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Abstract

Time scales have been constructed in different ways to meet the many demands placed upon them for time accuracy, frequency accuracy, long-term stability and robustness. Usually, no single time scale is optimum for all purposes. In the context of the impending availability of high-accuracy intermittently-operated cesium fountains, we reconsider the question of evaluating the accuracy of time scales which use an algorithm to span interruptions of the primary standard.

We consider a broad class of calibration algorithms that can be evaluated and compared quantitatively for their accuracy in the presence of frequency drift and a full noise model (a mixture of white PM, flicker PM, white FM, flicker FM and random walk FM noise). We present the analytic techniques for computing the standard uncertainty for the full noise model and this class of calibration algorithms. The simplest algorithm is evaluated to find the average-frequency uncertainty arising from the noise of the cesium fountain's local oscillator and from the noise of a hydrogen maser transfer-standard. This algorithm and known noise sources are shown to permit interlaboratory frequency transfer with a standard uncertainty of less than 10^{-15} *for periods of 30-100 days.*

Introduction: The Need for Evaluating Algorithm Accuracy

For the near future, new primary (cesium fountain) frequency standards [1] [2] are likely to operate intermittently, rather than to operate continuously as primary clocks. Other new frequency standards of high potential accuracy, such as single-ion optical frequency standards coupled to a divider chain [3], are also likely to operate intermittently, at least initially. More reliable secondary standards of high stability (such as hydrogen masers) will be needed to span the gaps between periods of operation of the primary standard. To evaluate the accuracy of time scales that are to be calibrated with these new standards, one must address the question of how the random noise of the primary standard, of its local oscillator, and of the secondary standards all combine to influence the accuracy of the time scale or its average frequency. We want to examine how these noise sources affect the results of different interpolation and extrapolation algorithms, and to predict the accuracy that could be delivered, in the presence of mixed types of noise, to a local time scale or to TAI. Our main interest is in the frequency accuracy of the secondary time scale after calibration using some algorithm, but many of the same ideas are also applicable to time accuracy around an interval.

This is not a wholly new question. Intermittent operation of primary cesium frequency standards was universal two decades ago. Continuous operation of these standards as primary clocks, first at NRC [4] and then at PTB, waited until time laboratories had sufficiently evaluated their primary cesium frequency standards and had improved their mean time between failures. Standard techniques for analyzing frequency standards' stability and characterizing mixed types of noise were adopted and refined [5] [6] [7]. A body of very useful guidance was developed [8] for extrapolation in the presence of different (but unmixed) types of noise.

The main new element to be addressed is the quantitative estimation of accuracy for the mixed types of noise which have to be faced for our problem, and which has not been needed for previous standards where the dominant noise has usually been flicker frequency noise for primary and secondary standards. Simulations [9] could give the required guidance, but fully analytic techniques are preferable, and are developed here for a widely used class of algorithms.

Metrics

In choosing and in judging accuracy of the "optimum" algorithm for a purpose, a *metric* should be used for ordering possible algorithms and for guidance of minimal ambiguity. A priori, there are many possible metrics.

The class of metrics of interest to us quantifies the difference between any two functions of time, $A(t)$ and $B(t)$, sampled at a set of discrete times $\{t_i\}, i = 0..N$ during the time interval $[t_0, t_N]$. A metric expresses as a real number the difference between two vectors $\mathbf{A}$ and $\mathbf{B}$ in this N-dimensional vector space: $\|\mathbf{A} - \mathbf{B}\|$, and permits the unambiguous ordering of the quality of a fit from "good" to "bad". Any metric must meet the requirements that (1) $\|\mathbf{A}\| \geq 0$, (2) $\|a\mathbf{A}\| = |a|\|\mathbf{A}\|$, and (3) $\|\mathbf{A} + \mathbf{B}\| \leq \|\mathbf{A}\| + \|\mathbf{B}\|$. A very useful subclass of metrics is the class of "Holder norms", or L_p-norms ($p \geq 1$): $\|\mathbf{A} - \mathbf{B}\| = [\sum_{i=0}^{N} w_i \mid (A_i - B_i) \mid^p]^{(1/p)}$. The weights w_i are positive definite. If the difference between A_i and B_i is a random variable z_i distributed around Z_i, and is described by a probability distribution $e^{-[w_i^p|(z_i - Z_i)|^p]}$, then the minimizing the corresponding L_p-norm will give the maximum likelihood fit of $\mathbf{A}$ to $\mathbf{B}$. When fitting an approximation to a mathematical function, the norm ($\lim p_{\rightarrow\infty}$) is usually used, as the min-max norm, to minimize the maximum error between the function and its approximation on the interval. The absolute-value norm ($p = 1$) is occasionally used as an uncritical way of fitting to give minimum fitting weight to erroneous outliers while formally retaining a metric. When fitting experimental data, where normal (gaussian) distributions are common, p=2 is generally appropriate. It is appropriate for describing our expected distributions, and we will concentrate on this type of metric.

When measuring the quality of a fit to the measurements at the N times t_i, the value of the metric, divided by the degrees of freedom (N minus the number of fitting parameters), is often used. For a least-squares fit ($p = 2$) this measure of the quality of fit becomes the square root of the familiar reduced χ^2, and for unweighted least-squares fits ($w_i = 1$) it is the even more familiar root-mean-square residual. The residual is formally a metric in an N-dimensional vector space. As they are formally defined, weights can in principle be used to change the scale factor on each axis of the vector space, and even to project the metric into a vector subspace. Minimizing such a reduced metric rather than using the full maximum-likelihood weights can be advantageous: for example, the 10-day average frequency of a commercial cesium clock can be better determined from only the end points than by a least-squares fit to many points distributed across the 10-day interval [8].

Thus the quality of the fit at the experimental points is *not* all that is required. Rather, since the fitted function is used for interpolation to other values of t between t_i and t_{i+1}, or for extrapolation to values of t outside $[t_0, t_N]$, it is the accuracy at these points which can be more important. The accuracy of an algorithm is not uniform, but varies with t in a way which depends on the set of fitting points $\{t_i | i = 0..N\}$, the fitting algorithm and the random (and deterministic) noise. Considering this type of problem from the perspective of the residuals seems to require the magic of rotations into a different vector space. Interestingly, exactly this task can be done for the L_2 norm and a rather broad class of fitting functions, although the metric projection picture is unhelpful in determining the fitting accuracy at an arbitrary time.

The accuracy can be determined for any system experimentally by repeated cycles of measurements, doing repeated fitting of one particular pattern of time samples and by statistical analysis of residuals determined at unfitted points. Another approach would be computer simulation of this process - if a sufficiently good description of the noise model is available; or it might be done analytically. We show that a rather broad class of noise models and fitting procedures *can* be treated analytically, to obtain an accuracy estimate for the interpolation or extrapolation of many commonly used algorithms.

Modelling the Difference: Deterministic plus Random Noise

To describe the time-dependence $x(t)$ of the time difference between the primary frequency standard's time scale and the secondary time scale, we model it with $x_m(t)$, and explicitly include a random part $x_0(t)$ as well as a deterministic part. The deterministic part allows for a time offset, a frequency difference, and a drift rate of the frequency of the secondary time scale with respect to the primary standard.

$$x_m(t) = a^k + b^k t + \frac{1}{2} c^k t^2 + x_0(t). \tag{1}$$

The superscript k labels the uninterrupted intervals of operation of the primary standard. For each interval, a new value of a^k is required, and other values of b^k and c^k may (or may not) be used. We will examine the accuracy of a class of fitting functions $x_p(t)$, fit on the interval k, linear in the fitting parameters $\{d_l\}$, and including a broad class of basis functions $g_l(t)$:

$$x_p^k(t) = d_1^k + d_2^k t + d_3^k t^2 + \sum_{l=4}^{n} d_l^k g_l^k(t). \tag{2}$$

In the random noise part, $x_0(t)$, we include the "full" noise model that is usually covered in discussions of frequency standard stability [5]: a sum of five noise processes, each normally distributed about the mean (but with variances which depend on the time sampled in different ways) that have spectral densities of phase noise ($S_x(t)$) that are power laws which range from flat to increasingly divergent at low frequencies. Expressing the five terms in terms of the spectral density of the mean-square of the fluctuations in $\frac{dx_0(t)}{dt}$ (or $y_0(t)$) at a frequency f, $S_y(f)$, each noise term is described by an amplitude h_α which is taken to be independent of any time translations (stationarity and random phase approximations). The sum includes ($\alpha = 2$) white phase noise in x, ($\alpha = 1$) flicker ($1/f$) noise in x, ($\alpha = 0$) white frequency noise and random walk phase noise, ($\alpha = -1$) flicker frequency noise and ($\alpha = -2$) random walk frequency noise. The spectral density of the mean-square fluctuations in $x_0(t)$ is $S_x(t)$, and for this noise model

$$S_y(f) = \sum_{\alpha=-2}^{2} h_\alpha f^\alpha \qquad \text{and} \qquad S_x(f) = \sum_{\alpha=-2}^{2} \frac{h_\alpha f^{(\alpha-2)}}{(2\pi)^2}. \tag{3}$$

A Useful Tool

For many cases we might expect mean-square accuracy estimates to be calculable from the autocorrelation function $\langle x_0(t)x_0(t+\tau)\rangle$. Although it is not easy to use, the autocorrelation function of frequency-standard noise has been rather neglected in our view. It is divergent for four of our five types of noise unless a low-frequency cutoff is applied, and even then can challenge the accuracy and dynamic range capacities of classical computing. Analytic expressions for this autocorrelation function are given in the Appendix for each type of noise, and modern arbitrary-precision computer languages should routinely be able to cope directly with the autocorrelation function. In our analysis of the uncertainty associated with any useful time algorithm we expect no divergences to infinity, and so the combinations of the autocorrelation functions must have their divergent parts cancel, with the algorithm itself acting as low-frequency cutoff. To simplify the numerical evaluation of combinations of the autocorrelation, it can be useful to find an analytic expression for the general two-interval covariance of the random noise model, that is the covariance of the time-scale departure over the time interval $[t_1, t_2]$ with the time-scale departure over the time interval $[t_3, t_4]$:

$$S \;=\; \langle [x_0(t_2) - x_0(t_1)]\,[x_0(t_4) - x_0(t_3)]\rangle \;=\; \int_{t_1}^{t_2}\int_{t_3}^{t_4}\langle y_0(t')\,y_0(t'')\rangle\, dt''\, dt'. \tag{4}$$

This is just $(t_2 - t_1)(t_4 - t_3)$ times $\left\langle \bar{y}_{[t_1,t_2]}\bar{y}_{[t_3,t_4]}\right\rangle$, the general covariance of the average frequency, which is a generalization of the two-sample variance of the average frequency. The generalization includes the possibility of an overlap of the intervals (as well as the possibility of a "dead time" between the intervals), and incorporates the possibility of considering the frequency average over two time intervals of different duration. Just as for the two-sample variance of y, and for the autocorrelation function of $x(t)$, the covariance separates into the five terms of the noise model.

Analytic forms for the five terms of the autocorrelation function of $x(t)$ and for the five terms of the general cross-correlation of $\bar{y}$ are presented in as Equations 18 to 25 in the Appendix, derived with only the usual assumptions about high and low frequency limits to the noise bandwidth. Some comments are made on practical methods for computing values using these forms.

Algorithms for Accuracy Evaluation

For many, but not all, widely-used interpolation or extrapolation algorithms, it is possible to use the cross-correlation expressions and a knowledge of the noise to calculate the expected root-mean-square (i.e. $p = 2$) standard uncertainty [10] of the time or of the mean frequency extrapolated or interpolated by the algorithm. Based on the noise model (and a very large body of confirming experiment), the distributions expected for deviations from the fit are normal, and so the root-mean-square deviation calculated for the standard uncertainty is rigorously correct, and can be used in the conventional way for predicting confidence intervals from normal distributions [10]. The fitting process yields parameters for a parameterized functional form of $x_p(t)$, which may be of the general form (around the k^{th} interval of continuous operation) given in Equation 2. Nonlinear fitting parameters are not considered.

The algorithm should satisfy two criteria. *Firstly*, the algorithm should be unbiased by the deterministic part of the noise model: any change in a deterministic parameter (a^k, b^k or c^k in Equation 1) should be taken up by the algorithm and not bias the final result. Note that it is the final deviation which is to be unbiased, and some apparently biased forms for $x_p(t)$ may still be used in ways that are unbiased. In addition to being patently desirable, this condition also removes any need for considering cross-correlations between the deterministic and random noise parts of $x_m(t)$. *Secondly*, the coefficients d_l^k must depend linearly on sums over differences in $x(t)$. This includes fitting functions that are constrained to go through one point: least squares fits of polynomials of general order, and other functions with linear coefficients. It includes constrained weighted least-squares fits, as long as the weights do not themselves depend on the values of $x^k(t_i)$ or the variances on the k^{th} fitting interval. With this condition we ensure that we do not have to calculate any higher-order correlations than the general covariances evaluated in the Appendix.

What algorithms does this exclude? The first condition would not seem to exclude any serious contenders for fitting methods and fitting functions: if one is taking care to evaluate accuracy, then presumably one also values an unbiased fitting form. The second criterion admits many algorithms easily. However, to analyze rigorously the accuracy of a Kalman filter, where fitting weights depend on past variances, appears to require a study of higher-order autocorrelations of the random noise, at least to the level of identifying the magnitude of these corrections. We therefore exclude this important class of algorithms from our present considerations.

Many extrapolation and interpolation algorithms that are useful for time-scale purposes are very simple: for example, constrained to go through the last experimental point [8], or constrained to go through both the first and last points on an interval. However, it is instructive to consider first the most general least-squares fitting case for N points on a single calibrating interval.

Weighted Fits of General Functions with Linear Coefficients

The least-squares fit of the n parameters d_l of a function of the form of Equation 2, to $N + 1$ points $x(t_i)$, each point being taken with a weight w_i, is found by taking the partial derivative of the weighted L_2 norm with respect to its n coefficients. The resulting n simultaneous equations in n unknowns are of the form $\mathbf{G}\vec{d'} = \vec{s'}$, where $\mathbf{G}$ is an $n \times n$ matrix with elements $G_{qr} = \sum_{i=0}^{N} w_i^2 g_q(t_i) g_r(t_i)$, and $\vec{s'}$ is an n-dimensional vector with elements $s'_r = \sum_{i=0}^{N} w_i^2 x_m(t_i) g_r(t_i)$. Here $x_m(t_i)$ is used to model $x(t_i)$, exactly as one might do in a numerical simulation. Simple inspection shows that if $g_1(t) = 1, g_2(t) = t$ and $g_3(t) = t^2$, and $s_r = \sum_{i=0}^{N} w_i^2 x_0(t_i) g_r(t_i)$, then $\mathbf{G}\vec{d} = \vec{s}$, where $\vec{d}$ is the vector of least-squares coefficients for the n functions, and $d_1 = d'_1 - a, d_2 = d'_2 - b$, $d_3 = d'_3 - c/2$ and $d_r = d'_r$ for $r \geq 4$. Thus for any set of weights, the fit exactly absorbs the deterministic part of the model function $x_m(t)$ and we have only to deal with the function $x_0(t)$. We can replace any difference between $x_m(t)$ and $x_p(t)$ (fit to the $x_m(t_i)$) with the difference between $x_0(t)$ and the $x_p(t)$ (fit to the $x_0(t_i)$). The fitting coefficients vector $\vec{d} = \mathbf{G}^{-1}\vec{s}$. The form of this equation is instantly quite revealing, for it shows that the least squares coefficients d_r only involve simple sums over the $x_0(t_i)$'s.

We will study all the effects of algorithm at t, reacting to the noise through the fitting procedure, by comparing $x_0(t)$ to the function fitted to the random part of the noise: $\vec{d} \cdot \vec{g}(t)$, where $\vec{g}(t)$ is the n-dimensional vector of the basis functions evaluated at t. This fitted function can in turn be transformed into a simple weighted sum over the $N+1$ of the $x_0(t_i)$'s: $\vec{d} \cdot \vec{g}(t) = \sum_{i=0}^{N} D_i(t) x_0(t_i)$, and $D_i(t) = w_i^2 \sum_{q=1}^{n} \sum_{r=1}^{n} (\mathbf{G}^{-1})_{qr} g_r(t_i) g_q(t)$.

The fitting algorithm and the noise model contribute a standard uncertainty [10] u_x in the least-squares fitted time which is $\langle [x_m(t) - x_p(t)]^2 \rangle$. This is the appropriate metric for judging the quality of the fit at t (relative to the set of $N+1$ specific fitting times $\{t_i\}$).

$$\begin{aligned} \left\langle [x_m(t) - x_p(t)]^2 \right\rangle &= \left\langle \left[x_m(t) - \vec{d'} \cdot \vec{g}(t) \right]^2 \right\rangle &= \left\langle \left[x_0(t) - \vec{d} \cdot \vec{g}(t) \right]^2 \right\rangle \\ &= \left\langle \left[x_0(t) - \textstyle\sum_{i=0}^{N} D_i x_0(t_i) \right]^2 \right\rangle &= \textstyle\sum_{i=-1}^{N} \sum_{j=-1}^{N} D_i D_j \left\langle x_0(t_i) x_0(t_j) \right\rangle , \end{aligned} \tag{5}$$

when t is labelled as t_{-1} and $D_{-1} = 1$ in the last equation. The sum over the $(N+2)^2$ autocorrelations simplifies since the autocorrelation depends on $\mid t_i - t_j \mid$. When the data are equally spaced, "only" $N+2$ different autocorrelations of $x_0(t)$ must be evaluated for a general value of t. The autocorrelations for our noise model can be evaluated using the expressions in the Appendix for $\mathcal{R}(\tau)$, if calculations can be done with sufficient numerical precision.

Constrained Least-Squares Fits

Fits constrained to go through one or more points can be considered as special cases in the above analysis through appropriate choices of weights. However, there is an interesting computational simplification which warrants explicit derivation: we can replace computations of the autocorrelation function of $x(t)$ with the simpler to compute S of Equation 13. Consider using a weighted least-squares fit constrained to go through one of the $x_m(t_i)$'s, for $i = i_c$ in general - although this might often be either end point: $i = 0$ or $i = N$ since we consider $\{t_i\}$ as being ordered so that $t_j < t_{j+1}$. For a constrained fit, $x_m(t_{i_c}) = \vec{d'_c} \cdot \vec{g}(t_{i_c})$, determined by substituting $\vec{g}(t_{i_c})$ for the first row of $\mathbf{G}$ to obtain $\mathbf{G}_c$, and by substituting $x_m(t_{i_c})$ for the first element of $\vec{s'}$ to obtain $\vec{s'_c}$. The weight w_{i_c} is assigned the value 0. The constrained fit is also unbiased by the deterministic part of the noise model, satisfying the condition so that again we only have to consider the behaviour of $x_0(t)$ when evaluating the accuracy of the constrained fit. The fitted function is $\vec{d}_c \cdot \vec{g}(t)$, where $\vec{d}_c = \mathbf{G}_c^{-1}\vec{s}_c$ and $\vec{s}_c$ is just $\vec{s}_c'$ with $x_0(t)$ substituting for $x_m(t)$. For this constrained fit we can use the equality of x_m and x_p at t_{i_c}, or the equality $x_0(t_{i_c}) = 0$:

$$\begin{aligned}
&\left\langle [x_m(t) - x_p(t)]^2 \right\rangle = \left\langle \left[\{x_m(t) - x_m(t_{i_c})\} - \left\{\vec{d}_c \cdot (\vec{g}(t) - \vec{g}(t_{i_c})\right\}\right]^2 \right\rangle = \\
&\Bigg\langle \Big[\{x_0(t) - x_0(t_{i_c})\} \\
&- \left\{\textstyle\sum_{q=1}^n \{g_q(t) - g_q(t_{i_c})\} \left\{(\mathbf{G}_c^{-1})_{q1}\, x_0(t_{i_c}) + \sum_{r=2}^n (\mathbf{G}_c^{-1})_{qr} \sum_{i=0}^N w_i^2 g_r(t_i)\, x_0(t_i)\right\}\right\}\Big]^2 \Bigg\rangle = \\
&\left\langle \left[\{x_0(t) - x_0(t_{i_c})\} - \left\{\textstyle\sum_{i=0}^N (D_c)_i x_0(t_i)\right\}\right]^2 \right\rangle = \\
&\left\langle \left[\{x_0(t) - x_0(t_{i_c})\} - \left\{\textstyle\sum_{i=0}^N (D_c)_i \left\{\sum_{j=1}^i (x_0(t_j) - x_0(t_{j-1})) - \sum_{j=1}^{i_c} (x_0(t_j) - x_0(t_{j-1}))\right\}\right\}\right]^2 \right\rangle \\
&= \left\langle \left[\{x_0(t) - x_0(t_{i_c})\} - \left\{\textstyle\sum_{j=1}^N (\hat{D}_c)_j \{x_0(t_j) - x_0(t_{j-1})\}\right\}\right]^2 \right\rangle \\
&= \left\langle \left[\left\{\textstyle\sum_{j=0}^N (\hat{D}_c)_j (x_0(t_j) - x_0(t_{j-1}))\right\}\right]^2 \right\rangle,
\end{aligned} \tag{6}$$

where $(\hat{D}_c)_j$ is just the reordered sum defined above for $j = 1$ to N, with $(\hat{D}_c)_0$ defined as 1.

Thus the constrained fit's standard uncertainty in time can be calculated more easily at a general time t, using only our expressions in the Appendix for $\mathcal{I}(\tau)$ rather than for $\mathcal{R}_x(\tau)$ to evaluate the standard uncertainty in time, which can done conveniently with 64-bit floating point calculations. Note that this is also the mean square of the time interval error over the time interval $[t_{i_c}, t]$.

Standard Uncertainty in Average Frequency

In a similar way we can calculate our model's estimate for the unconstrained least-squares fit's standard uncertainty [10] of the average frequency over an interval $[t, t+\tau]$, $u_y(t,\tau)$. We can calculate $u_y^2(t,\tau) = \left\langle [(x_m(t+\tau) - x_m(t)) - (x_p(t+\tau) - x_p(t))]^2 \right\rangle / \tau^2$ in terms of expressions using only the function $\mathcal{I}(T)$. For convenience, we will define $t_{-1} = t$ and $t_{N+1} = t+\tau$, neither restricting the value of t to be less than t_0 nor restricting the value of $t+\tau$ to be greater than t_N.

$$\begin{aligned}
u_y^2(\tau)\tau^2 &= \left\langle [(x_m(t+\tau) - x_m(t)) - (x_p(t+\tau) - x_p(t))]^2 \right\rangle = \\
&\left\langle \left[\{x_0(t+\tau) - x_0(t)\} - \left\{\vec{d} \cdot (\vec{g}(t+\tau) - \vec{g}(t))\right\}\right]^2 \right\rangle = \\
&\left\langle \left[\textstyle\sum_{j=1}^{N+1} \{x_0(t_j) - x_0(t_{j-1})\} + \sum_{j=1}^N \check{D}_j \; \{x_0(t_j) - x_0(t_{j-1})\}\right]^2 \right\rangle = \\
&\left\langle \left[\textstyle\sum_{j=0}^{N+1} \tilde{D}_j \; \{x_0(t_j) - x_0(t_{j-1})\}\right]^2 \right\rangle
\end{aligned} \tag{7}$$

where $\check{D}_j = \sum_{i=j}^N w_i^2 \sum_{q=1}^n \sum_{r=1}^n (\mathbf{G}^{-1})_{qr} g_r(t_i)(g_q(t+\tau) - g_q(t))$ and $\tilde{D}_j = [\check{D}_j + 1]$ for $j = 0$ to N, and where both $\tilde{D}_0$ and $\tilde{D}_{N+1}$ are equal 1. Again the uncertainty can be calculated conveniently with 64-bit floating point calculations from the expressions in the Appendix for $\mathcal{I}(\tau)$ rather than the more awkward $\mathcal{R}_x(\tau)$.

Multiple Calibration Runs

The time interval error that accumulates on an interval spanning m calibration runs is just the sum of time interval errors (the difference between the evolution of x and the evolution of the calibrated extrapolation x_p) on the interval $[t_{l^k}, t_{r^k}]$ around the k^{th} calibration run. The calibrated time scale is continuous, so that if the k^{th} fit yields to the next fit $(k+1)$ at a time $t_{r^k} = t_{l^{k+1}}$, then $\vec{d}^k \cdot \vec{g}^k(t_{r^k}) = \vec{d}^{k+1} \cdot \vec{g}^{k+1}(t_{l^{k+1}})$. Thus, across the m runs, the time interval error of the algorithm reacting to our noise model is

$$\sum_{k=1}^{m} E^k = \sum_{k=1}^{m} [x_0(t_{r^k}) - x_0(t_{l^k})] - \left[x_p^k(t_{r^k}) - x_p^k(t_{l^k})\right]. \tag{8}$$

To show the general form, consider the set of $\{t_\eta\}$, with the index η running in turn over the start time, the fitting times and the stop time for each interval, from 1 to M - the grand total of points (with N^k measurable subintervals and two extrapolated subintervals in the k^{th} interval). To analyze a fit on the k^{th} interval that extracts information from other intervals, we consider the k^{th} fit to be from t_{L^k} to t_{R^k}, with zero weight at the unmeasured times t_η where $\eta = l^j$ or r^j, $j = 1 \ldots m$. Equation 8 can then be combined over any overlap of the fits into a global weighted sum over the differences $[x_0(t_\eta) - x_0(t_{\eta-1})]$, weighted by $\mathcal{D}_\eta$ which sums over the fits which have used the η^{th} time interval. The mean square time uncertainty in the time scale algorithm over the total time interval $T = \sum_{\eta=1}^{M}[t_\eta - t_{\eta-1}]$ is $u_x^2(T)$, the mean square of the sum over E_i. Since for any algorithm of the class

$$\left\langle \left(\sum_{\eta=1}^{M} E_\eta \right)^2 \right\rangle = \left\langle \sum_{\eta=1}^{M} \sum_{\zeta=1}^{M} E_\eta E_\zeta \right\rangle = \sum_{\eta=1}^{M} \sum_{\zeta=1}^{M} \mathcal{D}_\eta \mathcal{D}_\zeta \left\langle [x_0(t_\eta) - x_0(t_{\eta-1})] [x_0(t_\zeta) - x_0(t_{\zeta-1})] \right\rangle. \tag{9}$$

The full evaluation of all terms of this $M \times M$ cross-correlation matrix, $\mathcal{E}$ (where $\mathcal{E}_{ij} = E_i E_j$) is possible for any particular set of calibration runs. With M^2 terms to evaluate, an efficient method for computing $\mathcal{S}$ is highly desirable. The method outlined in the Appendix will generally suffice. Fortunately, there can be very significant simplifications: $\mathcal{E}$ is symmetric, the main diagonal contributes most to the sum, the block-diagonal terms from the individual fits are the next most important parts (together these would contribute the quadrature sum of the standard time uncertainty u_x contributed across each individual interval, but neglecting interval-to-interval correlations), and generally the matrix elements far from the diagonal will not contribute significantly. Any regularity in the fitting times will also reduce the computational burden.

Examples

We will apply the above methods to one of the simplest algorithms that might be used: a linear fit constrained through two points, as shown in Figure 1. Here the mean square of the standard uncertainty in time is [11]

$$u_x^2 = 2\left[(1+\frac{\tau}{t_a})\mathcal{I}(\tau) + \frac{\tau}{t_a}(1+\frac{\tau}{t_a})\mathcal{I}(t_a) - \frac{\tau}{t_a}\mathcal{I}(t_a+\tau)\right] \tag{10}$$

This expression can be separated into the standard uncertainty u_x for each noise type, as illustrated in Figure 2. In this figure, u_x for each noise type has been normalized to equal 1 at the midpoint of the calibration interval t_a. The upper frequency cutoff ω is $100/t_a$, and the lower cutoff $\epsilon = 10^{-5}$ radians/second. To use a figure like this for a mixed noise model, recall that the standard uncertainties of the different noise types must be added in quadrature, with appropriate weights.

The above example shows how an rms residual at a time offset τ can be calculated, and that even in the simplest case it varies with position in different ways for the different types of noise. Using $\mathcal{I}(\tau)$ it is calculable in a perfectly straightforward manner.

Figure 3 shows the time interval error that develops from extrapolation to both earlier and later times than the calibration interval: from t_l earlier than the first point and to t_r later than the second fitted point. The standard uncertainty in frequency, $u_y(\tau)$, on this extended interval of τ is [14]

$$u_y^2 = \frac{2}{\tau^2}\left\{\mathcal{I}(\tau) + \left(\frac{\tau}{t_a}\right)^2\mathcal{I}(t_a) + \frac{\tau}{t_a}\mathcal{I}(t_r) - \frac{\tau}{t_a}\mathcal{I}(t_l+t_a) + \frac{\tau}{t_a}\mathcal{I}(t_l) - \frac{\tau}{t_a}\mathcal{I}(t_a+t_r)\right\} \tag{11}$$

As an interesting application of this simple algorithm, we can show how the local oscillator limit [12] might be circumvented for a pulsed cesium fountain. Consider the evaluation of different types of local oscillator for a pulsed cesium fountain that employs this algorithm and hyperfine phase differences [11] to span 0.01 s dead times between 0.99 s Ramsey times. The atomic polarization is measured for each pulse of atoms, and attributed (after calibration) to the discrepancy of the microwave phase compared to the primary hyperfine phase of the ensemble of cesium atoms. Thus the frequency of the local oscillator is known across the 0.99 s interval, with an uncertainty that may be limited by (among other things) atom shot noise in the ensemble. The average frequency from the preceeding and following Ramsey time is used to estimate the frequency of the local oscillator across the 0.01 s dead time between Ramsey pulses. If there is but a single ensemble "in flight" through the cesium fountain at any given time, then the simplest algorithm is the only one worth considering.

To analyze this system, we choose a symmetric interval centred on t_a, the active time, and $\mathbf{t}_l = \mathbf{t}_r = t_d/2$. Using the calibrated frequency from a single active interval for the two adjacent dead time half-intervals is equivalent to using the average frequency from two adjacent active intervals across any dead time. In this way we might hope to minimize the cross-correlations that need to be evaluated between neighbouring active times. We can use Equation 11 for the first estimate, but we should verify the size of the correction from neighbouring intervals. With a cycle time $t_a + t_d = T$, and N equal-length cycles, Equation 9 becomes

$$\begin{aligned}\mathcal{E}_{j+l,j} = &\mathcal{I}(lT+T) + \mathcal{I}(lT-T) - 2(1+[\tfrac{T}{t_a}]^2)\mathcal{I}(lT) + [\tfrac{T}{t_a}]^2\left\{\mathcal{I}(lT+t_a)+\mathcal{I}(lT-t_a)\right\} \\ &-2\tfrac{T}{t_a}\left\{\mathcal{I}\left(lT+\tfrac{1}{2}[T+t_a]\right)+\mathcal{I}\left(lT-\tfrac{1}{2}[T+t_a]\right)-\mathcal{I}\left(lT+\tfrac{1}{2}[T-t_a]\right)-\mathcal{I}\left(lT-\tfrac{1}{2}[T-t_a]\right)\right\}.\end{aligned} \tag{12}$$

Fortunately, for $l > 1$, the off-diagonal corrections are negligible. Depending on α, the adjoining term, $l = 1$, gives corrections to the diagonal terms of either sign and of up to 50% in magnitude. Thus correlations are significant in this case even though we tried apply our algorithm in a way to minimize the correlations. Figure 4 shows the standard uncertainty in frequency due to the local oscillator noise for three local oscillators. The curvature reflects some of the effects of correlations. The Allan deviation predicted [12] for the same three local oscillators in a conventional frequency servo is also shown (with a modulation frequency of 0.5 Hz). Clearly this hyperfine phase measurement plus post-processing algorithm is an interesting possibility as a replacement of the conventional servo, at least in some applications. It is crucial to have full confidence in the analysis of the complete effects of the interaction of the noise and the algorithm: our analysis is complete within the constraints of the noise model.

In the initial period of operation of a cesium fountain frequency standard, after having been evaluated as a standard, there might be a hour per day devoted to calibrating a time laboratory's secondary standards. In the case of NRC, this would mean the use of our new hydrogen masers [14], [15]. A crucial question in designing a cesium-fountain frequency-standard project is to choose the desired level of accuracy which might be used, either transferred to another laboratory or used to compare the frequency of two configurations of the cesium fountain which cannot coexist. The answer to this question can be obtained by our method for secondary frequency standards with well understood noise. As always, common mode noise between similar frequency standards is difficult to rule out - but the intent of these considerations is to establish a goal for an initial working standard that is not overbuilt, considering available frequency transfer characteristics. We present the analysis of a possible frequency-transfer budget at NRC.

The main question is the frequency transfer capabilities of our hydrogen masers. The Allan deviation of our two new masers has been measured with respect to each other. Attributing the noise equally to the two masers, we can calculate the best case for frequency transfer from one hour out to a day or so [14]. We again use the symmetric linear extrapolation from the end points. In this example, additional information will be available during the interval, but the "best case" for our noise types comes from using the end points [8]. By using the symmetric extrapolation, the frequency transfer will not be biased by any constant drift of the maser frequency [13].

Figure 5 shows an estimate for the standard uncertainty in frequency due to a hypothetical cesium fountain [11],[15], and the modelled Allan deviation one of the new NRC hydrogen masers [14]. The random-walk FM rise at large times is a somewhat pessimistic (or realistic ?) guess - the masers have not operated for a long enough time to properly evaluate their long-term stability $\sigma_y(\tau > 30 \text{ days})$. Also shown is the calculated standard uncertainty of the average frequency of the fountain-plus-maser for the extrapolated frequency on an interval τ for a calibration run of 3000 s.

Using Equation 12, we can again evaluate cross-correlations for a regular series of runs (daily in this example). However, in this example there are no corrections larger than 1% to the $N^{-1/2}$ trend line. At each end of τ we include a two-way time transfer uncertainty of 2 ns (1 - σ per transfer) as a realistic estimate of the state-of-the art (and including 0.2 ns as a worthwhile objective). The daily recalibration trend line gives the noise limit to the standard uncertainty for cesium fountain frequency transfer to another laboratory. It is encouraging in that the noise limit is well below 10^{-15} for an ambitious but realistic cesium fountain calibration schedule for the hydrogen masers. The estimated standard uncertainties for the as-transferred average frequency may facilitate the acceptance of the new standards, for example for the judging or steering of TAI. The predicted level of residual fluctuations will need to be experimentally verified to be fully confident that some significant common-mode noise source (random or deterministic) has not been missed, but even here having a baseline prediction will be very helpful in planning the evaluation level which is appropriate for any given frequency-transfer program.

Conclusions

We have developed, calculated and applied some useful metrics for judging the accuracy of algorithms extrapolating time and average frequency in the presence of noise that can be represented by a rather general noise model which includes all common types of power-law random noise as well as deterministic noise. For many algorithms the (rms) standard uncertainty in time, $u_x(t)$, and the (rms) standard uncertainty in average frequency across τ, $u_y(t,\tau)$, both can be calculated in terms of the noise model power law coefficients. This significantly enhances the attractiveness of standard uncertainties in time and frequency metrology where techniques for measuring the coefficients are widely used. The metrics can be used for guidance in the choice of algorithms and procedures (how often to recalibrate, and for how long), but a larger role can be played by these two "metrics", for rigorously judging the noise floor of different hardware and potential hardware used in novel ways.

The calculated standard uncertainty in time, $u_x(t)$, might also play a very useful role in the calculation of a reduced χ^2 for a set of experimental data for which one wishes to judge the adequacy of the fit and noise model. Conventionally, $\chi^2 = \frac{1}{N-n}\sum_{i=1}^{N}[x(t_i) - x_p(t_i)]^2/\{2[u_x(t_i)]^2\}$, where $N - n$ is used for the degrees of freedom: the number of (independent) data points minus the number of (independent) fitting parameters. Since we would be able to compute the cross-correlations between data points, it should also be possible to determine a better estimate of the degrees of freedom for the fit.

The procedures outlined here could be automated. Standard uncertainties could be used routinely in time and frequency metrology, for many common fits to a set of data points, in the presence of a general noise model. In all fields of metrology, where the use of standard uncertainties is now recommended [10], the very valuable techniques (such as the use of the modified Allan deviation) developed for analysing power law noise of frequency standards could be applied in other fields to give rigorous results for the standard way of reporting uncertainties.

Appendix: Autocorrelation Functions and General Interval Covariance for Power-law Noise Spectra

Consider two time intervals that may (or may not) overlap, and are not necessarily of equal duration. The general interval covariance of the random part of the time scale difference accumulated on the time interval $[t_1, t_2]$ with that accumulated on $[t_3, t_4]$ is

$$\begin{aligned}\mathcal{S} &= \langle [x_0(t_2) - x_0(t_1)]\,[x_0(t_4) - x_0(t_3)] \rangle = \langle x_0(t_2)x_0(t_4)\rangle + \langle x_0(t_1)x_0(t_3)\rangle \\ &\quad - \langle x_0(t_2)x_0(t_3)\rangle - \langle x_0(t_1)x_0(t_4)\rangle .\end{aligned} \tag{13}$$

where $\langle x_0(t)x_0(t-\tau)\rangle$ is the autocorrelation function: $\mathcal{R}_x(\tau) = \int_0^\infty S_x(f)\cos 2\pi f\tau\, df$. We use the usual [5] upper-frequency limit $f_u = \omega/(2\pi)$ and low-frequency limit $f_l = \epsilon/(2\pi)$. The sharp upper cutoff is an artifice, although one which could be implemented with a digital filter applied to the output of a phase comparator. The lower frequency needs to be low enough so that it does not perturb the low-frequency rolloff supplied by the fitting function. A too-low value for ϵ will exacerbate the numerical precision problems in calculating and using $\mathcal{R}_x(t)$, which diverges as $\epsilon \to 0$. For the usual noise model of $S_x(f) = \sum_{\alpha=-2}^{2} \frac{h_\alpha f^{(\alpha-2)}}{(2\pi)^2}$, we have

$$\mathcal{R}_x(\tau) = \sum_{\alpha=-2}^{2} \frac{h_\alpha \tau^{(1-\alpha)}}{(2\pi)^{\alpha+1}} \int_{\epsilon\tau}^{\omega\tau} u^{\alpha-2}\cos u\, du = \sum_{\alpha=-2}^{2} R_\alpha(\tau). \tag{14}$$

It is possible to express $\mathcal{S}$ as a sum over the functions $R_\alpha(\tau)$'s, or as a sum over functions of similar form $I_\alpha(\tau)$'s that are less divergent as $\epsilon \to 0$:

$$\begin{aligned}\mathcal{S} &= -[\mathcal{R}_x(t_4 - t_1) + \mathcal{R}_x(t_3 - t_2) - \mathcal{R}_x(t_4 - t_2) - \mathcal{R}_x(t_3 - t_1)] \\ &= \mathcal{I}(t_4 - t_1) + \mathcal{I}(t_3 - t_2) - \mathcal{I}(t_4 - t_2) - \mathcal{I}(t_3 - t_1),\end{aligned} \tag{15}$$

where $\mathcal{I}(\tau)$ is

$$\mathcal{I}(\tau) = \sum_{\alpha=-2}^{2} \frac{h_\alpha \tau^{(1-\alpha)}}{(2\pi)^{\alpha+1}} \int_{\epsilon\tau}^{\omega\tau} u^{\alpha-2}\{1 - \cos u\}\, du = \sum_{\alpha=-2}^{2} I_\alpha(\tau). \tag{16}$$

With the help of mathematical tables or a symbolic algebra program such as Maple V, the integrals for $R_\alpha(\tau)$ and $I_\alpha(\tau)$ can be done analytically for our values of α.

$$R_2(\tau) = \frac{h_2}{(2\pi)^3}\omega \left\{ \frac{\sin(\omega\tau)}{\omega\tau} \right\} \tag{17}$$

$$I_2(\tau) = \frac{h_2}{(2\pi)^3}\omega \left\{ 1 - \frac{\sin(\omega\tau)}{\omega\tau} \right\} \tag{18}$$

are the integrals for white phase noise ($\alpha = 2$). I_2 is proportional to the high frequency cutoff ω, as is the Allan deviation.

$$R_1(\tau) = \frac{h_1}{(2\pi)^2}\left\{Ci(\omega\tau) - Ci(\epsilon\tau)\right\} \tag{19}$$

$$I_1(\tau) = \frac{h_1}{(2\pi)^2}\left\{\gamma + \ln(\omega\tau) - Ci(\omega\tau)\right\} \tag{20}$$

are the integrals for flicker phase noise ($\alpha = 1$). $Ci(x)$ is the Cosine Integral function, which can be easily approximated by using numerical approximation as in Abramovitz [16] for arguments greater than 1, or by direct numerical integration of the expression between brackets (see end of this Appendix). The time interval τ tempers the logarithmic dependence on the frequency cutoff.

$$R_0(\tau) = -\frac{h_0}{2\pi}\tau\left\{\frac{\cos(\omega\tau)}{\omega\tau} + Si(\omega\tau) - \frac{\cos(\epsilon\tau)}{\epsilon\tau} - Si(\epsilon\tau)\right\} \tag{21}$$

$$I_0(\tau) = \frac{h_0}{2\pi}\tau\left\{\frac{\cos(\omega\tau) - 1}{\omega\tau} + Si(\omega\tau)\right\} \tag{22}$$

are the integrals for white frequency noise ($\alpha = 0$). $Si(x)$ is the Sine Integral function, which can be treated in the same way as the Cosine Integral for arguments greater than 1, or by direct numerical integration of the definition of $Si(x)$ for small arguments. This term depends linearly only on the time interval τ, and not on value of the high frequency cutoff.

$$R_{-1}(\tau) = h_{-1}\frac{\tau^2}{2}\left[\left\{\frac{-\cos(\omega\tau)}{(\omega\tau)^2} + \frac{\sin(\omega\tau)}{\omega\tau} - Ci(\omega\tau)\right\} - \left\{\frac{-\cos(\epsilon\tau)}{(\epsilon\tau)^2} + \frac{\sin(\epsilon\tau)}{\epsilon\tau} - Ci(\epsilon\tau)\right\}\right] \tag{23}$$

$$I_{-1}(\tau) = h_{-1}\frac{\tau^2}{2}\left[1.5 - \gamma - \ln(\epsilon\tau) - \left\{\frac{1 - \cos(\omega\tau)}{(\omega\tau)^2} + \frac{\sin(\omega\tau)}{\omega\tau} - Ci(\omega\tau)\right\}\right] \tag{24}$$

are the integrals for flicker frequency noise ($\alpha = -1$), where γ is 0.57721..., Euler's constant. The logarithmic term looks as if it will diverge to infinity for a low frequency cutoff as $\epsilon \to 0$, but in combinations like in S normally the combination of terms using $I_{-1}(\tau)$ is such that the terms multiplying $1.5 - \gamma$ will cancel out, as will the logarithmic divergence with ϵ, leaving a term depending only on the square of the time interval and a geometric structure factor that depends on the logarithm of ratios of the time intervals concerned: for the Allan deviation this is ln(2) as expected, and for S it is $\ln\left(\frac{(t_4-t_1)(t_3-t_2)}{(t_3-t_1)(t_4-t_2)}\right)$.

$$\begin{aligned} R_{-2}(\tau) &= \pi h_{-2}\tfrac{\tau^3}{3}\left[\left\{\tfrac{\sin(\omega\tau)}{(\omega\tau)^2} + \tfrac{\cos(\omega\tau)}{\omega\tau} + Si(\omega\tau) - 2\tfrac{\cos(\omega\tau)}{(\omega\tau)^3}\right\}\right. \\ &- \left.\left\{\tfrac{\sin(\epsilon\tau)}{(\epsilon\tau)^2} + \tfrac{\cos(\epsilon\tau)}{\epsilon\tau} + Si(\epsilon\tau) - 2\tfrac{\cos(\epsilon\tau)}{(\epsilon\tau)^3}\right\}\right] \end{aligned} \tag{25}$$

$$I_{-2}(\tau) = \pi h_{-2}\frac{\tau^3}{3}\left[\frac{3}{\epsilon\tau} - \left\{2\frac{1 - \cos(\omega\tau)}{(\omega\tau)^3} + \frac{\sin(\omega\tau)}{(\omega\tau)^2} + \frac{\cos(\omega\tau)}{\omega\tau} + Si(\omega\tau)\right\}\right] \tag{26}$$

are the integrals for random walk frequency noise ($\alpha = -2$) for a low frequency cutoff $\epsilon \to 0$. As expected, this expression will diverge to infinity in the limit $\epsilon \to 0$, but the combination of terms will cancel that divergence in many of our accuracy prediction problems, since our fitting procedures will act as an effective low-frequency rolloff for the residuals of the fit. In practice, the low frequency cutoff will depend on the observation (active) time and is always some value greater than zero. In our analysis of uncertainty, we should use the same value of ϵ that was used in determining h_{-2} from measured Allan variances of the standard in question.

Using standard expansions for the Sine and Cosine Integrals [16], it is easy to compute with enough accuracy the values needed for arguments greater than 1. For arguments smaller than one, numerical integration can be done easily for $Si(x)$. For $Ci(x)$, the following transformation is helpful, since the second integral is easy to do numerically for small arguments:

$$Ci(x) = \gamma + \ln x - \int_0^x \frac{1-\cos u}{u} du = \gamma + \ln x - \int_0^x \frac{\sin^2 \frac{u}{2}}{u} du. \tag{27}$$

In debugging any code written to evaluate $\mathcal{R}_x(\tau)$ or $\mathcal{I}(\tau)$, it is worthwhile noting that the two-sample variance or Allan variance is

$$\sigma_y^2(\tau) = \frac{-4\mathcal{R}_x(\tau)+3\mathcal{R}_x(0)+\mathcal{R}_x(2\tau)}{\tau^2} = \frac{4\mathcal{I}(\tau)-\mathcal{I}(2\tau)}{\tau^2}, \text{ where} \tag{28}$$

$$\mathcal{R}_x(0) = \frac{h_2}{(2\pi)^3}(\omega - \epsilon) + \frac{h_1}{(2\pi)^2}\ln\frac{\omega}{\epsilon} + \frac{h_0}{2\pi}(\epsilon^{-1} - \omega^{-1}) + \frac{h_{-1}}{2}(\epsilon^{-2} - \omega^{-2}) + \frac{h_{-2}2\pi}{3}(\epsilon^{-3} - \omega^{-3}),$$

which should reflect the traditional expressions [5] when the typographical errors have been corrected (their equations 101 through 105 have had the term $\gamma + \ln(2\pi f_h \tau)$, where γ is Euler's constant, incorrectly typeset as $2 + \ln(2\pi f_h \tau)$). Some approximations used to obtain their traditional expressions have not been made. The expressions given above for $I_\alpha(\tau)$ are correct for all α even for $\omega_c \tau < 1$, so that differences are to be expected if calculations are made for τ near to or less than $1/(2\pi f_c)$, where f_c is the upper frequency cutoff or bandwidth of the phase measurement system used to measure $x(t)$: the expressions above give the correct results.

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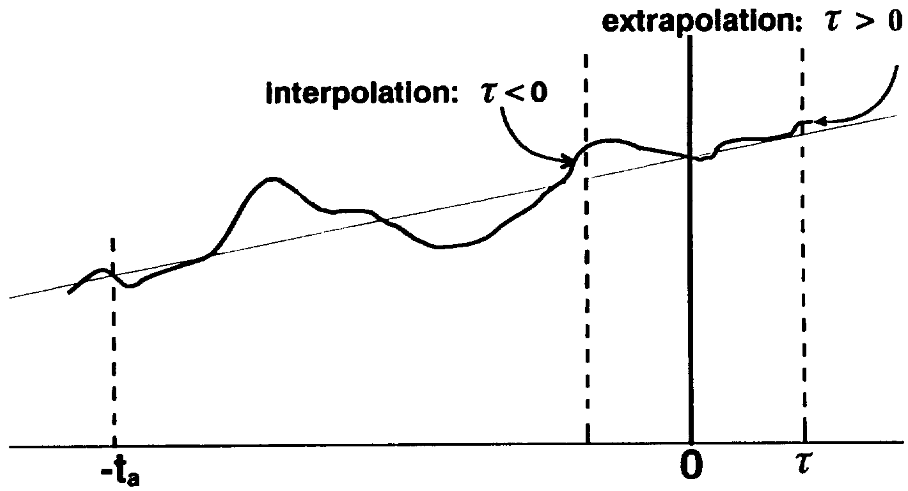

Figure 1. A simple algorithm: linear extrapolation or interpolation from a line constrained to lie through two points on x(t), separated by a time t_a. Its standard uncertainty in time, $u_x(\tau)$, can vary with extrapolation time τ, as shown in Figure 2.

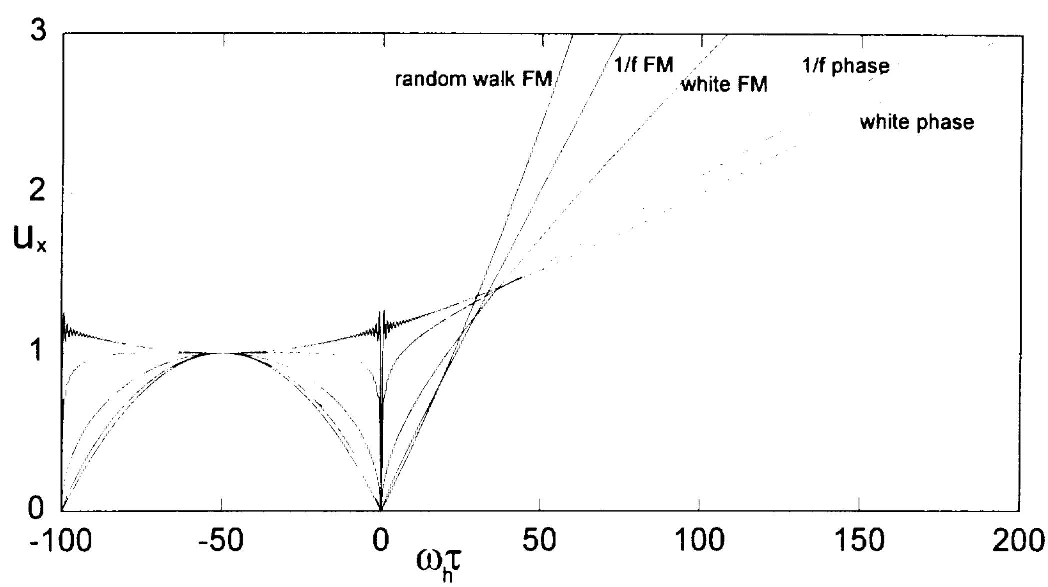

Figure 2. The standard uncertainty in time, $u_x(\tau)$, developed by the algorithm of Figure 1 for an extrapolation time τ. It is shown separately for the five types of noise, each normalized to 1 at the midpoint of the fitting interval t_a. In this example, $\omega_h = 100/t_a$.

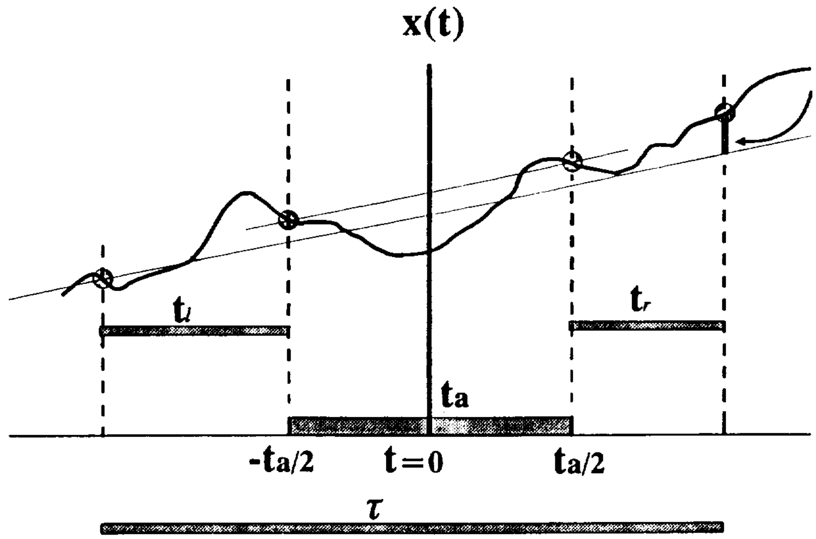

Figure 3. A simple algorithm: linear fit constrained to lie through two points on x(t). The variation in frequency from the calibration interval t_a is illustrated. With $t_l = t_r$, this is the basis for Figures 4 and 5.

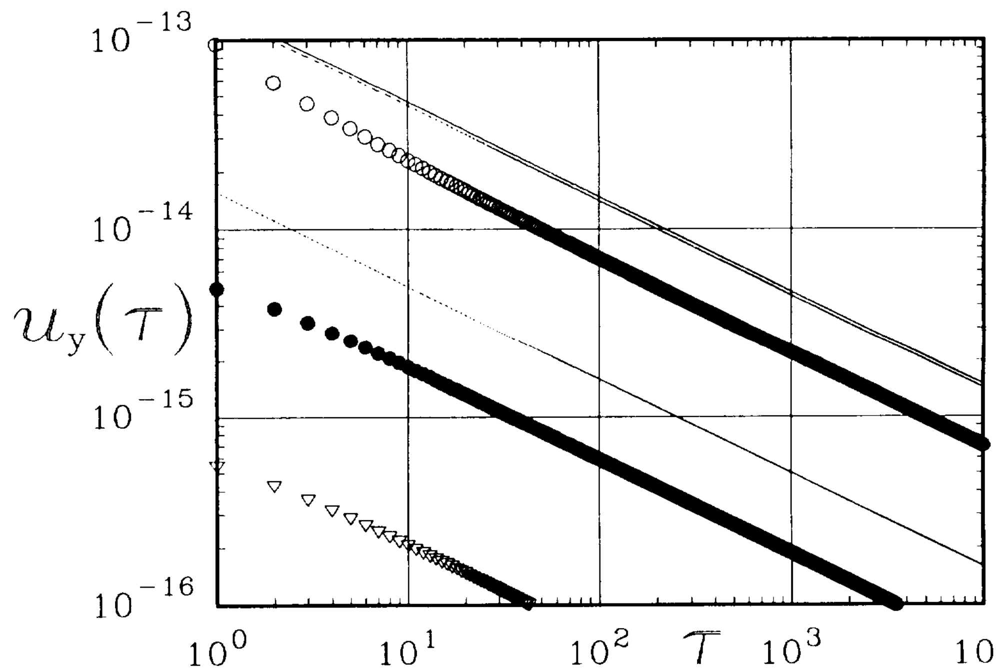

Figure 4. Local oscillator contribution to the standard uncertainty of the average frequency for a pulsed-ensemble cesium fountain, with a cycle time of 1 s and a dead time of 0.01 s. The light lines show the classical stability limit of the three oscillators, and the heavy symbols show the pulsed-ensemble result using linear extrapolation in phase to bridge the dead time. For each type of servo, the top curve is for an Oscilloquartz 8600-3 ($h_{-1} = 8\times10^{-26}$, $h_1 = 8\times10^{-27}$, $h_2 = 5.6\times10^{-29}$), the middle curve for a Wenzel 500-03475 100MHz &5 MHz ($h_{-1} = 8\times10^{-26}$, $h_1 = 1.6\times10^{-30}$, $h_2 = 1.3\times10^{-34}$), and the bottom curve is for a JPL-type 77K sapphire X-band frequency discriminator ($h_{-1} = 1\times10^{-27}$). Optimally used, their noise corresponds to a shot noise of 700, 8×10^4 and 6×10^6 atoms/s respectively.

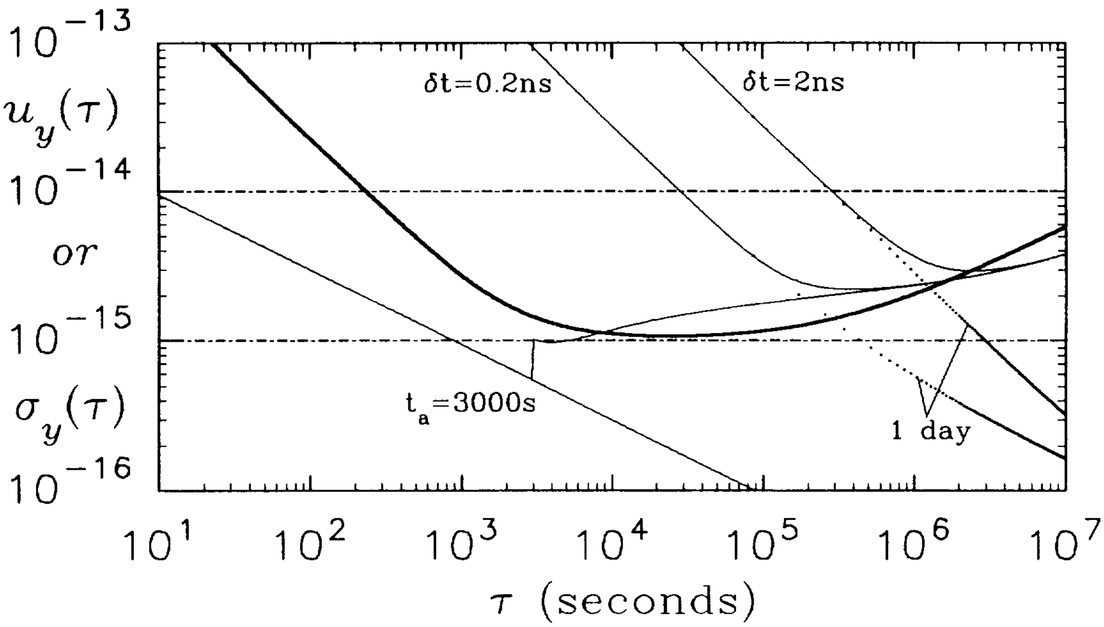

Figure 5. Cesium fountain's standard uncertainty of average frequency over an interval τ,due to random noise. The maser noise model 's Allan deviation is also shown as the heavy curve. A cesium fountain with a $u_y(t) = 10^{-14}\tau^{-1/2}$ is operated for 3000 s , calibrates a maser, the standard uncertainty of the extrapolation from one calibration is indicated by the light curve that rises abruptly at t = 3000 s . The other curves show what can be done with current (2 ns) and a possible future two-way time transfer at the ends of the interval τ. The dots show what can be done if a 3000 s calibration run is performed every day.

a-4.

N94-30657

TIME TRANSFER USING GEOSTATIONARY SATELLITES : IMPLEMENTATION OF A KALMAN FILTER

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Abstract

Since 1988, various experiments [1, 2, 3, 4] have shown that the TV signals transmitted by direct TV satellites may easily be used to perform time transfers at the level of a few tens of nanoseconds, the main source of error being the uncertainty on the satellite position.

We first present the two methods used in our experiment to reduce the effects of the satellite residual motion : the first one consists in estimating the longitude variations of the satellite and then using this information to improve other measurements. This allows to reduce the uncertainty to values between 9 and 50 nanoseconds according to the position of the involved stations.

In the second method we determine the satellite position by using the data collected by three calibrated stations. Time transfer between each of these stations and a fourth one has been shown to be achievable at the precision level of ten nanoseconds.

A new approach based on the use of a Kalman filter is proposed in order to take into account the dynamics of the geostationary satellite.

The precisions on orbital elements and clock differences and rates determination given by the first simulated applications of the Kalman filter are presented and compared to those obtained by the other methods.

INTRODUCTION

The principle of this kind of time transfer consists in timing the arrival of a given pulse at two different locations and deducing the time difference of the two clocks from these data and from the co-ordinates of the receiving antennas and of the satellite [1].

But while the position of the stations are often known with a sufficient precision, it is not the case for the satellite position. The tolerance on the geostationary satellite longitude and latitude is generally ± 0.1 degree. This causes significant errors on time transfer as soon as the stations are distant from more than a few kilometers : between Paris and Besançon (324 km) the error can reach 3 microseconds.

Until now, different methods have been used to overcome that problem. Some of them imply external information on the satellite position such as laser ranging [4] or more directly position data from the satellite control center [3]. The method we carried out to determine the satellite position uses the time measurements made between three externally calibrated (GPS) stations to precise the satellite position and will be shortly outlined hereafter.

A second kind of method takes into account the known geometry of the involved links [2] and some properties of the satellite orbits [1] to remove the effects of unknown parameters. The performances of this last method will also be presented.

A third approach [3] simultaneously estimates the orbital elements of the satellite and the clock differences and rates from the time delays measured between three stations and from pseudo-ranging given by a two-way measurement performed at one of the station.

In section 3, we propose to do the same thing by using Kalman filtering, that is known as an excellent way of reconstructing satellite trajectory. The final aim of this method is to reach the limit of accuracy (a few ns) that can be obtained from passive use (one way) of the signals transmitted by geostationary satellites.

1. PREVIOUSLY USED METHODS

The results presented in this section are based on measurements provided by four receiving stations located in Besançon (OB), Paris (OP), Toulouse (CT), and in the Observatoire de la Côte d'Azur in Grasse referred to as OC. Those four stations track the TDF2 satellite, located at 18.9° W and transmitting a D2-MAC standard TV signal. The caesium clocks of these four stations are also linked by GPS allowing the calibration of our results.

1.1. Time transfer using longitude calibration

The main source of uncertainty on the time transfer is due to the residual motion of the satellite in its "parking box". For a given couple of stations it depends on two parameters : the difference between the two unit vectors station-satellite (see table 1, row 1) on the one hand, and the vector defined by the real position of the satellite and its mean position. Usually the satellite is maintained in a cell of ± 0.1° (i. e. ± 73.6 km at the geostationary radius) in longitude and latitude, what implies variations of ± 10 km in radius ; taking into account the longitude of the satellite (about 18.9° W for TDF1-2) , we obtain values varying between 2.5 and 5.5 µs for the 6 different links of our experiment. The observed variations are well within these theoretical limits.

The satellite geostationary orbit is mainly composed of daily and half-daily periodic longitude, latitude and radius variations (due to residual eccentricity and inclination) and a non periodic longitudinal drift (due to irregularities of the gravitational potential). Consequently, it is possible to averaged out the influence of the periodic components, by averaging two measurement values separated by 12 hours. This reduces the errors on time transfer to values around 1 µs. Furthermore, if we assume that the link is calibrated by an external way (GPS), we can say that the observed variations of the residuals are the effect of the satellite longitudinal drift. The importance of this effect depends on the position on each of the two involved stations with respect to the satellite position and can be easily calculated for each couple of stations. So once the longitude variations have been determined by one particular link (figure 1), it is possible to correct the data concerning other links for the effects of these variations. According to the link corrected and the one used for calibration, the precision obtained varies from 9 ns to 50 ns in the worst case (Table 1). The Allan variance of the residuals for two configurations are shown on figure 2.

Calibration link / Corrected link	OP-CT	OB-OP	OP-OC	CT-OB	CT-OC	OB-OC
OP-CT	_	13	12	20	15	11
OB-OP	35	_	11	20	12	24
OP-OC	53	18	_	43	15	23
CT-OB	35	13	17	_	14	27
CT-OC	52	15	11	27	_	27
OB-OC	19	16	9	27	13	_

Table 1. Uncertainty for the corrected links (ns)

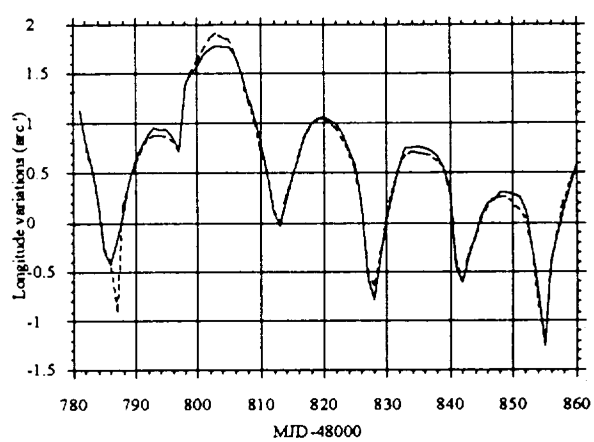

Figure 1 : Longitude variations determined by OP-CT (dash line) and OP-OC (bold line)

1.2. Time transfer using explicit determination of the satellite position

This method uses three calibrated stations (two usable links) to reduce the uncertainty on the satellite position. It is as precise as the above method and far less sensitive to the position of the station to be linked. It consists in solving the geometric problem of finding the set of solutions of the system defined by the differential data obtained from the three calibrated stations. This gives the equation of a curve (intersection of two hyperboloïds) on which the satellite must be found. The dispersion of the residuals is about 15 ns for the link between station OC and the triangle of stations OP-CT-OB. A better spatial resolution can be obtained by using the triangle OP-CT-OC that is a little bit more extended to reach a precision of about 11 ns for the link between the stations OB and OP.

Figure 2 (plots 2 and 3) shows that the accuracy reached by this method is of the order of a few 10^{-14} for the triangle OP-CT-OC as for OP-CT-OB.

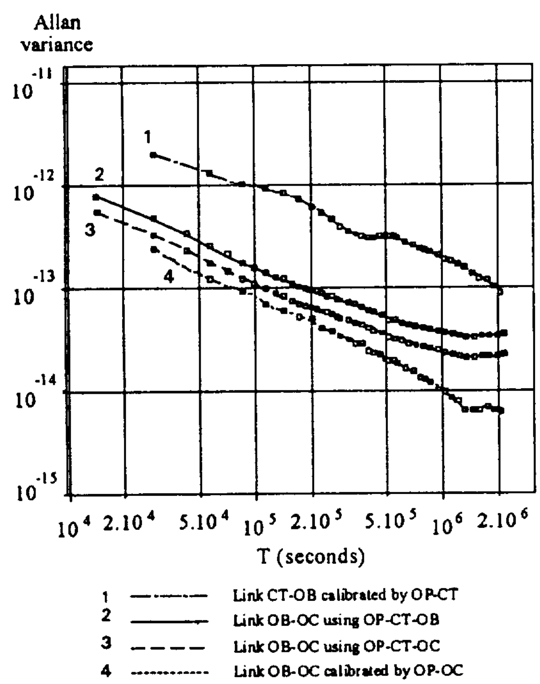

Figure 2 : Log-Log plots of Allan variance versus averaging time

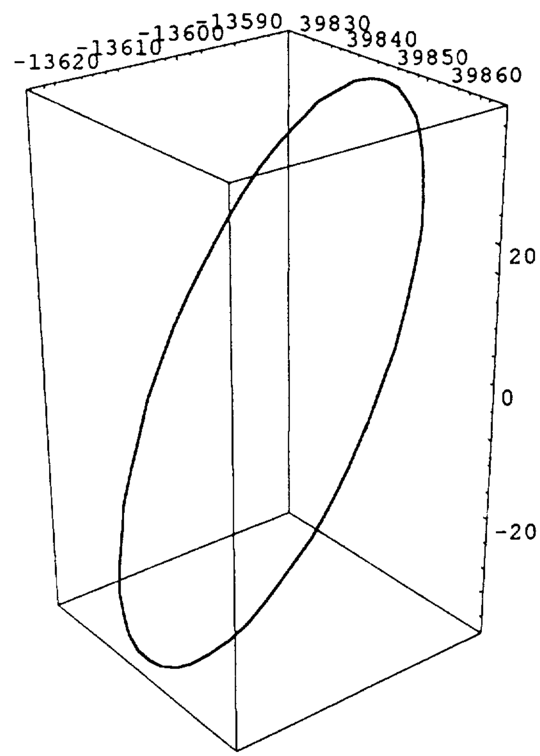

Figure 3 : Example of typical 24-hour residual orbit in a rotating reference frame (graduations in km).

2. ORBIT MODEL

If we neglect at the present the different causes of perturbation of the satellite motion, this motion in a non-rotating geocentric reference frame is ruled by equation 1 :

$$\frac{d^2\vec{r}}{dt^2} = -\mu\frac{\vec{r}}{r^3}$$

where $\vec{r} = \begin{pmatrix} x_{sat} \\ y_{sat} \\ z_{sat} \end{pmatrix}$ and μ is a function of the semi-major axis a and period T. Associated to initial conditions $(\vec{r}_0, \dot{\vec{r}}_0)$ this system defines a unique trajectory. If defined with classical Kepler's elements (semi-major axis a, eccentricity e, inclination i, longitude of the ascendant node ω, argument of the perigee Ω, mean anomaly M), this system is equivalent to :

$$\frac{d\vec{S}}{dt} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ n_0 \end{pmatrix} \quad \text{where} \quad \vec{S} = \begin{pmatrix} a \\ e \\ i \\ \Omega \\ \omega \\ M \end{pmatrix} \quad \text{and} \quad n_0 = \sqrt{\frac{\mu}{a_0^3}}$$

In the case of geostationary orbits, since e and i are very close to zero, it is usual to use the following state vector :

$$X = (a, e_x = e.\cos(\omega + \Omega), e_y = e.\sin(\omega + \Omega), h_x = i.\cos(\Omega), h_y = i.\sin(\Omega), L = \omega + \Omega + M)^T$$

We can then express $\vec{r}$ as a function of these elements :

$$\vec{r} = \begin{pmatrix} a\left[(\cos(L) - \frac{1}{2}(3e_x + e_x\cos(2L) + e_y\sin(2L))\right] \\ a\left[(\sin(L) - \frac{1}{2}(3e_y + e_y\cos(2L) + e_x\sin(2L))\right] \\ a\left[h_x\sin(L) - h_y\cos(L)\right] \end{pmatrix}$$

The time measurements ρ_{ij} made between two stations S_i $(\vec{r}_i)$ and S_j $(\vec{r}_j)$ at the instant t are a function of X and t that can be written as :

$$\rho_{ij}(X,t) = \frac{\sqrt{(\bar{r}-\bar{r}_i)^2 - (\bar{r}-\bar{r}_j)^2}}{c}$$

where c is the speed of light. $\bar{r}_i$ and $\bar{r}_j$ are a function of the sidereal time (they would be constant in a rotating reference frame).

3. KALMAN FILTER SETUP

To apply the Kalman filter to a given system, we must be able to :

1. elaborate an evolution model of the system, i. e. estimate from a value at an instant k of a quantity X called state vector the value of X at the instant k+1. This simply reflects the dynamics of the system.

2. correct the preceding estimation with the help of measurements concerning a function of one or more of the components of X and of the prediction of what these measurements should be when taking into account the current state.

In our case, the system dynamics is simple in first approximation. We have :

$$\frac{dX}{dt} = (0,0,0,0,0,n_0)$$

Also, there is no problem to include in state vector X the clock difference and rate of two given stations. Then, if x_k stands for the estimated state vector at instant k, we can easily define the matrix $\varphi_{t_k,t_{k+1}}$ so that we have :

$$x_{k+1} = \varphi_{t_k,t_{k+1}} x_k$$

The observation equation however is not so simple since $\frac{d\rho_{ij}}{dt}(X,t)$ is not a linear function of the orbital elements. So the computation of the correction to the predicted measurement requires a linearisation around the current estimation x_k of these elements. This leads to the extend Kalman filter formulation [5] in which we have to determine the matrix :

$$H_k = \frac{\partial\rho_{ij}(X,t_k)}{\partial X}$$

	$\frac{\partial \rho_{ij}}{\partial L}\Delta L$ $\Delta L = 0.1°$	$\frac{\partial \rho_{ij}}{\partial a}\Delta a$ $\Delta a = 10^4 m$	$\frac{\partial \rho_{ij}}{\partial e_x}\Delta e_x$ $\Delta e_x = 7.10^{-5}$	$\frac{\partial \rho_{ij}}{\partial h_x}\Delta h_x$ $\Delta h_x = 10^{-3}$
OP-CT	0.4 µs	3 ns	70 ns	3 µs
OP-OB	2.0 µs	<1 ns	180 ns	1.2 µs
OP-OC	3.1 µs	15 ns	220 ns	2 µs
OB-OC	1.2 µs	16 ns	100 ns	1.6 µs
CT-OC	2.5 µs	15 ns	10 ns	2.4 µs
CT-OB	1.2 µs	30 ns	84 ns	1.6 µs

Table 2. Influence of the different orbital elements

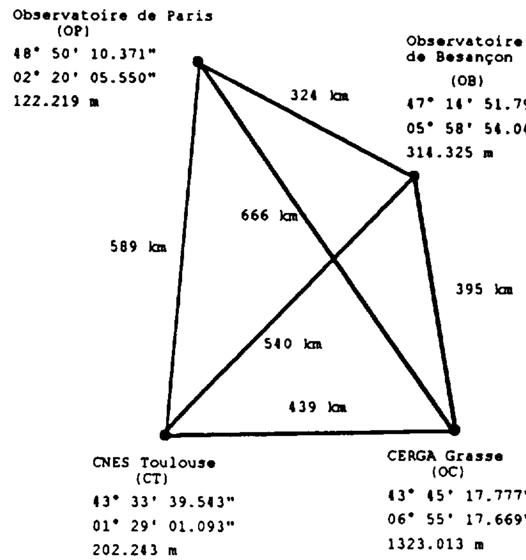

Figure 4 : Location of the stations

The influence of the variations of the different orbital elements on the measurements varies according to the relative geometry of the stations involved in the measurements. Table 2 shows the maximum error generated by the maximum authorised variations (in the sense of station keeping) of each orbital element for each of the 6 links of our experiment. The values obtained for e_x (resp. h_x) are of course the same for e_y (resp. h_y). We see that the main source of error are the mean longitude and the inclination vector. These values of $\frac{\partial \rho_{ij}}{\partial L}\Delta L$ confirm the ones obtained in a different way [1]. Table 2 also confirms the influence of the geometry of a given link on the partial derivatives (figure 4).

Because of a mistake on error estimation, the first simulation results are irrelevant and have to be recomputed.

Nevertheless, a separate study lead by the CNES demonstrates that when using the data from 4 calibrated stations, these elements can be determined with the imprecision given in table 3 [6], assuming an uncertainty on the measurements of a given link of 100 ns. In the near future, we expect to lessen this value to about 10 ns by performing a calibration of the 4 receiving sets.

Errors	a (m)	e_x (10^{-6})	e_y (10^{-6})	h_y (10^{-3} deg)	h_y (10^{-3} deg)	L (10^{-3} deg)
4 days	1.4	8.1	8.0	1.2	1.1	2.5

Table 3 : Theoretic imprecision on the orbital elements.

CONCLUSION

We have presented the different methods we used to reduce the influence of the satellite motion on time delay determination. A data processing algorithm based on the application of an extended Kalman filter has been proposed and is currently being tested.

It could appear to be necessary to include in the model some known orbital perturbations, particularly those concerning the mean longitude L and to perform better calibration of the receiving sets [1], as this appears in [6] to be the most important source of uncertainty on the measurements, and then, in the determination of the satellite orbit.

A large amount of results have been obtained very recently by the CNES [6] and will be of great help in the continuation of the experiment.

ACKNOWLEDGEMENTS

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The Two–Way Time Synchronization System via a Satellite Voice Channel

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Abstract

A newly developed two–way time synchronization system is described in this paper. The system uses one voice channel at a SCPC satellite digital communication earth station, whose bandwidth is only 45 kHz, thus saving satellite resources greatly. The system is composed of one master station and one or several, up to sixty-two, secondary stations. The master and secondary stations are equipped with the same equipment, including a set of timing equipment, a synthetic data terminal for time synchronizing, and a interface unit between the data terminal and the satellite earth station. The synthetic data terminal for time synchronization also has an IRIG–B code generator and a translator. The data terminal of master station is the key part of whole system. The system synchronization process is full automatic, which is controlled by the master station. Employing an autoscanning technique and conversational mode, the system accomplishes the following tasks: linking up liaison with each secondary station in turn, establishing a coarse time synchronization, calibrating date (years, months, days) and time of day (hours, minutes, seconds), precisely measuring the time difference between local station and the opposite station, exchanging measurement data, statistically processing the data, rejecting error terms, printing the data, calculating the clock difference and correcting the phase, thus realizing real–time synchronization from one point to multiple points. We also designed an adaptive phase circuit to eliminate the phase ambiguity of the PSK demodulator. The experiments have shown that the time synchronization accuracy is better than 2 μS. The system has been put into regular operation.

Introduction

Two–way time comparison via satellite is an important method for laboratories which require high precision time synchronization. Due to the wide frequency band and steep pulse edge, its precision is a few nanoseconds. If MITREX modems are used, the precision can be as good as subnanoseconds. In consideration of various delay corrections, the accuracy can achieve ten nanoseconds to one hundred nanoseconds. Because it necessary to use two satellite transponders, this method is not universally practical. There are quite a number of satellite earth stations of the CVSD/PSK/SCPC system in China. Generally, each station consists of several digital voice channels and several low rate data channels. Can the voice channel be used for a two–way time comparison? We analyzed carefully the composition and the principle of the earth station, and discovered that the CVSD circuit has the larger error and the PSK demodulator has a phase ambiguity. Thus we worked out a plan in which digital signal inputs to the PSK modulator and outputs from the PSK demodulator, designed an adaptive phase circuit to eliminate the phase ambiguity, developed related equipment, and established a complete time synchronization network via the satellite.

System Configuration

The two–way time synchronization system via a satellite voice channel is composed of one master station and one or several, up to sixty–two, secondary stations. The equipment configurations of master and secondary stations are basically identical, including a set of timing equipment, a synthetic data terminal for time synchronization, and an interface unit between the data terminal and the satellite earth station, which are shown in Figure 1.

The master station terminal is the heart of whole system. The system synchronization process is full automatic, and is controlled by the master station. The master station controls scanning to all secondary stations, transmits standard time to secondary stations, controls the two–way comparison and monitors the secondary station status at any time, and determines what to do next according to secondary station status.

The data terminals of secondary stations are the same as the master except for work mode: one of the terminals is set up as master mode, the others are set up as secondary mode. They accomplish the different tasks. In fact, the interface unit is a signal format converter. It receives and demodulates the IRIG–B code from the terminal, converts it to the code data current for the PSK modulator, and generates a carry active signal for the voice channel. At the same time it receives and demodulates the code data current from the PSk demodulator, eliminates the phase ambiguity, and converts it to the IRIG–B code to be transmitted to the terminal.

Features

- 1. **Narrow Frequency Band**—The two–way time transfer using earth stations generally requires two satellite transponders. However our system only requires one digital voice channel, its bandwidth is 45 kHz, thus saving satellite resources greatly.
- 2. **Powerful Real–time**—The two–way time transfer using earth stations is not real–time. It is necessary to bring the data from the two stations together, then the data are processed and the clock difference is obtained. In our system, the master and each secondary station directly exchange the data using the same voice channel, and realize real–time synchronization.
- 3. **High Automatization**—The procedure of real–time synchronization is fully automatic without manual intervention.
- 4. **Multi–point Synchronization**—The system adopts the scanning method, thus realizing time synchronization from one point to multi–point. At present, the number of the secondary stations may be one up to sixty–two. If needed, the number can increase more.
- 5. **Short Synchronization Time**—The period from the time when a secondary station runs free after tuning on to the time when it synchronizes accurately with the master

station is less than two minutes.

- **6. Multi–function**—Besides displaying the transmitting time and receiving time, having a phase shifter with a resolution of 0.1 microsecond, processing the data, printing the data, the data terminal also has a time interval counter with a resolution of 0.1 microsecond and the input and output interfaces for standard IRIG–B time code.

Synchronization Procedure

The system adopts a scanning method, each secondary station has a specially designated number. The voice channels of all secondary stations have the same receiving frequency which corresponds with the transmitting frequency of the master station and the same transmitting frequency which corresponds with the receiving frequency of the master station.

The data terminal of the master station first receives and demodulates IRIG–B code from the timing equipment, accomplishes the synchronization with it and calibrates the date and the time of day. Then it outputs the signal to the interface unit, the converted signal is input in the voice channel. Next the master channel transmits a selective calling code, the date and the time of day to all secondary stations.

All the secondary stations will go into receiving mode after turrning on, demodulate the signal from the master station. When the demodulated selective calling code is same with the local station number, the secondary station activates the carry of the voice channel, accomplishes a coarse time synchronization, and calibrates the date and the time of day, then transmits a responding signal to the master station. After knowing that the secondary station had accomplished the coarse synchronization, the master station transmits a command to the secondary station. Then the two–way comparison starts. The time interval counter of the master station is started by the 1 PPS which is being transmitted by the master station and stopped by the 1 PPS which is received from the secondary station. The measured time difference and the time of the measurement are transmitted to the secondary station immediately. Similarly, the time interval counter of the secondary station is started by the 1 PPS which is being transmitted by the secondary station and stopped by the 1 PPS which is received from the master station. The measured time difference and the time of measurement are transmitted to the master station immediately. Both the stations print out the measured and received data. Besides, the data terminal of the secondary station processes the time difference data one by one, rejects error terms, calculates the clock difference between two stations on the basis of the two–way principle, and controls the phase shifter to shift the phase according to the calculated amount and sign. Then the secondary station transmits a synchronization success signal to the master station. After it has received the signal, the master station transmits a command to the secondary station to stop activating the carry. When it has detected that the secondary station really had stopped transmitting, the master station automatically calls the next secondary station, and so on. Thus it can be seen that the transmitting frequencies of the secondary stations are all the same, but only one of the secondary stations is transmitting the signal whenever so as to avoid confusion. The time need for above procedures is less than two minutes.

After the synchronization has been accomplished, the data terminal of the secondary station automatically outputs the 1 PPS and IRIG–B code signals to the timing equipment.

Experiments and Results

In order to test and verify the system accuracy, we have made experiments for two cases.

The first case refers to single station experiment. We put three data terminals in a timing room. One of them is assigned as the master station. Others are secondary stations. Three terminals use three voice channels of the same satellite earth station for comparison. The system configuration of a single station experiment is shown in Figure 2.

The input and output signals of the three terminals are connected with three interface units of the satellite earth station respectively by six paired cables with the same lengths. The voice channel of the master station transmits the messages at f_1 frequency to two secondary station channels, and receives the messages at f_2 frequency from two secondary station channels. Two secondary station channels transmit the messages at the same f_2 frequency to the master station channel by time division mode, and receive the messages at f_1 frequency from the master station channel. The time differences for the 1 PPS signals between the master station and two secondary stations are measured respectively by a time interval counter. The readings of the counters are the time synchronization accuracies.

The second case refers to two station experiment. We put three data terminals (one master station and two secondary stations) in a timing room. The master station terminal and one secondary station terminal are connected with two interface units of one satellite earth station with four paired cables. Another secondary station terminal is connected with an interface unit of another satellite earth station with two paired cables. The distance between the two earth stations is about five kilometers. The system configuration is shown in Figure 3. The experiment method is as same as described above.

For the above two cases, we changed different voice channels and tested many times. Table 1 lists the experiment results. The results have shown that the accuracy of the time synchronization system is better than one microsecond in most cases, and only for few cases the accuracy is worse than one microsecond, but better than two microseconds. This is caused by the voice channel delay.

Conclusions

The two–way time synchronization via a satellite voice channel has the features of narrow frequency band, powerful real–time, high automatization, short synchronization time, multi–function and so on. The system uses microprocessor control, adopts the scanning method and conversational model, automatically realizes real–time synchronization from one point to multi–point. The synchronization accuracy is better than two microseconds. The system has powerful practicality.

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Table 1
The Experimental Results

No.	Average (μS)	Standard Deviation (μS)
1	10.4	0.03
2	20.6	0.03
3	30.2	0.02
4	40.8	0.04
5	50.2	0.03
6	61.4	0.04
7	70.6	0.05
8	81.6	0.04

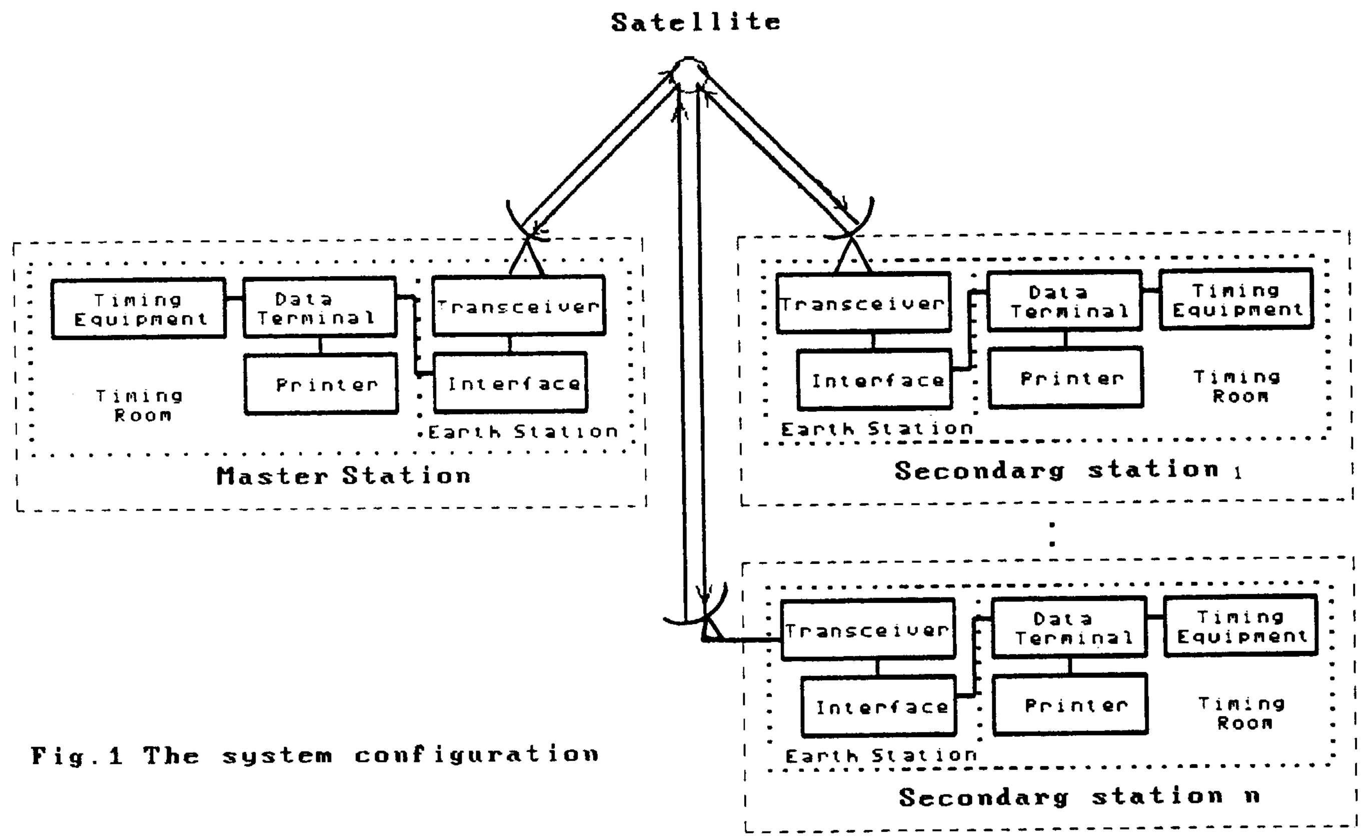


Fig.1 The system configuration

Fig.2 Single Station Experiment

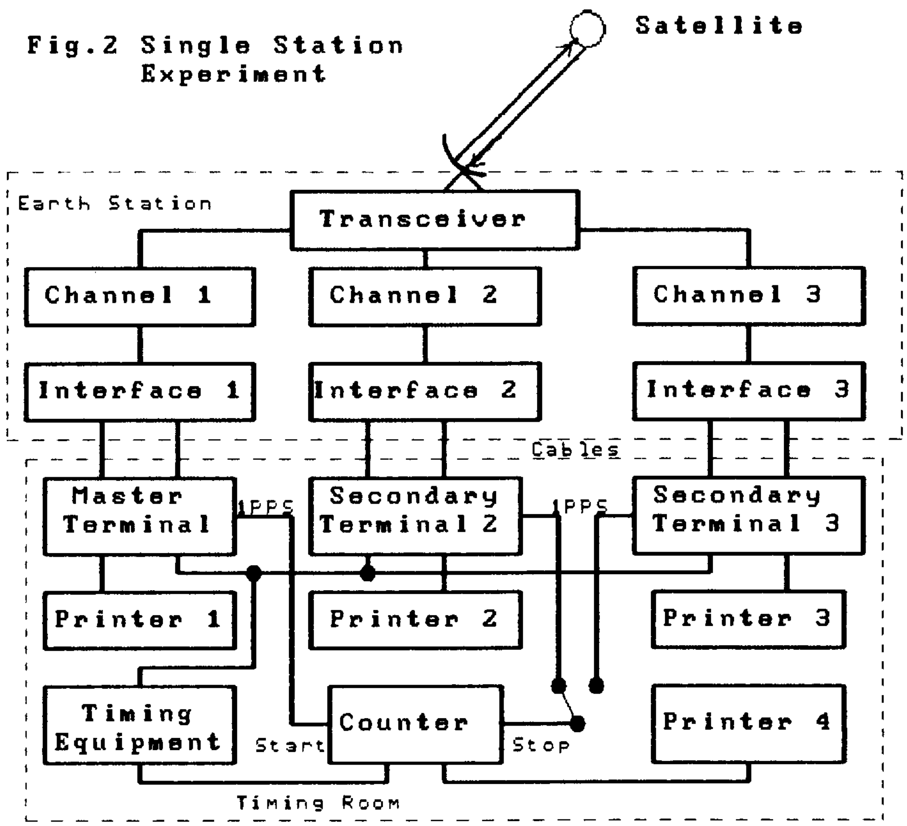
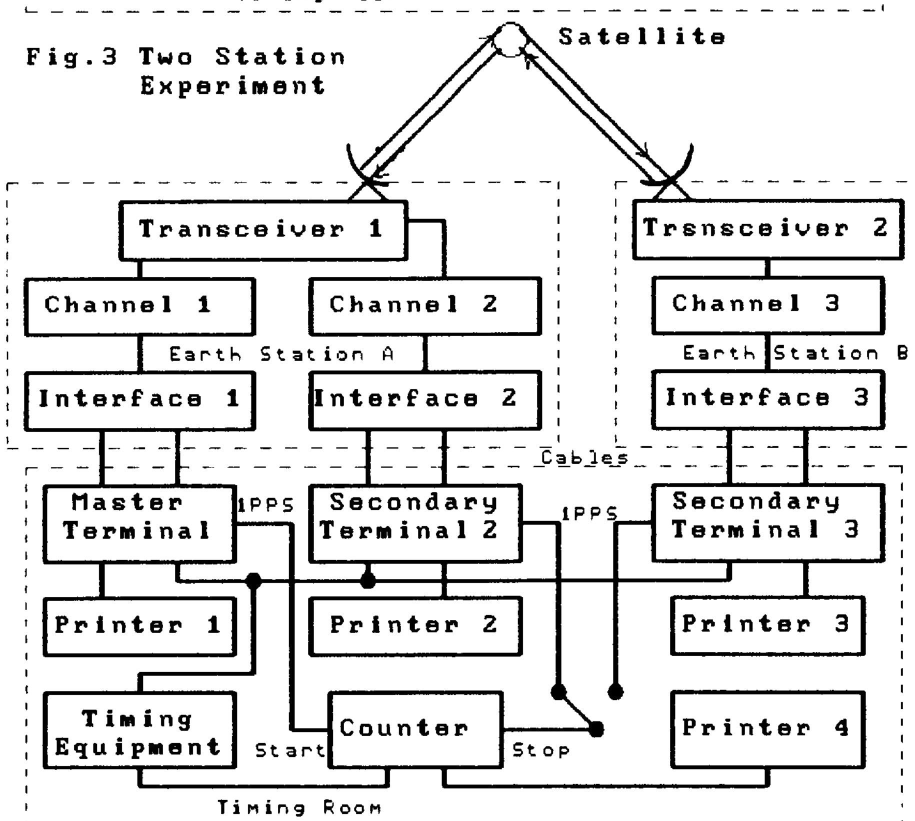


Fig.3 Two Station Experiment



Remote Clocks Linked by a Fully Calibrated Two—Way Timing Link

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Abstract

Fully calibrated two–way time transfers between the U.S. Naval Observatory (USNO) and the U.S. Naval Observatory Time Service Substation (NOTSS) have become operational. The calibration method employed was the co–located Earth station method. Results concerning timing, stability, comparison of two–way and Global Positioning System (GPS) timing links, and remote clock contribution to local time scale computation will be presented.

PART I: TWO–WAY OPERATIONS

INTRODUCTION

The U.S. Naval Observatory has been experimenting with two–way time transfer since the first communications satellites, i.e. Telstar and Relay–II, were put into operation in the 1960's [1,2]. The ultimate goals of the two–way project have been to improve the USNO's Master Clock of the United States by including remote clocks via the most precise and accurate timing links possible. Three key factors in the support of the USNO Master Clock System addressed by two–way are the direct clock comparisons, timescale comparisons, and the use of remote clocks in a local timescale production. The recent development of low–cost, portable, very small aperture terminals (VSAT) have allowed the two–way time transfer method to finally be put into an operational mode at the U.S. Naval Observatory.

THE PROCEDURE AT USNO

The two–way system employed at the USNO Washington, DC site employes a 4.57 meter satellite terminal and a MITREX model 2500 modem (analog version), while at the NOTSS Richmond, FL site a 1.8 meter VSAT and a MITREX model 2500A modem (digital version) are used. A "flyaway" 1.8 meter VSAT was used for the co–location calibrations and performed by the method discussed in [3]. The USNO Washington, DC reference is the operational USNO Master Clock #2 which is the Sigma Tau hydrogen maser N3 which is steered by small daily frequency changes in its synthesizer, while the NOTSS reference clock is an unsteered HP 5071A cesium beam frequency standard designated as CS152. The Satellite Business System Corporation's SBS–6 at 95 degrees West is the satellite used to make the time transfers. The time transfers are made every working day. The data are transferred daily by ftp via Internet to a central computer located at the USNO Time Service Department in Washington, DC. The appropriate data files are then matched and the final daily time differences are computed and made available, again by ftp.

The formulation used to generate the final time differences is

$$\begin{aligned} \mathrm{UTC(USNO)} - \mathrm{UTC(NOTSS)} = & \ 1/2[\mathrm{Ti(USNO)} - \mathrm{Ti(NOTSS)}] \\ & -\Delta\mathrm{Tx(NOTSS)} - \Delta\mathrm{Tx(USNO)} \\ & -\mathrm{d1PPS(NOTSS)} - \mathrm{d1PPS(USNO)} \\ & -S \\ & -R \end{aligned}$$

The first term on the right is the time interval counter differences which are recorded at each site, the second term is the transmit–to–receive delay difference also measured at each site, the third term is the delay from on time of the 1 PPS references as measured at each station, the fourth term is the computed relativistic time delay due to a rotating reference system, and the fifth term is the RF delay as measured by the co–located Earth station method. The ionospheric and tropospheric transmission delays introduced by the Ku band uplink/downlink frequency differences, on the order 100 ps [3] are currently ignored. Any satellite transponder delays are assumed to be reciprocal.

ANALYSIS OF INSTABILITY

Two main noise processes are evident in the instability tests of the frequency behavior of the two–way transfers. From 10^0 to 10^3 seconds white phase noise of the two–way system phase comparisions dominates, i.e. a $\log\tau^{-1}$ slope, (where τ is the sampling time), while from 10^3 to 10^7 seconds white frequency noise originating in the NOTSS cesium reference dominates, i.e. a $\log\tau^{-1/2}$ slope. It is expected, but not currently seen, that beyond 10^7 seconds the long–term steering of the USNO Master Clock will be the dominant "noise" contribution [4].

PART II: THE REMOTE CLOCKS AT NOTSS

INTRODUCTION

When two–way time transfer was begun between the USNO and the NOTSS, the latter had eleven clocks on location for use in its local timescale, and time transfer between these two locations was possible using either two–way or GPS.

PRELIMINARY STUDY AT NOTSS

Starting with the day on which two–way became operational, USNO clocks were incorporated into the NOTSS hourly time scale for a test period of 37 days using both GPS and two–way to determine which method of time transfer gave the better result. (See below for a brief description of the method.) For the period MJD 48983 to 49020 the rms of NOTSS Mean-CS152 was as follows:

NOTSS Mean formed from...	rms
9 local clocks only	± 2ns
9 local clocks plus 11 USNO clocks linked via GPS	± 3ns
9 local clocks plus 11 USNO clocks linked via two–way	± 2ns

It was decided to use two–way because of the smaller noise, but GPS would be an acceptable substitute when necessary. A similar accuracy for GPS as for two–way can only be expected using geodetic receivers, ultra–precise ephemerides, and the common–view technique [5].

THE PROCEDURE AT NOTSS

Every ten days, the difference between the USNO Master Clock and the NOTSS Master Clock at 0 hours UT every day is plotted using both two–way and GPS. This allows a comparison of the two methods and gives the difference between them, so that GPS can be used when two–way becomes unavailable for a lengthy period.

For example, for the period MJD 49150 – 49224, 10.1 nanoseconds would have to be added to the differences obtained using GPS to bring them into coincidence with the differences from using two–way. Over this period, this quantity had a slope of +0.08 ns/day and an rms of ± 4.6 nanoseconds, see Figure 3 . The last nine days were omitted from the plot because the plots overlap. In practice, a value taken from the current ten–day period is used.

The NOTSS GPS system has since been calibrated using the two–way data so that both time transfer methods give the same average result.

USNO hourly clock readings are downloaded at NOTSS and converted to the NOTSS reference system using the two–way data interpolated for 0 hours of each MJD. Another simple interpolation is done for the hours in between. The equation for clock conversion is:

$$\begin{aligned} \mathrm{UTC(NOTSS, MC) - REMOTE} &= [\mathrm{UTC(USNO, MC\#2) - REMOTE}] \\ &+ [\mathrm{UTC(NOTSS, MC) - REF}] \\ &- [\mathrm{UTC(USNO, MC\#2) - REF}] \\ &+ \mathrm{DIFF} \end{aligned}$$

where REMOTE is a clock located at USNO. When using two-way, REF is CS152 and DIFF=0. When using GPS, REF is GPS and DIFF is the difference between the two methods of time transfer.

For the period MJD 48983 to 49229, two-way was used for 232 days of hourly readings and GPS for 15 days.

These resulting (NOTSS - REMOTE) values are then interleaved with the NOTSS readings of its local clocks. The timescale program is rerun with both the local clocks and the remote clocks included to form a NOTSS timescale with several dozen clocks instead of about half a dozen clocks. By using clocks at a remote location, the NOTSS timescale can be better carried through local interruptions in its methodical gathering of hourly clock readings, such as clock vault temperature failures, computer down-time, etc.

CLOCK WEIGHTING

In the NOTSS timescale, the weights given the local clocks are as suggested by Breakiron [6], further modified after studies of the two-pair variances of the various clock types [7]. HP 5061s are given a weight of 0.657 of the HP 5071As. Remote clocks (all of them HP 5071As) were initially given less weight than the local HP 5071As because of expected higher noise due to the time transfer process.

To determine how much noise the two-way time transfer actually adds to the remote clocks, every clock (both local and remote) used in the NOTSS timescale was referenced to the local Sigma Tau hydrogen maser N1 and the rms of the data calculated. A period of time in the range of MJD 49142 to 49227 was chosen for each clock on the basis of having had no rate adjustments during that period. The results were as follows:

Local clocks:

Single HP 5071A:	rms = $\pm$ 2ns
Average of eight HP 5061s:	rms = $\pm$ 5ns

Remote clocks:

Average of thirty three HP 5071As:	rms = $\pm$ 4ns

It thus appears that the two-way time transfer process and the interpolation for the hours in between "degrades" a remote HP 5071A to the noisiness of a local HP 5061. Much of the degradation in the two-way time transfer process is probably related to a problem with the MITREX 2500A modem used at NOTSS, which introduces unmodeled systematics into the timing data. Resolution of this problem awaits a new generation of modems for use in two-way time transfers.

If total clock noise is the basis for determining the clock weights, then the decision to give the remote HP 5071As a weight equal to the local HP 5061s is justified. However, there is no reason to believe that the stability of a remote clock is less than that of a local clock of the same model. A method of making weight more responsive to a clock's past performance may be undertaken at USNO in the future [7].

ACKNOWLEDGEMENTS

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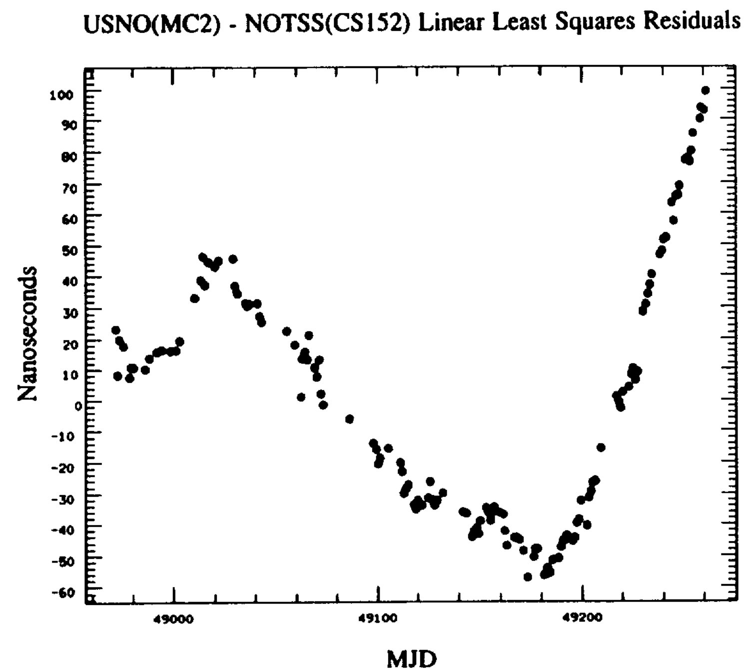

Figure 1. The residuals of the USNO-NOTSS two-way timing link after a linear least squares removal of a 3.89 ns/day slope. Each point is a daily mean generated from 300 to 1500 1-PPS phase comparisons and after application of Equation 1.

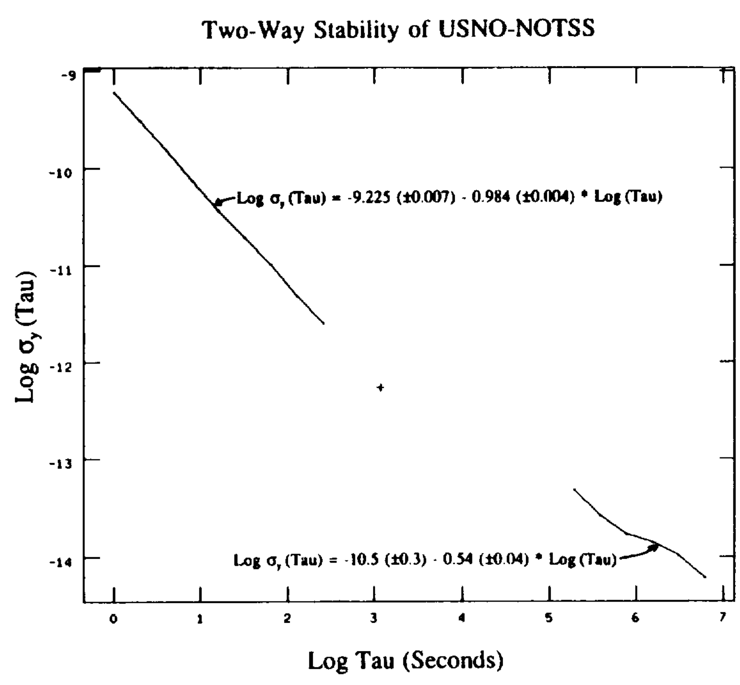

Figure 2. Sigma-tau plot of the USNO-NOTSS time comparisons. A linear least squares fit to the 1-second sample rate phase measurements results in a slope of log tau^{-1} which indicates a white phase noise character for the two-way 1-PPS phase comparisons. The unequally spaced daily data least squares slope indicates a log tau$^{-1/2}$ slope caused by the white frequency noise behavior of the NOTSS HP 5071A cesium clock. A cross-over from white phase noise of the two-way phase comparisons to the white frequency noise of the clock occurs near a tau of 1500 seconds, currently no data is available at that tau, and is indicated in the plot by a "+" symbol.

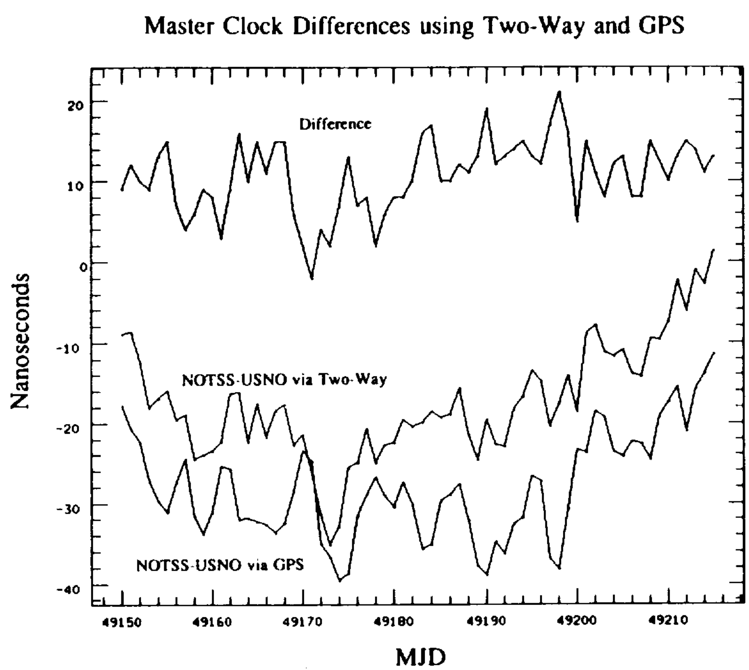

Figure 3. Clock differences as realized by GPS and the two-way timing links.

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A Comparison of GPS Broadcast and DMA Precise Ephemerides

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Abstract

We compare the broadcast ephemerides from Global Positioning Satellites (GPS) to the post-processed ephemerides from the Defense Mapping Agency (DMA). We find significant energy in the spectrum of the residuals at 1 cycle/day and higher multiples. We estimate the time variance of the residuals and show that the short term residuals, from 15 min, exhibit power law processes with greater low frequency perturbations than white phase modulation. We discuss the significance of these results for the performance of the GPS Kalman filter which estimates the broadcast orbits.

Introduction

We study here the accuracy and stability of the ephemerides broadcast from Global Positioning System satellites. We refer to them as the operational ephemerides (OE). We use as a reference, ephemerides computed in post-processed mode by the Defense Mapping Agency (DMA), called precise ephemerides (PE), and made available about 2-4 weeks after the fact. The OE are computed by the GPS operational control segment (OCS) based on data from their five tracking stations, four located near the equator nearly equispaced around the globe, and the station in Colorado Springs, Colorado, USA. The OCS uses a Kalman filter and data received from monitor stations in near-real time to update estimates of position every 15 min. The DMA ephemeris is computed based on data from the same five stations supplemented by their five tracking sites, four located at sites in the mid-latitudes of the northern and southern hemispheres. Part of the improvement in the PE is due to the improved geometry gained by having the extra stations. Other improvements inaccuracy come from estimating positions after the fact. The PE's are estimated once a week for the previous 8 d, thus providing the advantage of hindsight as well as the overlap of 1 d to maintain continuity.

The PE data are in the form of the estimates of x,y,z coordinates of each satellite referenced to each 15 minute of the day. The OE are Keplerian elements of the satellite orbit as estimated in real time by the Kalman filter in the GPS control segment at Falcon Air Force Base, Colorado

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Springs, Colorado. For each satellite, we evaluate the OE at each 15 minute of the day and subtract the resultant OE vector of the satellite position from the PE position for that time. We then cast the difference vector into components radial to the earth, along the satellite track, or on-track, and perpendicular to the satellite path, or cross track (r,o,c). We then analyze the resultant data. Such studies have been done before at different periods in the history of GPS[2].

The GPS is used as a source of precise time and time comparison in two modes, either by directly receiving the time from satellites or by using the common-view method[1]: measuring the time offset as received from a satellite at remote locations and transferring time between ground station clocks by differencing the measurements. Time transfer accuracies of 50 ns-1 s are available from direct measurement of GPS time in the presence of selective availability (S/A), for averaging times from 10 min to 1 day, depending on the algorithm used. S/A is the name for the deliberate degradation of the signals from GPS satellites to deny the full possible accuracy to the unauthorized user. Common-view time transfer accuracies vary from 30 ns to 1 ns with measurements once per day, depending on the baseline between sites and the use of corrections to transmitted data, assuming the local coordinates are appropriately accurate. International Atomic Time (TAI) is computed using mostly GPS common-view measurements to compare remote clocks. On intercontinental links measurements are corrected for the difference between broadcast and precise ephemerides. Both methods depend on the accuracy of broadcast ephemerides to compute the slant range to the satellite, hence the transmission delay.

Broadcast Ephemerides

The GPS broadcast ephemerides are computed by the Air Force Operational Control Segment (OCS). The OCS has global tracking and monitor stations located at:

- Falcon (longitude= 255.5° E, latitude= 38.5° N),
- Diego Garcia Island (longitude= 72.2°E, latitude= 6.3°S),
- Kwajalein Island (longitude= 167.3°E, latitude= 9.1°N),
- Hawaii (longitude= 201.8°E, latitude = 21.6°N).
- Ascension Island (longitude= 345.8°E, latitude= 7.6°S),

The stations measure pseudo–range to all satellites in view, correcting for S/A. The data are brought together at the Falcon site where they are processed in the OCS Kalman filter. This filter concurrently estimates states for monitor station clocks, satellite clocks, and satellite ephemerides. Operational ephemerides are estimated Keplerian elements of the satellite motion. The satellite ephemerides and clock predictions are uploaded to the satellites usually once per day, though more frequently if needed to maintain appropriate user range errors. We obtained the OE's for this paper from the International GPS Geodynamics Service (IGS).

In June 1992 the International Association of Geodesy set up the IGS to support geodetic and geophysical research activities[3]. Through a number of observatories equipped with

GPS receivers, archiving data centers and analysis centers, it collects GPS data and derives such products as ephemerides or earth orientation parameters. Three distribution centers (at NASA/Goddard Space Flight Center (NASA/GSFC), Greenbelt MD, University of California at San Diego (UCSD), Institut Geographique National Paris) are reachable by the INTERNET network for users to have access to data and products.

More than 30 receivers continuously operating throughout the world collect data and transmit it in a common format (RINEX) to regional data centers. Among the collected data are the broadcast ephemerides which are decoded from the navigation message. The Crustal Dynamics Data Information Service (CDDIS) at NASA/GSFC serves as a global collection center to gather all the data, check the uniqueness and consistency, then transfer them to the 3 distribution centers. We obtained our OE data from the CDDIS and from the center at UCSD.

Among the products, GPS precise ephemerides computed by seven analysis centers are available on a regular basis with a delay of about one week. They are the Center for Orbit Determination in Europe, University of Bern (CODE), the Geodetic Survey of Canada, Ottawa (EMR), the European Space Agency, Darmstadt (ESA), the GeoForschungsZentrum, Potsdam (GFZ), the Jet Propulsion Laboratory, Pasadena, California (JPL), the National Geodetic Survey, Rockville, Maryland (NGS), the Scripps Institution of Oceanography, La Jolla, California (SIO). The procedures of orbit determination are described in [4] and in messages available on the IGS computers [5]. The ephemerides represent an Earth–centered, Earth–fixed trajectory using GPS time as the time scale. While both the DMA PE and the GPS OE are expressed in the WGS–84 coordinate system, these ephemerides available from the IGS are referenced to the more accurate coordinate system defined by the International Earth Rotation Service's (IERS) Terrestrial Reference Frame (ITRF). IGS also plans to combine the results of the analysis centers to make available IGS combined precise ephemerides, with a delay of about two weeks.

Precise Ephemerides

The post–processed ephemerides used for this study were produced by the Defense Mapping Agency (DMA). These GPS precise ephemerides and clocks were computed at the Naval Surface Warfare Center (NSWC) starting from August of 1987. They were transferred to the DMA in July 1989 for Block I satellites and in January of 1990 for block II. Orbits, satellite clocks, station clocks, and Earth orientation are estimated simultaneously. Until recently, computations were broken into partitions of no more than seven satellites. Now all satellites are estimated in one partition. Details of these PE's are published elsewhere[6].

The pseudo–range measurements used for the computations of precise ephemerides are performed at ten tracking stations. Five of the stations are the Air Force's OCS monitoring stations mentioned in the previous paragraph. The other five stations are operated by DMA and are located in:

- Australia (longitude= 138.7° E, latitude= 34.7° S),
- Argentina (longitude= 301.5° E, latitude= 34.6° S),
- England (longitude= 358.7° E, latitude= 51.5° N),

- Bahrain (longitude= 50.6° E, latitude= 26.2° N),
- Ecuador (longitude= 281.5° E, latitude= 0.2° S).

The DMA provides both the x,y,z positions at every 15 minute of the day, as well as the satellite clock offsets from GPS time at each hour of the day.

Results

While we analyzed data for 22 satellites, for brevity we focus here on 4 satellites. These are fairly representative of the effects we found. We use one satellite from the early development phase of GPS, called block I. This one uses a rubidium clock with no base-plate temperature control. The other three are block II satellites, two with cesium clocks, and one with rubidium and with baseplate temperature control to 0.1 °C. These are described in Table I. There are two numbers for each satellite, though for most of the block II satellites they are the same. The PRN number is the pseudo-random code number (PRN) that the satellite transmits and is the number by which users know it. The satellite vehicle number (SVN) is a unique number associated with the particular satellite and is the number by which the operators know it. When a satellite becomes inoperable, its PRN number can be given to another satellite vehicle (SV).

Each of the four satellites PRN's 3, 14, 24, and 25 appear in plots labeled a, b, c, and d, respectively. We present three plots of the differenced ephemerides: 1) the r,o,c differences PE–OE plotted only for PRN's 3 and 14, plots 1a and 1b, respectively, 2) the modulus of the FFT of PE–OE data (using a cosine squared windowing function), Figures 2a–2d, and 3) the Time Deviation[7] of the PE–OE data in Figures 3a–3d. We also present the modulus Fast Fourier Transform (FFT) of the DMA estimates of satellite clock offsets from GPS time in 4a–4d. In plots 1a and 1b and 2a–2d we have offset some of the values to make the plot easier to view. In 1a and 1b we have subtracted 30 m from the radial residuals, and added 30 m to the cross-track residuals. In the log-log plots 2a–2d we have divided the radial errors by 100 and multiplied the cross-track errors by 100.

We consider the residuals in the PE–OE data to be dominated by errors in the OE. The accuracy of the PE is expected to be of the order of 1.5 m in each of the radial, on-track and cross-track components. In particular, the PE has a known radial error due to using the WGS–84 value of GM, the universal gravitational constant times the mass of the earth, for the earth. This produces an error of the order of 1.3 m. Since the OE uses the same value, this effect should cancel.

We consider two effects: periodic terms and underlying noise types. From Figures 2a–2d, we see significant energy in periodic terms with periods of 1, 2 and 3 cycles/day. There are often higher multiples of these as well. We plot the FFT of the clocks versus GPS time to look for correlation in Figures 4a–4d, considering the possibility that the cause of the variations are unmodelled clock variations being driven into forced error by the OCS Kalman filter. The filter has no model for periodicity in the clocks, hence could pass a periodic clock offset into positioning errors. We summarize the periodic terms in table II.

Figures 3a–3d show there are two underlying noise types present in the data beneath the periodic effects. The radial noise is much smaller than on– and cross–track noise for all satellites. The periodic terms bias the $\sigma_y()$ plots at half the period of the cycle, which generally occurs at 2–4 h. The slope for the short term data, before the effect of the periodic terms, typically varies from 0 to $\pm$ on the log–log plot. This indicates dominant noise types of flicker and random walk in position respectively, appearing significantly in at least intervals of 15–30 min. After that the values are biased by the periodic effects. For periods longer than 8 h of integration the dominant noise type is white noise in position, indicated by a $\pm 1/2$ slope. The random walk process has impulses of about 20 cm at 15 min, and then increases by the square root of the averaging time to about 1 m at 4 h. At that point the white process takes over with an equivalent standard deviation of 1 m at 4 h.

Since the noise type in long term is white modulation of position we are justified in computing the mean and standard deviation of the root–sum–square (RSS) error of the r, o and c errors. These are listed in table III.

Conclusions

We conclude first that the periodic ephemeris error terms are not generally correlated with satellite clock offsets. There are some periodic terms in the rubidium clocks, notably with the block I satellites. Since the block I rubidium clocks have no base–plate temperature control, and since rubidium clocks in general have significant temperature coefficients it is not unexpected that these SV clocks have periodic behavior coherent with the period of the orbits. These terms are not evident in the block II clocks, where we see only a white FM noise process with any confidence.

Assuming the PE errors are less than 1.5 m, the periodic terms in the PE–OE computation are residual errors in the OCS Kalman estimates of position. It is not surprising to find periodic terms coherent with the period of the Earth–satellite system, and higher multiples. The filters which estimate the PE and OE estimate Keplerian elements whose differences must produce periodic terms. However, the magnitude and persistence of some of the stronger terms suggest the possibility for improvement. Simply a consistent error in the orbit eccentricity could produce the sinusoid we see.

Periodicities in orbit errors can produce positioning error biases for users. It is common to try to improve a position fix by averaging. Typically navigation or positioning receivers use the best available satellites at a given time. Since this geometry repeats day to day, receivers will often repeat satellite configurations day to day used for positioning. Each such positioning may be biased by periodic errors in broadcast satellite coordinates. This suggests a strategy of randomizing the sequence of satellites used from day to day to improve the effects of averaging.

The residuals of an optimal filter should behave according to white noise modulation with no periodic behavior. One implication is that the periodicities could perhaps be removed. If the OCS had access to a post–processed ephemeris with a 2–3 day delay, they could use the periodic residuals to estimate corrections to Keplerian elements. The broadening of some of the spectral lines in the data suggests limits to this idea. The short term noise type of random walk in position indicates instability in the Kalman estimates.

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Table I

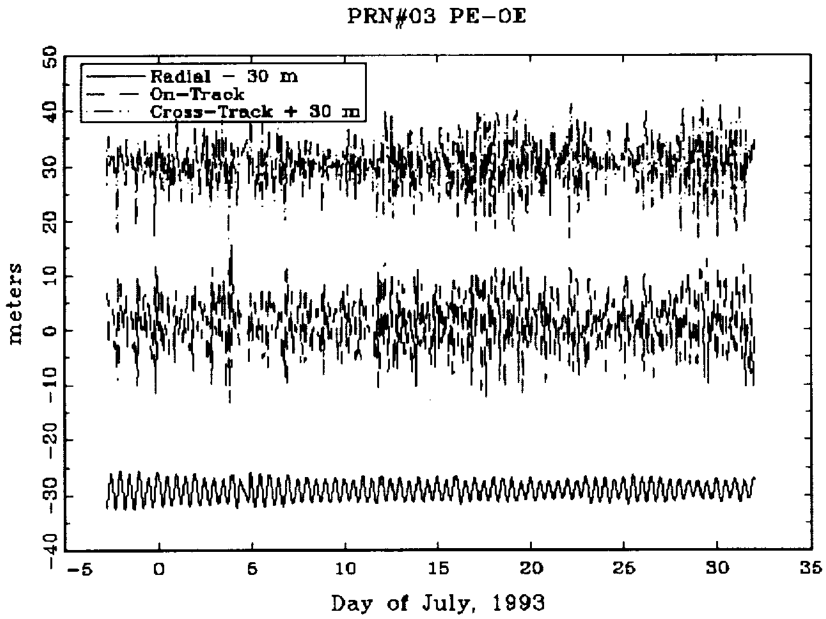
PRN#/SVN#	block #	Clock Type
3/11	I	Rb
14	II	Cs
24	II	Cs
25	II	Rb

Table II
Periodic Terms

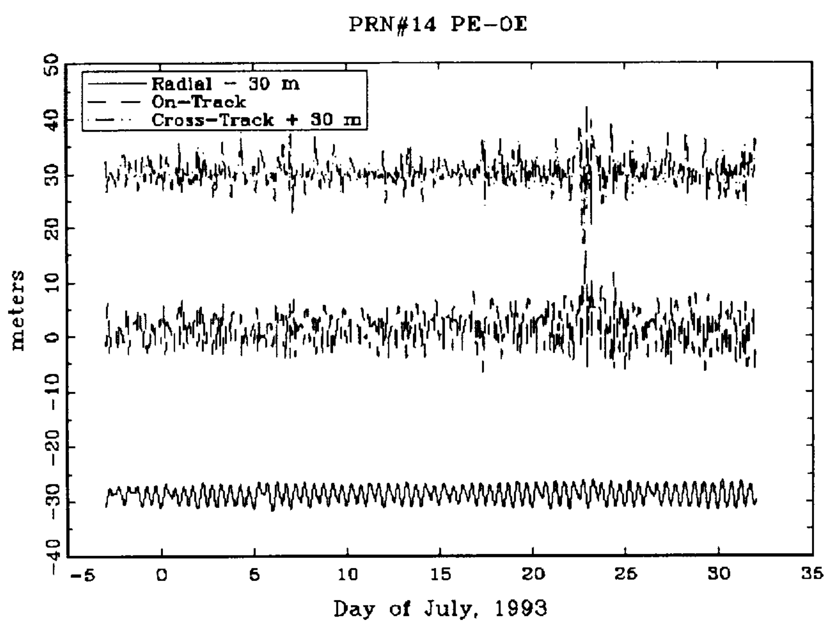
PRN#/SVN#	Periodic Terms PE-OE (cycles/d)			Amplitude Above Noise(db)			Periodic Terms Clock (cycles/d)	Amplitude Above Noise(db)
	r	o	c	r	o	c		
3/11	1 2 - -	1 2 3 h	1 - 3 h	6 32 -	16 17 16	16 - 20	2 4	18 16
14	1 2 - -	1 2 3 h	1 2 3 h	20 32 -	14 11 28	14 20 20	None Significant	
24	1 2 - -	1 - 3 h	1 2 3 h	12 38 -	32 - 20	30 25 20	None Significant	
25	1 2 3 -	1 - 3 h	1 2 3 h	9 30 12	20 - 20	12 14 14	1 2	6 9

Table III
Mean and Standard Deviation of RSS Errors

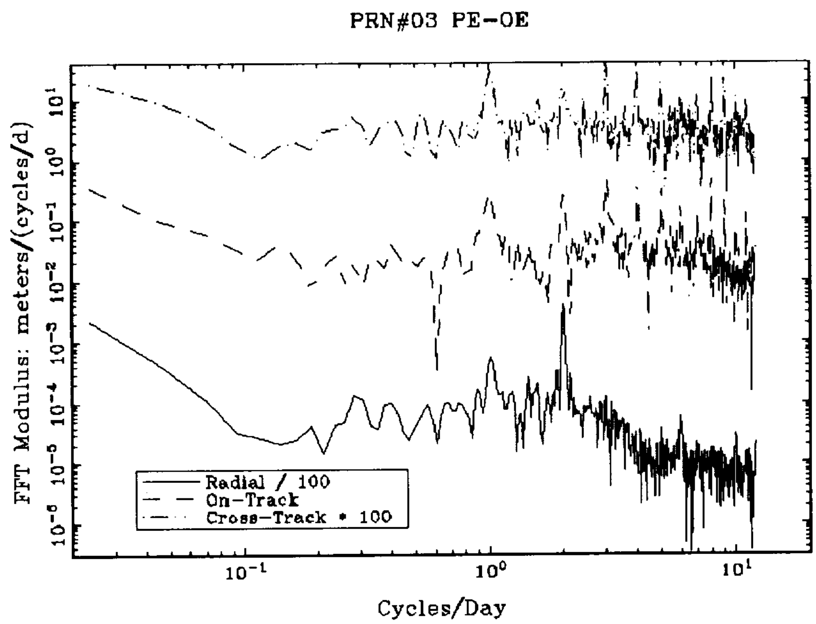
PRN#/SVN#	Mean RSS, meters	Standard Deviation of RSS, meters
03/11	7.6	3.0
14	4.7	2.4
24	10.4	4.1
25	5.3	2.6



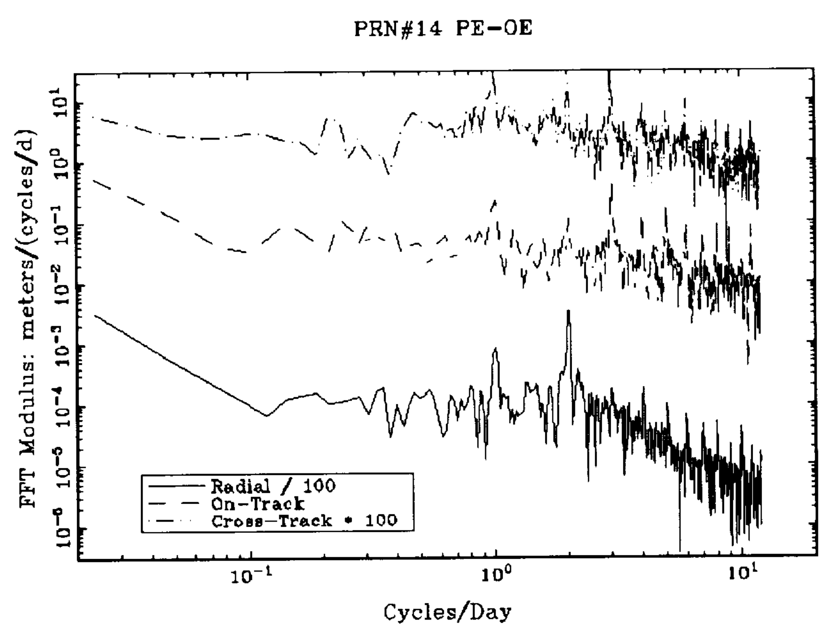
1a. The residuals of the Precise minus Operational ephemerides for PRN#3/SVN#11, a block I satellite with a rubidium clock on board. We have subtracted 30 m from the radial residuals, and added 30 m to the cross-track residuals to simplifiy the plot.



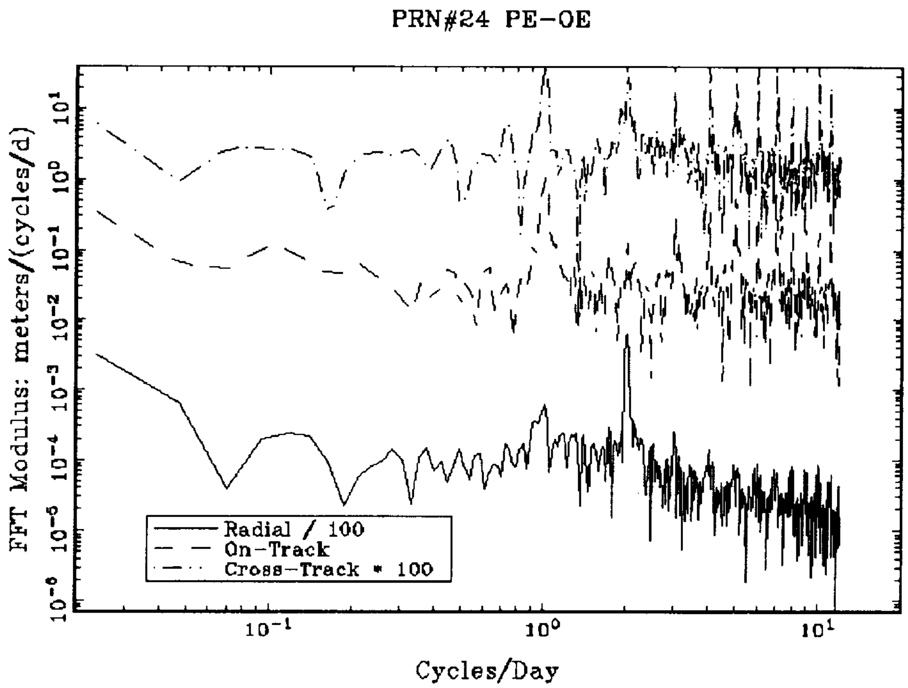
1b. The residuals of the Precise minus Operational ephemerides for PRN#14, a block II satellite with a cesium clock on board. We have subtracted 30 m from the radial residuals, and added 30 m to the cross-track residuals to simplifiy the plot.



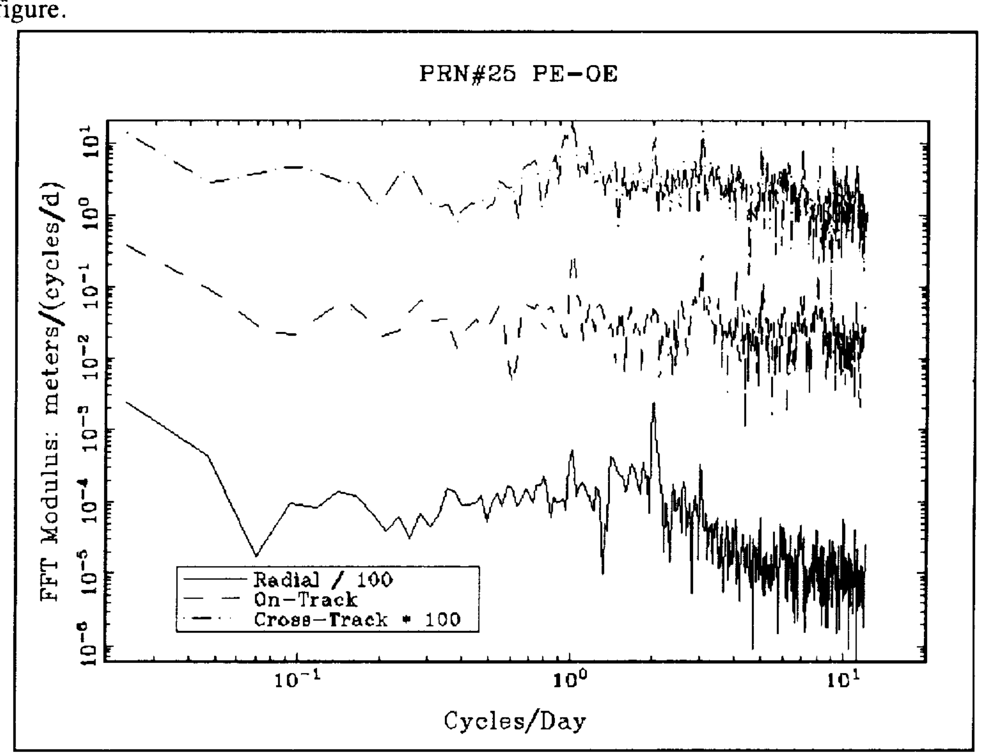
2a. A log-log plot of the FFT modulus of the PE-OE residuals for PRN#3/SVN#11 showing the presence of periodic terms above a noise floor. We have divided the radial errors by 100 and multiplied the cross-track errors by 100, to clarify the figure.



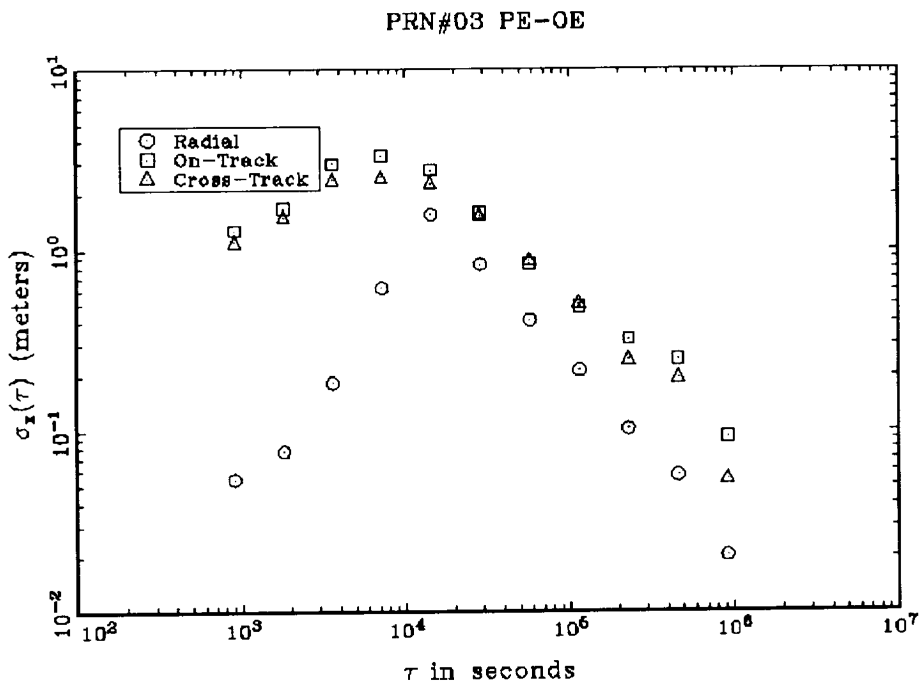
2b. A log-log plot of the FFT modulus of the PE-OE residuals for PRN#14 showing the presence of periodic terms above a noise floor. We have divided the radial errors by 100 and multiplied the cross-track errors by 100, to clarify the figure.



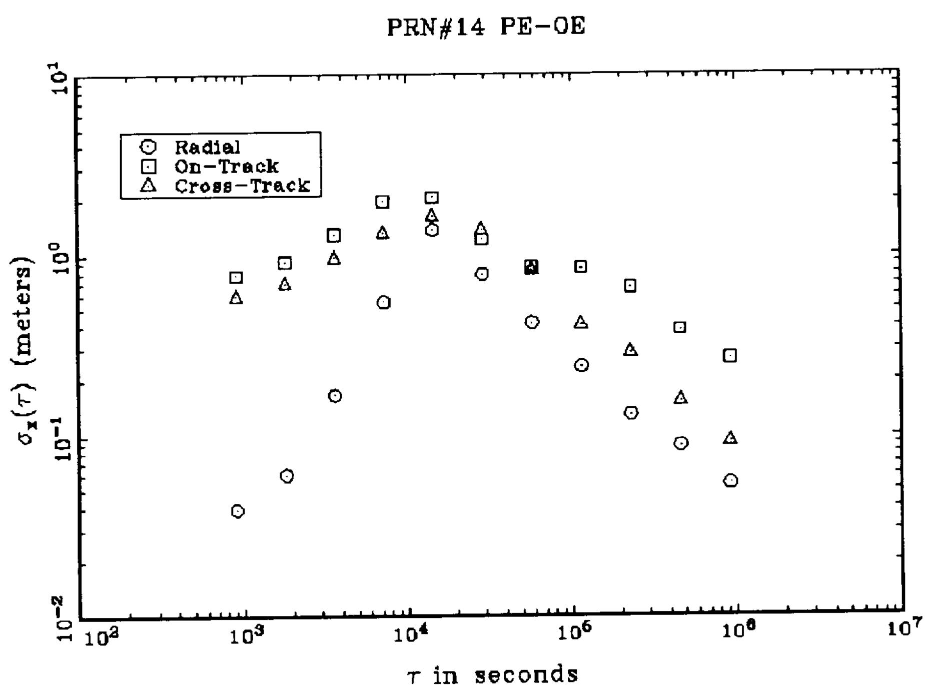
2c. A log-log plot of the FFT modulus of the PE-OE residuals for PRN#24 showing the presence of periodic terms above a noise floor. We have divided the radial errors by 100 and multiplied the cross-track errors by 100, to clarify the figure.



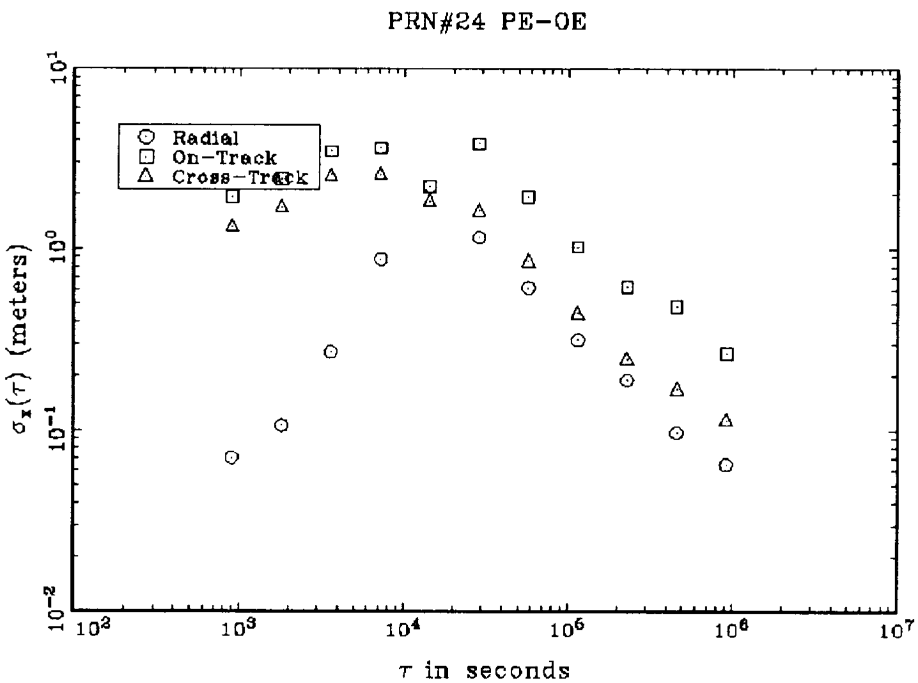
2d. A log-log plot of the FFT modulus of the PE-OE residuals for PRN#25 showing the presence of periodic terms above a noise floor. We have divided the radial errors by 100 and multiplied the cross-track errors by 100, to clarify the figure.



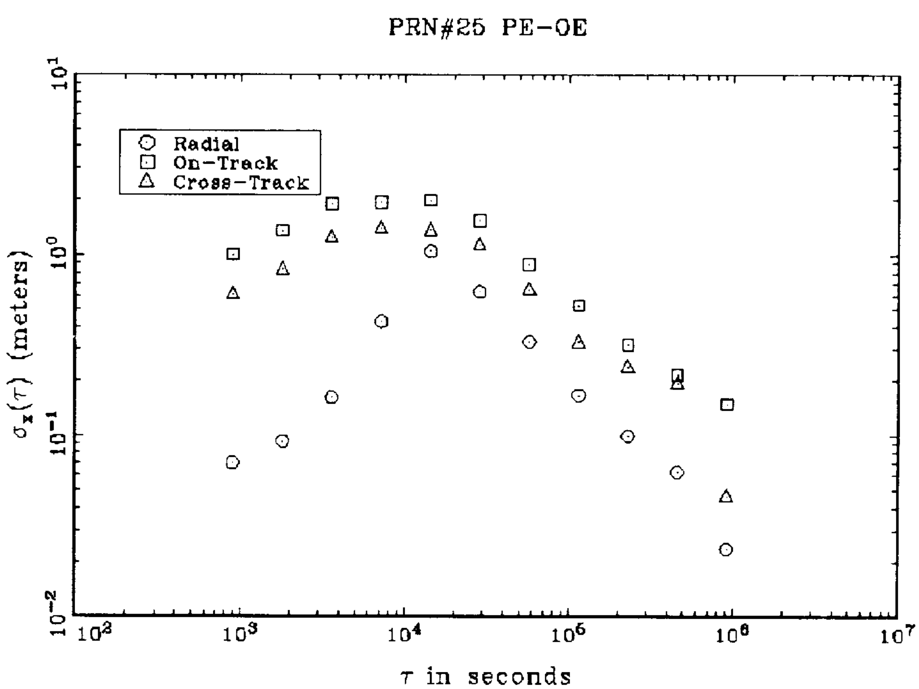
3a. The time variance of the PE-OE residuals for PRN#3/SVN#11.



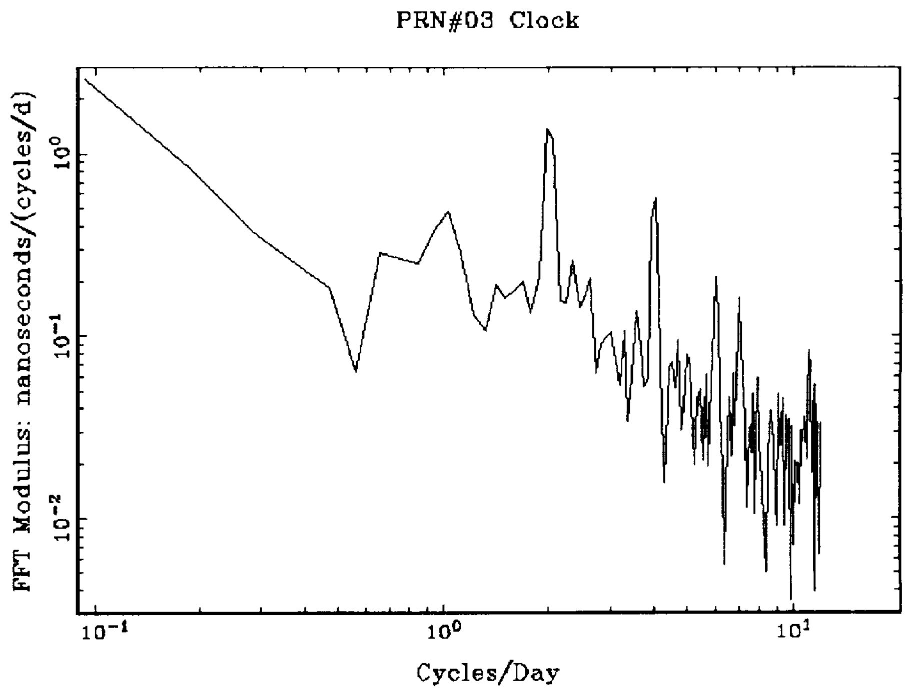
3b. The time variance of the PE-OE residuals for PRN#14.



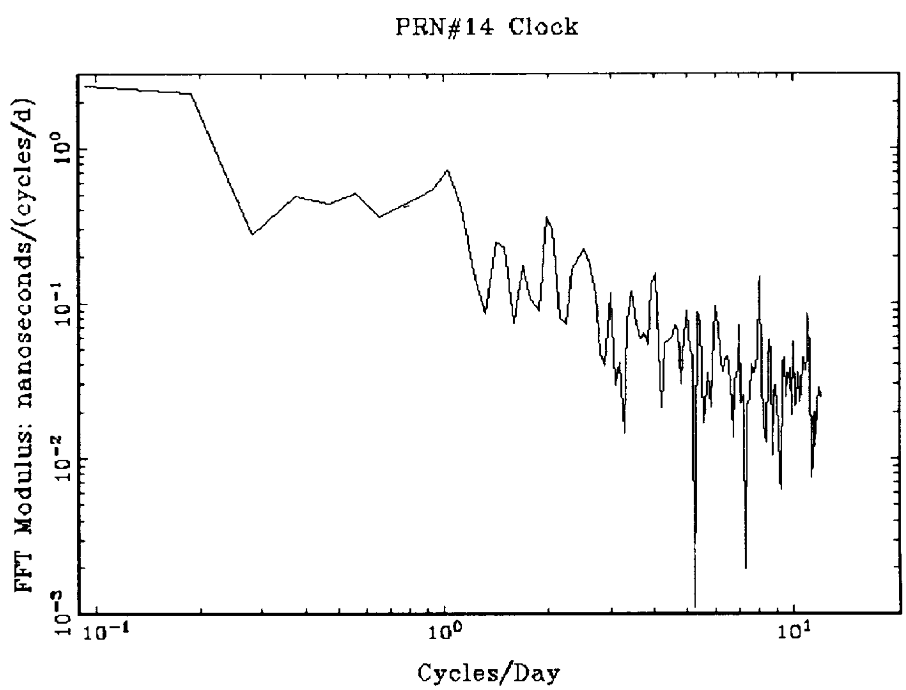
3c. The time variance of the PE-OE residuals for PRN#24.



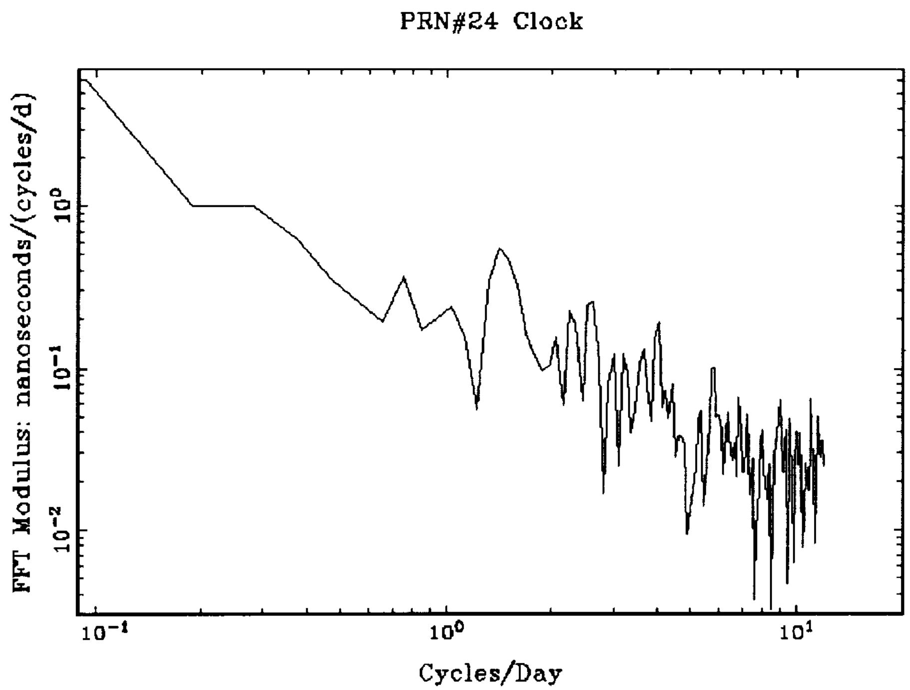
3d. The time variance of the PE-OE residuals for PRN#25.



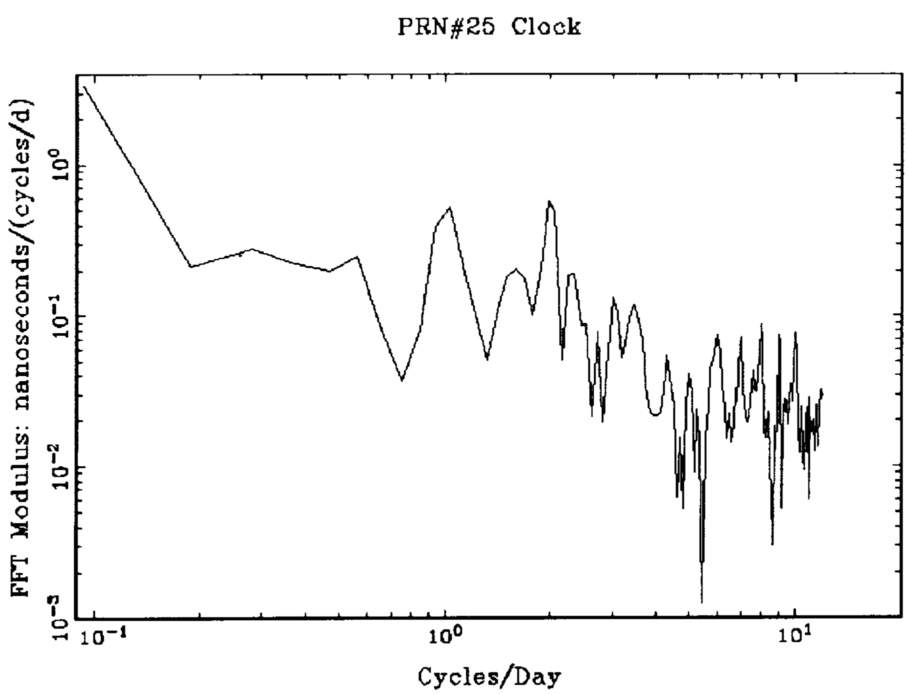
4a. The FFT of the modulus of the DMA clock estimates for PRN#3/SVN#11 offset from GPS composite clock time.



4b. The FFT of the modulus of the DMA clock estimates for PRN#14 offset from GPS composite clock time.



4c. The FFT of the modulus of the DMA clock estimates for PRN#24 offset from GPS composite clock time.



4d. The FFT of the modulus of the DMA clock estimates for PRN#25 offset from GPS composite clock time.

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SOME APPLICATIONS OF GPS TIMING INFORMATION

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INTRODUCTION

GPS Satellites transmit two independent signals. One is C / A code (course acquisition signal) could be utilized by all civilian users. This service is called as Standard Positioning Service (SPS). Another is P code (precise signal) that could be only accessed by those authorized users. The service is called as precise positioning service (PPS). SPS C / A code users can navigate with accuracy of approximately 100m and timing accuracy of about 250–300 ns (1 sigma). Such timing accuracy is not enough for precision time and frequency value transfer. For this reason we must do some research work to improve the SPS C / A code accuracy which SPS users can get.

This paper presents our recently progress on timing information analysis, its data processing and its timing and frequency measurement applications.

GPS TIMING SIGNAL

As we know, GPS signal can give very precision timing information. Each GPS satellite has a Cs atomic clock on it. And GPS ground monitor and control stations continuously monitor and find out every GPS satellile's timing data error via comparison with UTC (USNO) standard timing signal. Then the ground correction data pouring station transmits the correction data to corresponding GPS satellite and the satellite transmits the data to users. The user equipment could process the timing data and output very precision timing signal.

Typical error budget of GPS time comparisons in common view is shown in Table 1.

THE EFFECT OF 'SA' TO TIMING ACCURACY

In order to reduce the C / A code application accuracy further, the measurement so called selective availability (SA) has been taken on Block II GPS Satellites.

According to GPS overall design the timing accuracy related to UTC (USNO) is about 100ns. Our experimental measurements indicated that the timing accuracy is reduced to about 300ns. (see Figure 1)

THE TECHNIQUES TO IMPROVE THE ACCURACY FOR TIME AND FREQUENCY SYNCHRONIZATION

1 Applying better ionospheric time delay error correction algorithm model

"Klobuchar" model is used for ionospheric time delay correction in Model 9390 GPS Time Frequency Monitor. It could correct the C / A L1 signal ionospheric error for only about 50% (refer to Figure 2). Therefore we should use a better algorithm model to improve ionospheric time-delay error which is one main error for GPS time and frequency transfer.

2 Using better data processing techniques, such as Kalman filter

We have developed a sort of clock-difference (TI value) data Kalman filter. The Kalman filter can filter out the additional noise introduced during the GPS signal is propagated from GPS satellite to user's equipments.

The design, and measurement results refer to Figure 3 and Figure 4.

3 GPS common-view time comparison could eliminate the effect of 'SA' to timing precision

This is due to SA is a conjugating error for users of commonview time comparison.

We have developed a GPS time interval data collector which is used to replace the on–duty microcomputer to collect clock difference data of GPS common–view time comparison.

We have used the accumulator for more than 3 months (from January 1993 to April 1993) to do the International GPS common–view time comparison with Asia and Pacific nations Time Standard Laboratories.

The block diagram of GPS time interval data collector is shown in Figure 5.

4 Deducing the frequency measuring uncertainty of GPS timing signal via enlarging overall measuring period

The limitation for frequency measuring accuracy depends on the following two factors: one is the long–term frequency stability of the GPS satellite on–board Cs atomic clock. Another one is the corresponding long–term frequency stability of GPS arrival signal at user equipment. GPS Satellite on–board Cs clock's frequency stability per day is about 1×10^{-13}. While the frequency stability per day of GPS signal at user equipment is about 3×10^{-13} without switching–on 'SA'. Under switching–on 'SA' it deduced to 10^{-12} level. We enlarged the sampling time interval to 10 days, the frequency stability per 10 days for GPS signal at user equipment is deduced to about 5×10^{-13}. Thus by means of enlarging the sampling time interval to 10 days we could measure frequency with accuracy less than $\pm 1 \times 10^{-12}$(refer to Tables 2 and 3).

CONCLUSIONS

1. GPS Signal is a very useful, high–precision space information resource which can be shared anywhere in the world. GPS timing technique is the most accurate timing technique up to date.

2. According to the characteristics of time comparison we could process the time comparison data afterwards, use common–view technique, enlarge the measuring period and we only need tracking one GPS satellite for timing. We can fully use these characteristics to overcome "SA" effect to improve the timing accuracy.

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Table 1 Typical error budget of GPS time comparisons in common view (CV), at distance d, C / A–code (Unit: 1 ns)

Error	For a single CV		For 10CV, average over 1 day[1]	
d=	1000km	5000km	1000km	5000km
• Satellite clock error (cancelled in CV mode)	0	0	0	0
• Antenna coordinates[2]	20	20	7	7
• Satellite corrdinates	2	8	1	3
• Ionosphere (day time, normal solar activity, elevation >30 °)	6	15	1	3
• Troposphere (elevation >30 °)	2	2	0.7	0.7
• Instrumental delay (relative)	2	2	2	2
• Receiver software	2	2	2	2
• Multipath propagation	5	5	2	2
• Receiver noise (13–min average)	3	3	1	1
• Total	22	27	8	10

[1]The noise of the laboratory clocks and the rise time of reference pulse bring nonnegligible contributions, which are not considered here.

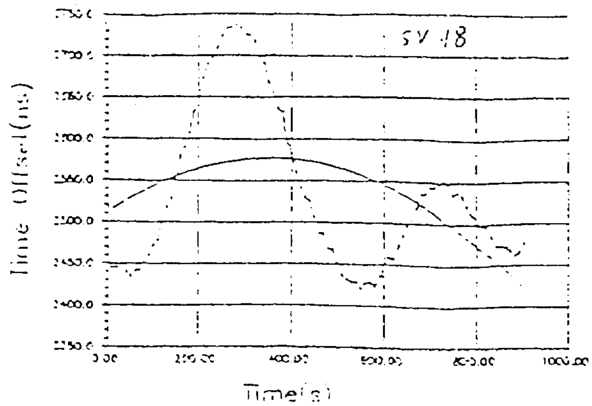
[2]Assuming uncertainties of the order of 3m. In practice, errors of coordinates can sometimes reach 30–40m.

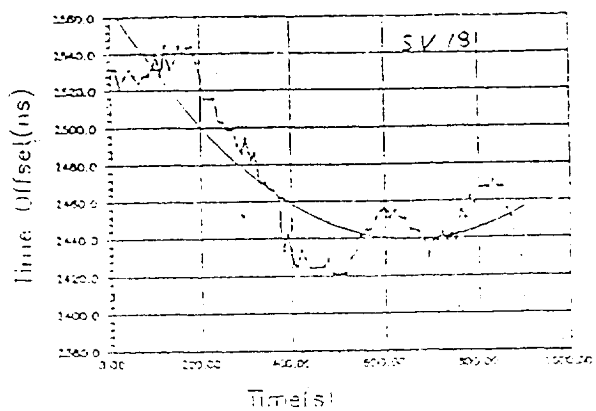
Table 2 The measurement results of GPS signal at user equipment

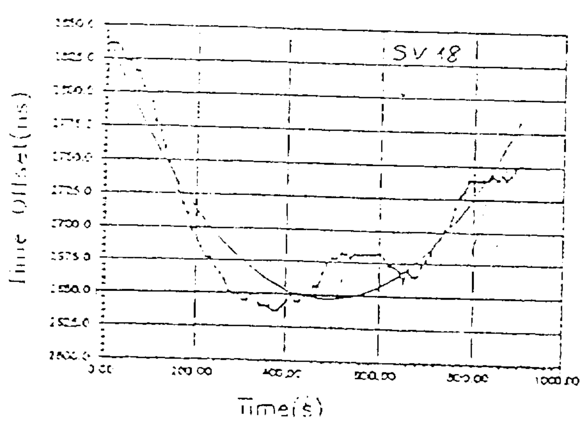
GPS signal frequency stability per day	GPS SV Number	Date Y M D	The length of measurements	The RMS of measurement residuals	The A_0 value of fit curve with 2nd items	Note
1.31×10^{-12} 2.60×10^{12}	28	93 06 27	820	94.5	75753.8	BLOCK II ('SA')
		93 06 28	840	111.9	75867.2	
		93 06 29	820	64.6	75642.4	
2.07×10^{-12} 2.36×10^{-12}	27	93 06 27	810	63.8	75896.6	BLOCK II ('SA')
		93 06 28	840	44.2	75718.1	
		93 06 29	840	77.2	75921.9	
1.24×10^{-12}	12	93 06 27	840	3.2	75882.3	BLOCK I
		93 06 28	840	0.9	75774.8	
1.49×10^{-2}	03	93 06 26	840	4.1	76032.0	BLOCK I
		93 06 27	840	10.2	75917.4	
		93 06 28	840	2.3	75775.1	

Table 3 The comparison between GPS signal frequency stability for 1d and 10d

τ \ SV	03	13	26	27
1d	2.96×10^{-13}	3.78×10^{-13}	1.29×10^{-12}	1.28×10^{-12}
10d	1.51×10^{-13}	2.71×10^{-13}	3.78×10^{-13}	2.48×10^{-13}







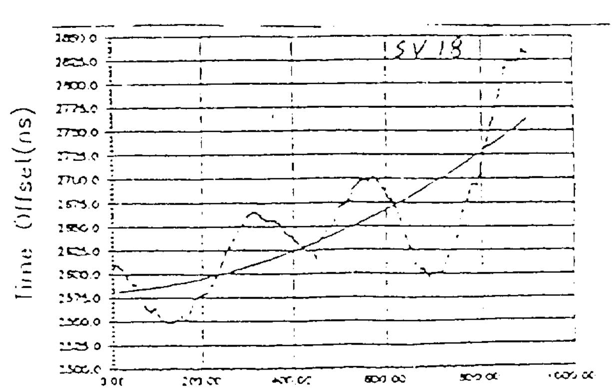


Fig.1. GPS sv 18 (Block II) T1Curve

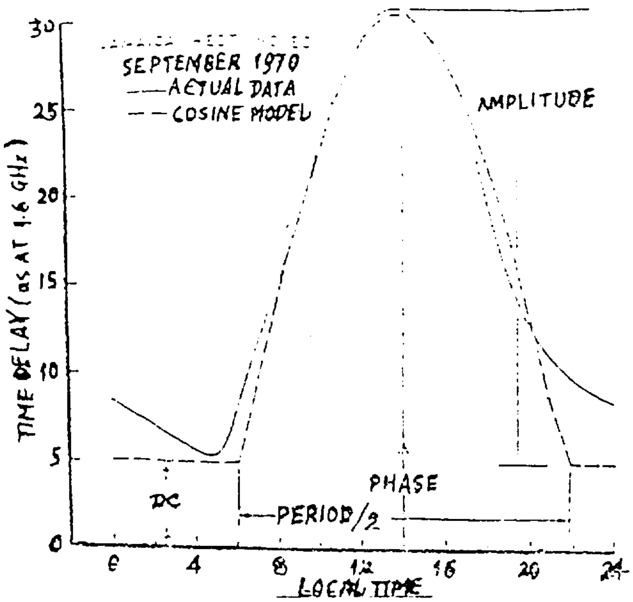


Fig.2. Klobuchar Algorithm Model

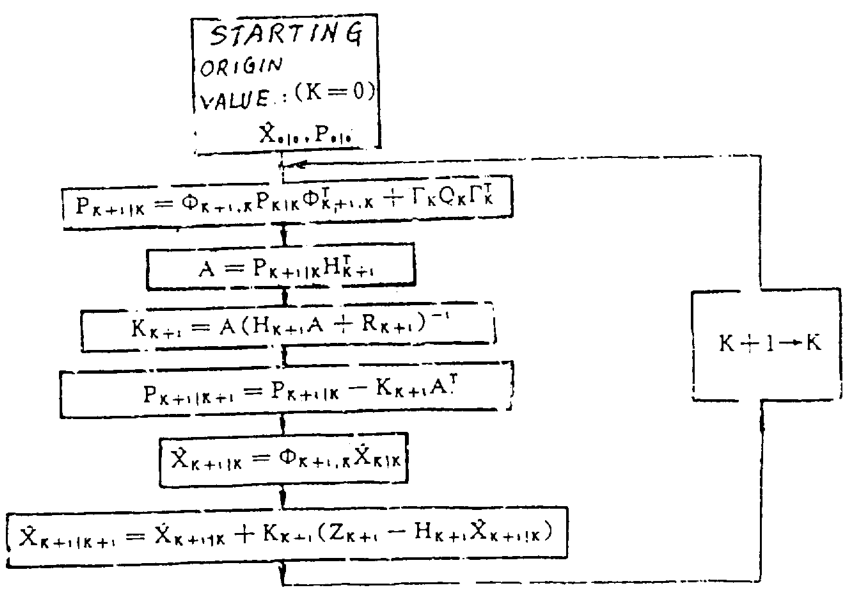


Fig.3. Standard Kalman Filter Algorithm

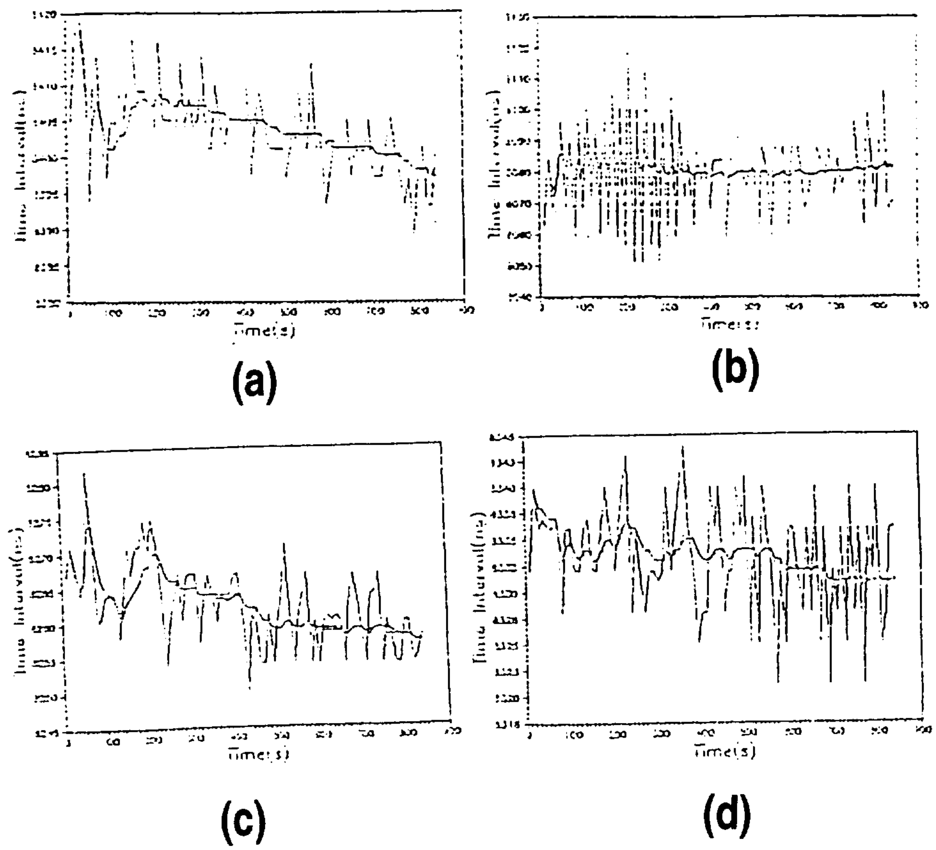


Fig.4. The Measured Curve of Data Kalman Filter Efficiency

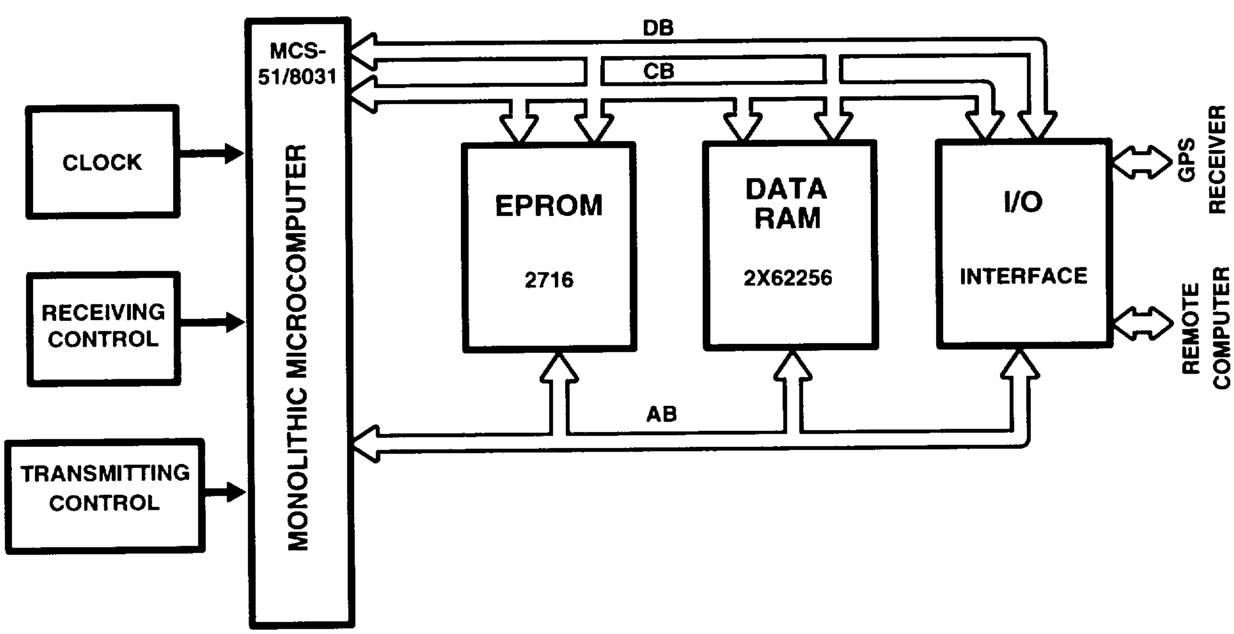


Fig. The Block Diagram of T1 Accumulator Hardware

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A COMPARISON OF SEVERAL GPS DATA REDUCTION METHODS

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Abstract

For several years, discussions have been ongoing about how to analyze GPS time information in order to get the most accurate and precise time comparison between two locations. Many similar studies were done several years ago before the constellation was dominated by Block II satellites. With the Block II satellites and the use of Selective Availability (S/A), time comparisons have lost some precision and accuracy. This paper presents the results of research that was performed to find not only the best of several time comparison methods, but also to determine to what degree precision and accuracy have declined due to S/A.

Introduction

The U.S. Naval Observatory (USNO) has been monitoring the GPS time signals for more than 15 years, and through the years, the timing community has been discussing the best reduction methods for those signals. GPS is to date the most accurate and precise navigation and timing system available. We in the timing community are constantly trying for better and, to that end, it was decided that a comparison study should be made of three easily implemented reduction methods. The object was to find the accuracy attainable, the pitfalls, and the effects of Selective Availability (S/A) on each method.

Data

The data used in this study were collected on an STel model 502 single frequency GPS receiver (SFR) at USNO in Washington, D.C. and at the Naval Observatory Time Service Substation (NOTSS) in Miami, FL. This receiver produces both a GPS and a UTC time value. Each data point used in the reduction was the result of a linear fit through approximately 130 six–second data points referred to the beginning of the track period. The use of 13 minute periods of data insures that the entire GPS message containing the ionospheric and UTC time corrections was received[1].

Reduction Methods Used

It was decided that three distinct time comparison methods should be compared. The first would use the UTC time correction as transmitted by the GPS satellites. This is the most easily obtained information and can be easily reduced to a relatively high level of accuracy when compared to LORAN and other timing sources. The second method would use common view data points. In this method, two locations monitor the same satellite simultaneously. Each receives a GPS time (or UTC time) from the satellite versus a local reference. Simple subtraction will yield the difference between the two locations. For official timing in the US, one of those locations is USNO in Washington, D.C., and the other location is the point to be synchronized. The third method of reduction would use a "melting pot" of data points. In this method, each location monitors either the most visible satellite (in the case of a single channel receiver) or all satellites possible (in the case of a multi–channel receiver). The individual GPS time versus the local standard's time comparisons are "lumped" together over a period of time. The linear fit solution of these points is considered the offset of the GPS time from the local standard's time. Subtracting one local standard's offset time from the other yields the time difference between the two locations. Again, for official timing in the US, one of those locations is USNO in Washington, D.C., and the other location is the point to be synchronized. The "melting pot" method is similar to the satellite hopping method[2] and has been employed by USNO for over 15 years[3].

In this study, it was recognized early that the common view method would be better for short distances between locations, but that it could have a problem over great distances due to geometric and ionospheric considerations. Aside from the coordination efforts and personnel needed to employ common view schedules at various locations, there is also the problem of local schedule demands that can prevent a fully optimized common viewing. Because this research could not interrupt ongoing operations, common view data values were taken whenever they could be obtained. This varied from under 60% to over 80% of the total number of data points collected at a location. It was also recognized that the "melting pot" method would have an accuracy problem if there were not enough data points to fit a curve. A preliminary item of research was to find how many data points were needed to get a valid solution to the "melting pot" linear fit solution. It was found that at least 70 data points per 48–hour period were consistently needed to obtain a result with less than one sigma deviation. A third problem was how to compare a solution that produced many time difference values (common view method) with one that would produce one time difference value per day (melting pot). It was found that the common view method produced scattered results (although not as much as the other methods). A linear fit of those common view points produced a higher level of accuracy and a way to compare common view data reduction one-on-one with "melting pot" reduction.

The linear fit solution method was chosen over more complex methods (e.g., Vondrak's[4]) because it was found to be the simplest method that would produce a reasonable result consistently. More elaborate methods were tried and found to agree with Winkler[5], that the more complex methods produced results that were no more accurate and, occasionally, less accurate. Data filtering for the linear fit solution was a two–step process. First, a coarse filter removed the obviously bad values (i.e., a value one microsecond off from its expected value). A first pass through the linear fit program was then performed, with slope and sigma values calculated. All points exceeding two sigma were then deleted from the reduction and all remaining points linear fitted for a second time. The result from this second pass is the reported value.

Block II results were compared to Block I results to see the degradation due to S/A. Then the results for the common view and "melting pot" reduction methods were compared to decide which is better.

Results

Method 1) Use the UTC time as transmitted by the satellites. This information can be used in several ways.

a) One satellite is observed for a brief time. The time difference between this transmitted UTC time value and the local time standard is taken as the offset between the local standard and UTC(USNO). (UTC(USNO) is the standard by which the GPS is compared.) This one–shot method can vary more than 60 nanoseconds, when using only Block I satellites or Block II with S/A off, and more than 300 nanoseconds, when Block II satellites are used with S/A on (see Fig. 1).

b) Several satellites are observed for extended periods of time. The running linear fit solution (a 48–hour period was used here) of the difference between the UTC time transmitted from these satellites and the local time standard is taken as the offset between the local standard and UTC(USNO). This linear fit method, using only Block I satellites, can vary more than 20 nanoseconds (see Fig. 2) with an rms of 10 to 20 nanoseconds (see Fig. 3). When using Block II satellites with S/A enabled, the difference can vary more than 30 nanoseconds (see Fig. 4) with an rms of 60 to 80 nanoseconds (see Fig. 5).

To get a better picture of the effects of S/A, we subtract the Block I linear fit result from the Block II result. This results in showing that S/A will affect the UTC timing by more than ± 20 nanoseconds (see Fig. 6).

With either of these methods, the data are dependent on the GPS Master Control Station (MCS) to upload in a timely manner the current UTC offset to the satellites. Currently, these corrections are uploaded once every 24 hours. However, these uploads may not be frequent enough to meet the needs of some locations.

Method 2) A time comparison between two locations can be made. Time offset data are collected at the standard (USNO) and at the location desiring time synchronization. By simple subtraction, the time offset between USNO and the remote site is found. This comparison can be done in several ways. To compare the various methods, avoid the problem of the MSC's failure to upload the UTC correction to the satellites simultaneously, and respond to local monitoring requirements, the GPS time transmitted by the satellites was used.

a) One satellite is simultaneously observed at both locations for a brief time. Values of USNO minus satellite time and local clock minus satellite time are obtained. Subtraction of the second from the first will yield USNO minus local clock. The values obtained from this one simultaneously observed satellite (single point common view) method can vary more than 20 nanoseconds, depending on which satellite is observed, when using only Block I satellites (see Fig. 7), to more than 40 nanoseconds, when Block II satellites are used with S/A enabled (see Fig 8).

b) One satellite is simultaneously observed at both locations for a brief time. Values of USNO minus satellite time and local clock minus satellite time are obtained. Subtraction of the second from the first will yield USNO minus local clock. This one simultaneously observed satellite value is then linear-fitted with other values over a specified period of time (48 hours were used here). This linear fitting of common view values method using Block I satellites can vary more than 5 nanoseconds (see Fig 9), with an rms of 2 to 10 nanoseconds (see Fig. 10). When Block II satellites are used with S/A enabled, the difference can vary more than 10 nanoseconds (see Fig. 11), with an rms of 5 to 10 nanoseconds (see Fig. 12).

Again, to get a better picture of the effects of S/A, we subtract the Block I linear fit result from the Block II result. This results in showing that S/A will affect the linear fitting of common view points by more than +/- 5 nanoseconds (see Fig. 13).

c) All satellites in view at each location are observed. Only a small amount of effort, if any, is made to observe the same satellite simultaneously at each location. The clock minus GPS time values from USNO and clock minus GPS time values from the local clock are linear-fitted separately. Then subtracting the second from the first, one obtains USNO minus local clock. The result is a "melting pot" of satellites' linear fit time transfer between two locations. This "melting pot" linear fit method using only Block I satellites can vary by more than 10 nanoseconds (see Fig. 14), with an rms of 10 to 25 nanoseconds (see Fig. 15). When using Block II satellites with S/A enabled, the difference can vary more than 20 nanoseconds (see Fig. 16), with an rms of 80 to 110 nanoseconds (see Fig. 17).

Yet again, to get a better picture of the effects of S/A, we subtract the Block I linear fit result from the Block II result. This shows that S/A affects the linear fitting of "melting pot" points by more than ± 10 nanoseconds (see Fig. 18).

This concludes the comparison of the effect of Selective Availability on time synchronization of a clock to UTC(USNO). However, a comparison of common view versus "melting pot" must yet be done to determine the better analysis method.

For Block I satellites, the "melting pot" solution minus a linear fit of the common view points is less than ± 20 nanoseconds (see Fig. 19). But, a running five-day average is less than 15 nanoseconds (see Fig. 20). A running 60-day average shows the difference in the two methods is less than 10 nanoseconds (see Fig. 21). Using Block II satellites, the difference will vary by ± 20 nanoseconds (see Fig. 22). Again, by averaging the differences over a period of time, the average difference is much less. For a five-day running average, the difference can be over 10 nanoseconds (see Fig. 23). When a 60-day running average is performed, the average difference is less than 10 nanoseconds (see Fig 24).

Conclusions

The level of accuracy and precision needed at a location will determine how best to synchronize a local clock to UTC(USNO). If the tolerance is more than half a microsecond (500 nanoseconds), the local clock can be set according to the UTC time transmitted by any satellite (Block I or II). For closer tolerance, data reduction methods must be employed and time comparisons must be made between USNO and the remote clock.

A one–time comparison using one satellite will yield an error of more than 40 nanoseconds for Block II satellites with S/A enabled. Linear fitting of several common view time comparisons will yield an error of more than 10 nanoseconds, with an rms of over 10 nanoseconds, for Block II satellites with S/A enabled. A "melting pot" time comparison will yield a tolerance of more than 20 nanoseconds, with an rms of over 100 nanoseconds, for Block II satellites with S/A enabled. The linear–fitted common view solution is within 10 nanoseconds difference from the "melting pot" solution when averaged over 60 days. Although the "melting pot" method is more than ten times noisier, it is far less work to implement. Exact viewing schedules do not have to be loaded into each GPS receiver. The "melting pot" method requires many data points to maintain its accuracy (70 to 80 passes per 48–hour period), whereas the common view method needs considerably fewer data points (at least five to ten per 48–hour period) to maintain its high level of accuracy. The analysis of common view points also requires that the data reduction program do a considerable amount of verification and resynchronization of those data points whose collection times do not exactly match. As a result, the initial programming takes longer to develop and the program execution takes fractionally longer than the "melting pot" analysis.

The final judgement of whether performing the extra work in programming and maintaining common view time comparison is offset by the lower noise level of the results must be left to the individual centers of operations. Each center's procedure is governed by its own allowable tolerances.

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[3] Winkler, G.M.R. (USNO), private communication, 1993

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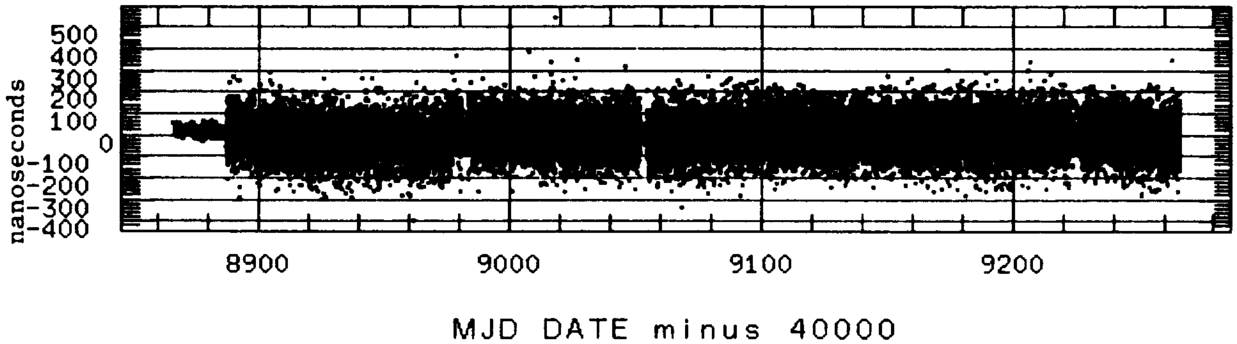
[5] Winkler, G.M.R., *"Introduction to Robust Statistics and Data Filtering"*, 1993 Frequency Control Symposium Tutorials, June 1993

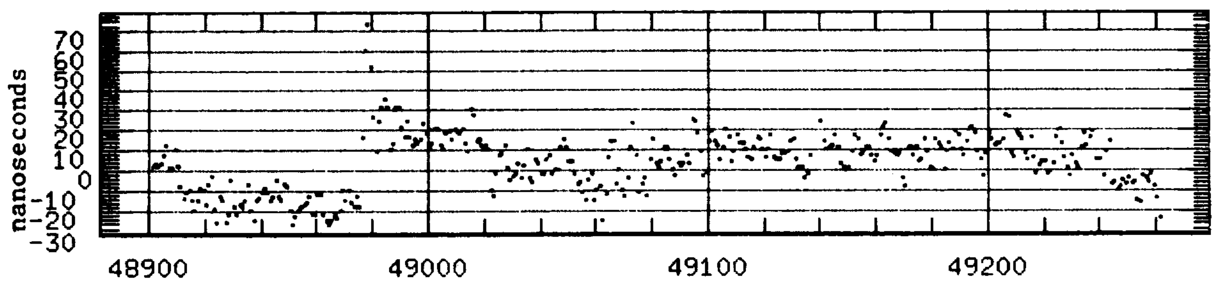
USNO MC MINUS GPS UTC TIME RAW DATA

(Fig. 1)



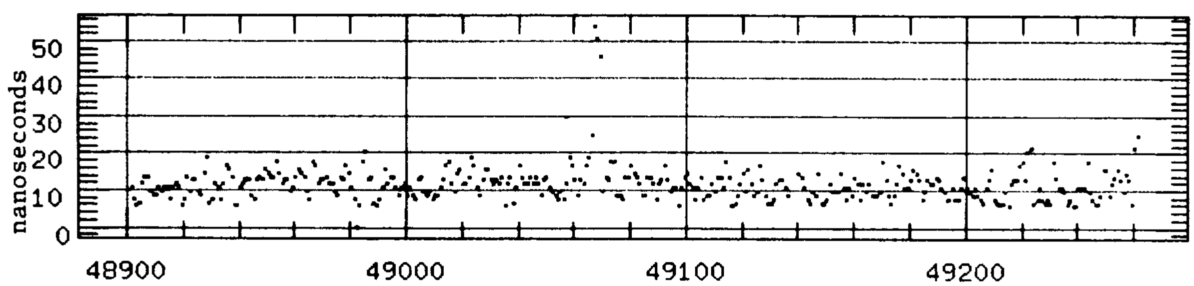
USNO MC - BLOCK I UTC TIMES, 48-HOUR LINEAR FITTED

(Fig. 2)



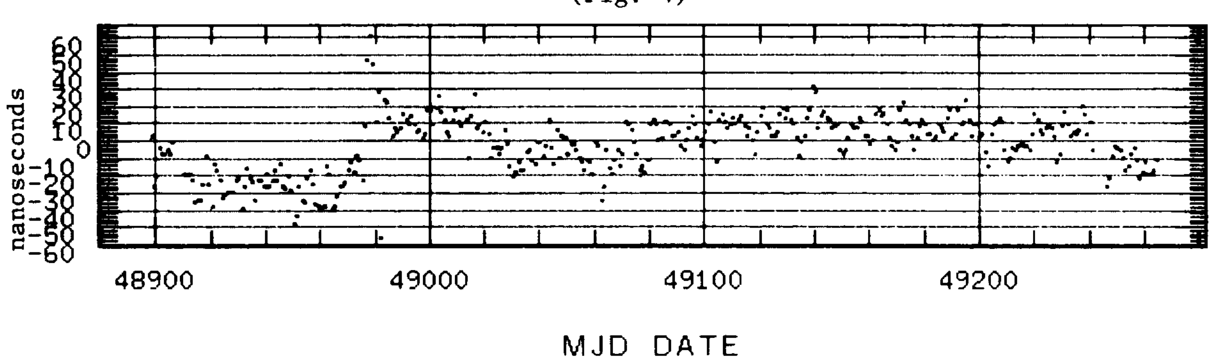
USNO MC - BLOCK I UTC TIMES, LINEAR FIT RMS

(Fig. 3)



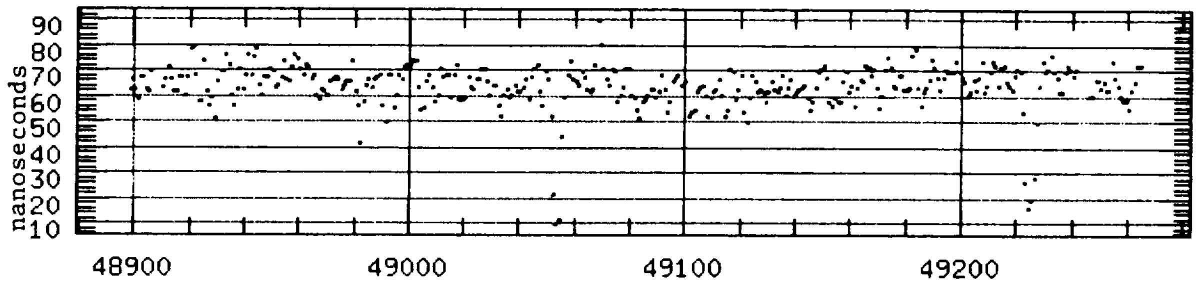
USNO MC - BLOCK II UTC TIMES, 48-HOUR LINEAR FITTED

(Fig. 4)



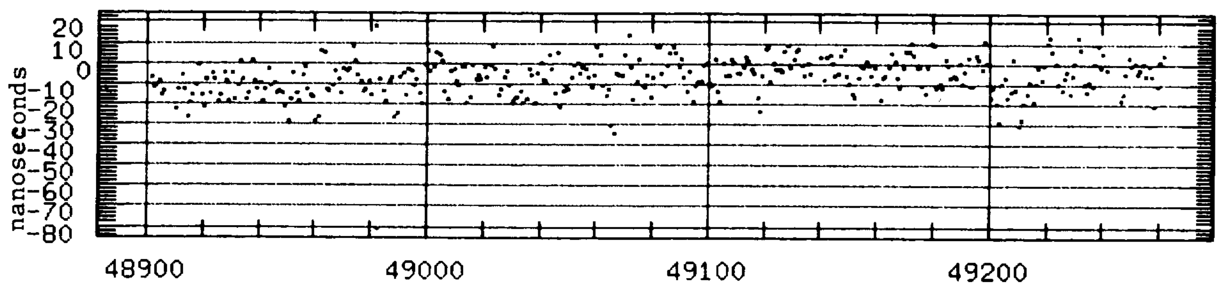
USNO MC - BLOCK II UTC TIMES, LINEAR FIT RMS

(Fig. 5)



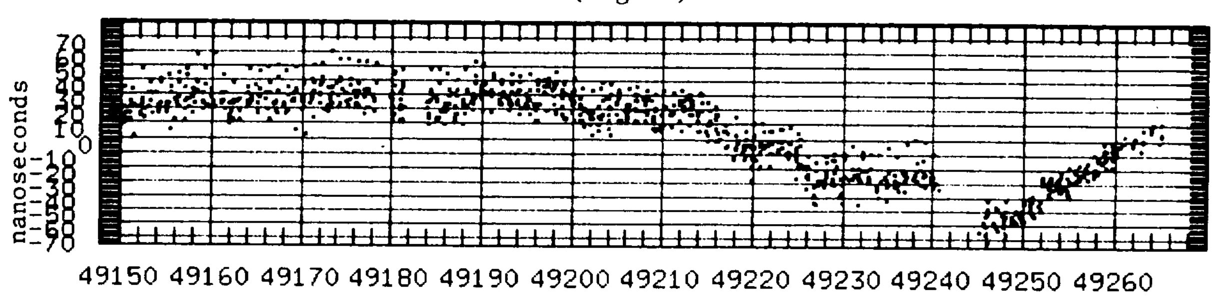
BLOCK II MINUS BLOCK I LINEAR FITTED UTC TIMES

(Fig. 6)



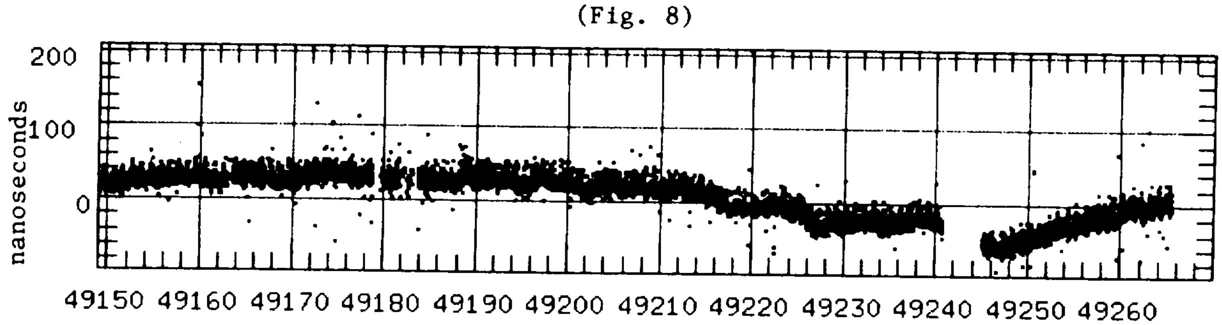
USNO MC - NOTSS VIA SINGLE BLOCK I COMMON VIEW POINTS

(Fig. 7)



USNO MC - NOTSS VIA SINGLE BLOCK II COMMON VIEW POINTS

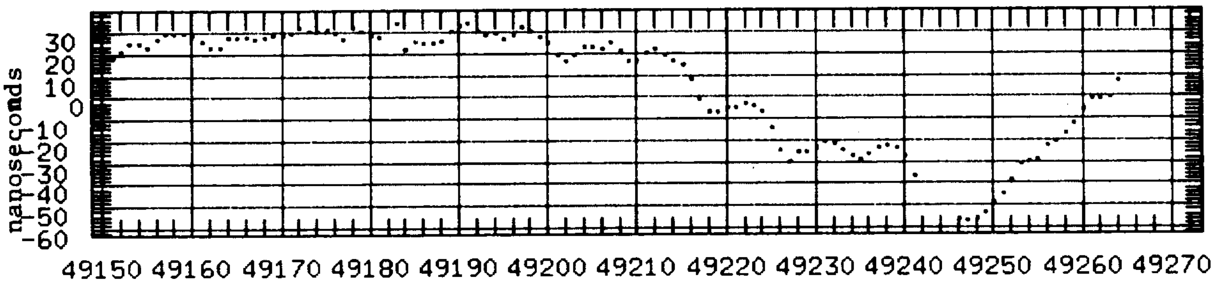
(Fig. 8)



MJD DATE

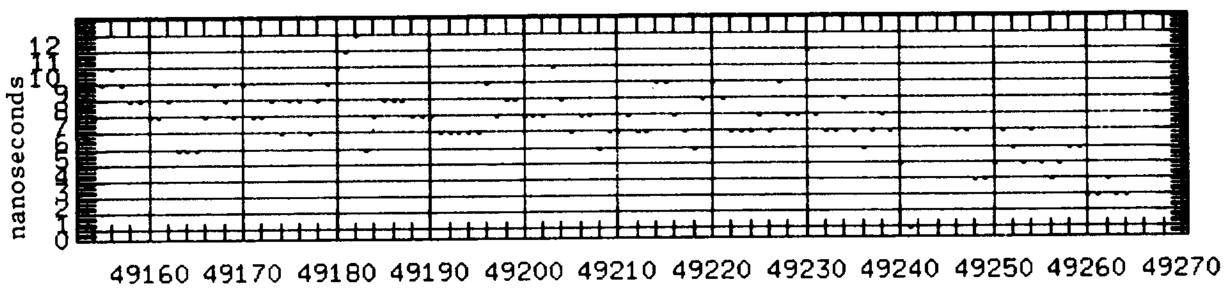
USNO MC - NOTSS VIA FITTED BLOCK I COMMON VIEW POINTS

(Fig. 9)



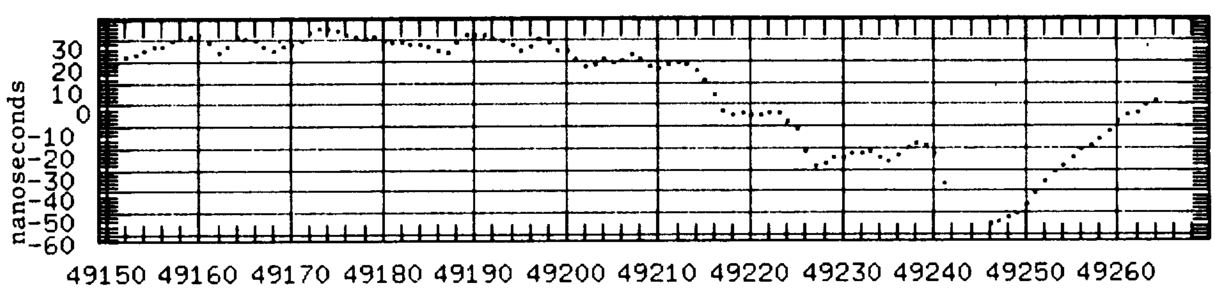
USNO MC - NOTSS FITTED BLOCK I COMMON VIEW POINTS RMS

(Fig. 10)



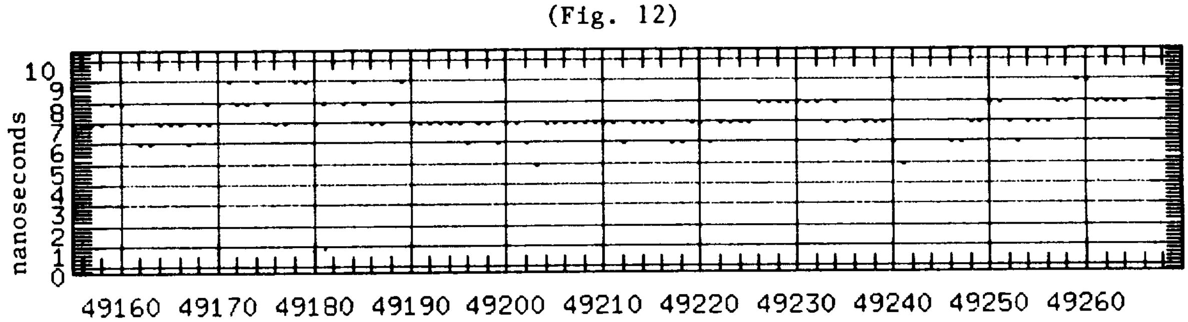
USNO MC - NOTSS VIA FITTED BLOCK II COMMON VIEW POINTS

(Fig. 11)



USNO MC - NOTSS FITTED BLOCK II COMMON VIEW POINTS RMS

(Fig. 12)



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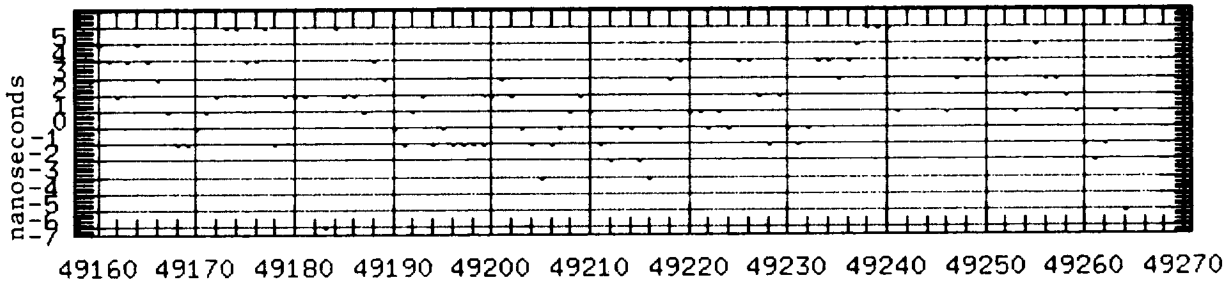
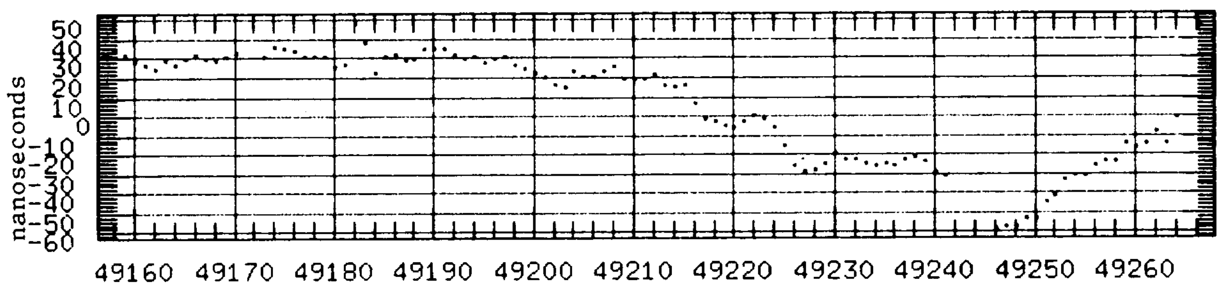
BLOCK II - BLOCK I FITTED COMMON VIEW POINTS

(Fig. 13)



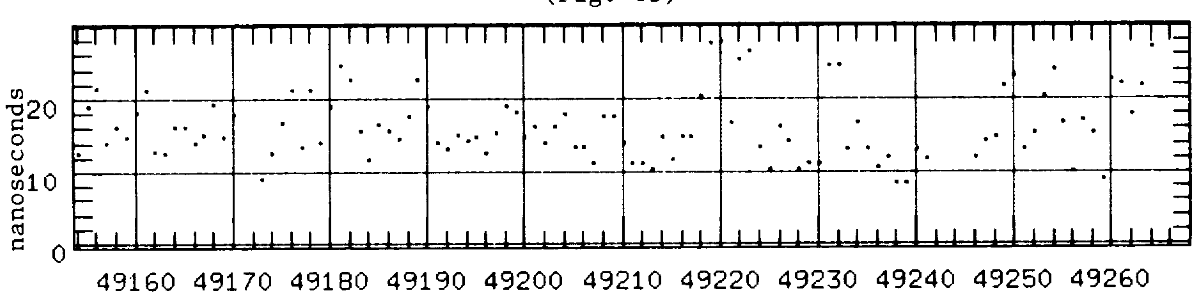
USNO MC - NOTSS BLOCK I MELTING POT LINEAR FIT

(Fig. 14)



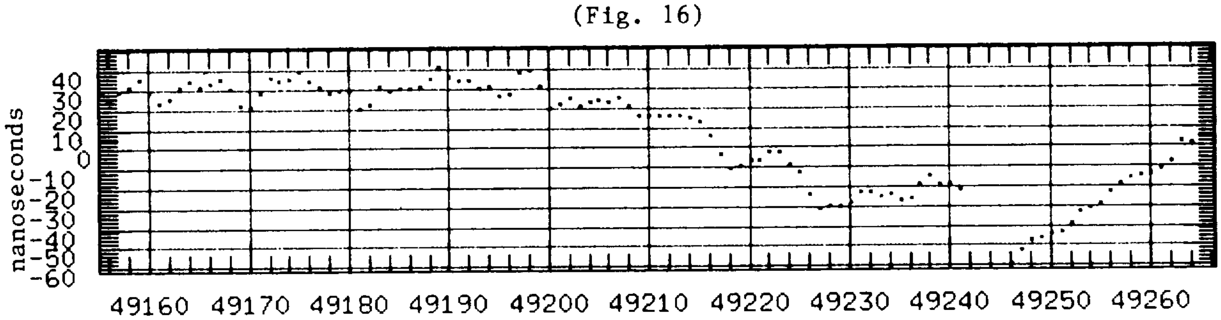
USNO MC - NOTSS BLOCK I MELTING POT LINEAR FIT RMS

(Fig. 15)



USNO MC - NOTSS BLOCK II MELTING POT LINEAR FIT

(Fig. 16)



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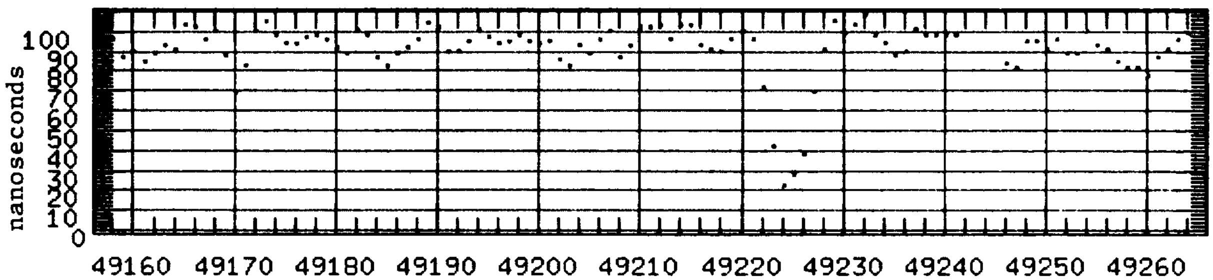
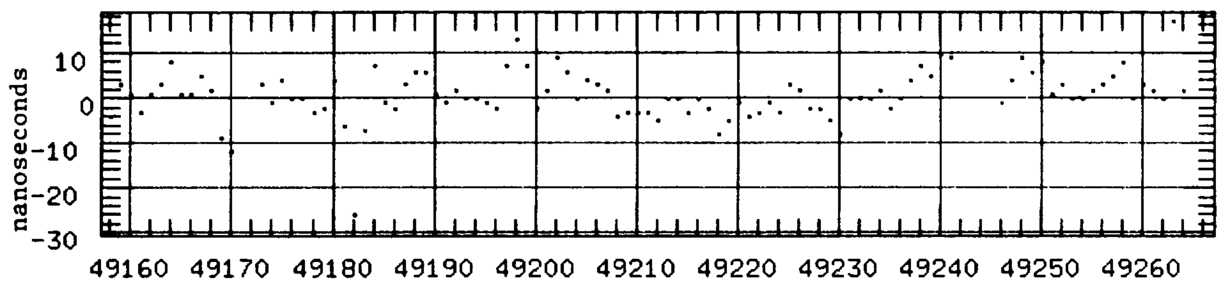
USNO MC - NOTSS BLOCK II MELTING POT LINEAR FIT RMS

(Fig. 17)



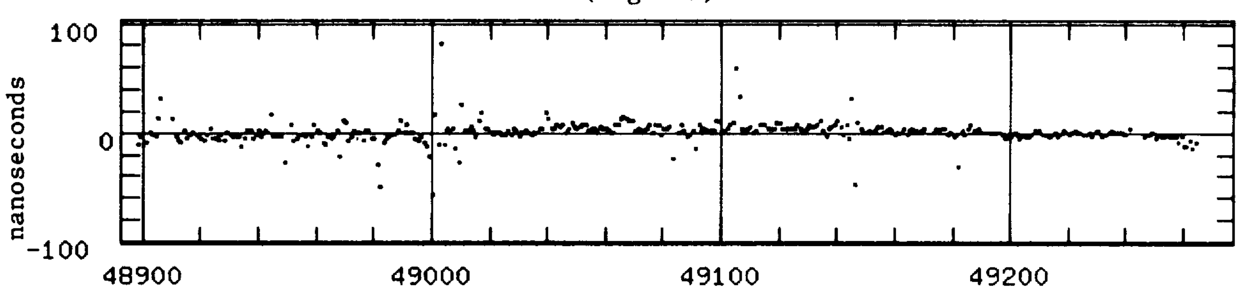
BLOCK II - BLOCK I MELTING POT LINEAR FIT POINTS

(Fig. 18)



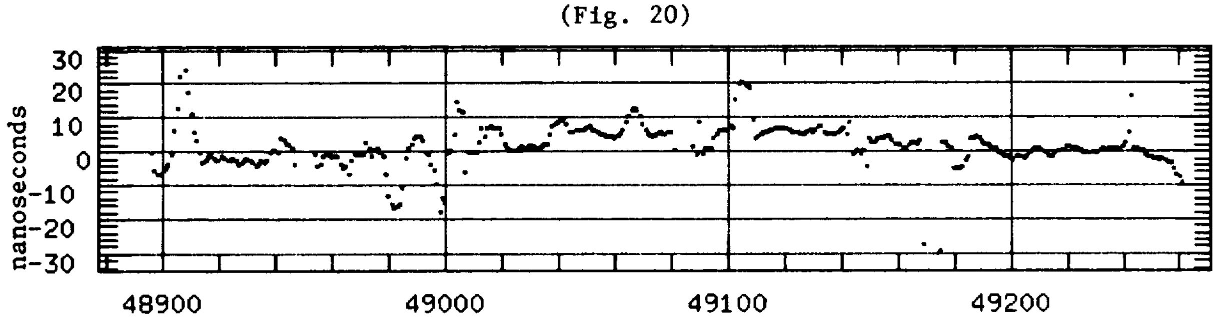
USNO MC - NOTSS BLOCK I MELTING POT - COMMON VIEW

(Fig. 19)



USNO MC - NOTSS BLOCK I MELTING POT - COMMON VIEW

(Fig. 20)



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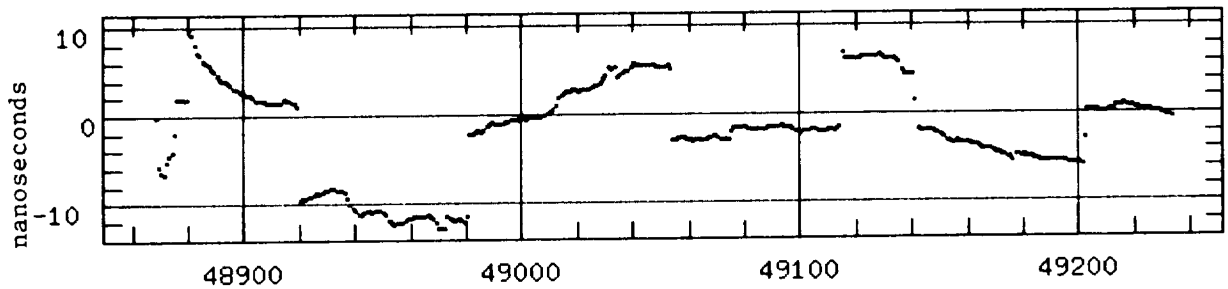
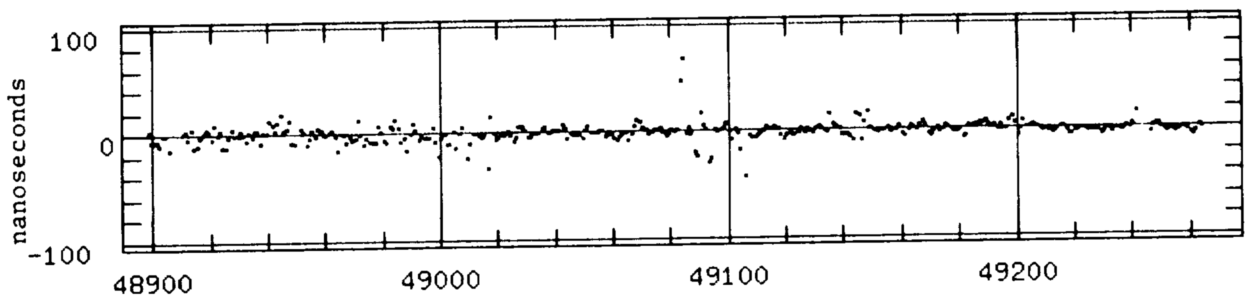
USNO MC - NOTSS BLOCK I MELTING POT - COMMON VIEW

(Fig. 21)



USNO MC - NOTSS BLOCK II MELTING POT - COMMON VIEW

(Fig. 22)



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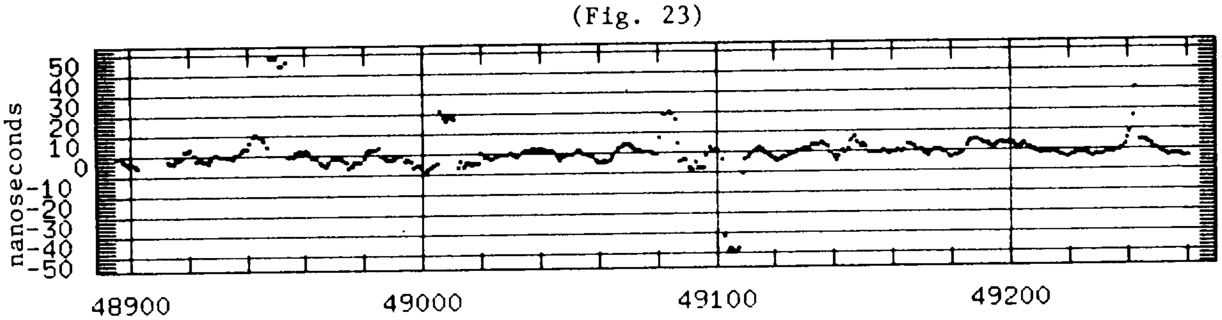
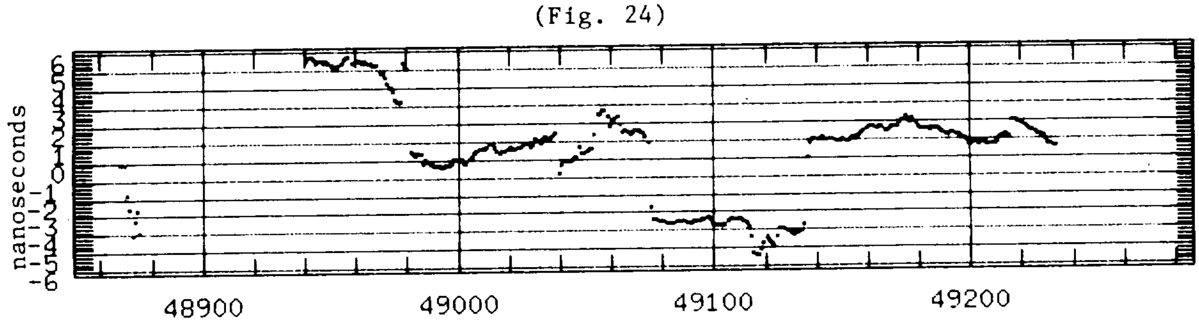
(Fig. 23)



USNO MC - NOTSS BLOCK II MELTING POT - COMMON VIEW

(Fig. 24)



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CESIUM AND RUBIDIUM FREQUENCY STANDARDS STATUS AND PERFORMANCE ON THE GPS PROGRAM

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Abstract

This paper is an update of the on-orbit operational performance of the frequency standards on the Block I GPS 8 to 11 Navstar satellites, the Block II GPS 13 to 21 Navstar satellites and the Block IIA GPS 22 to 40 Navstar satellites. A brief history of the frequency standards depicting improvements incorporated in the GPS Program with corresponding results will be presented.

The frequency standards configurations from the start to the present, including the various Block IIA clock configurations will be discussed. Topics such as clock observations and long term trending analysis which could enhance on-orbit performance analysis will be covered. endabstract

INTRODUCTION

The evolution of the frequency standards on the GPS Program started with the Block I concept validation program which included the prototype (GPS 1 through 8) space vehicle contract in 1974. The full-scale development vehicles (GPS 9 through 11) contracted in 1978 provided both navigational and nuclear detection capability. The production qualification vehicle (GPS-12) was contracted in 1980 and the production vehicles (GPS-13 through 40) were contracted in 1983. These production vehicles were divided into two groups, Block II (GPS 13 through 21) and Block IIA (GPS 22 through 40).

A considerable amount of effort was devoted to the frequency standards since there were no space-qualified Rubidium or Cesium frequency standards available at the start of this GPS Program. The initial GPS vehicles (1 through 3) utilized three Rubidium Frequency Standards (RFS), each with a back-up mode, to minimize the risk to the GPS Program on this critical item for achieving high user position accuracy. Later space vehicles, starting with GPS-4 and ending with GPS-11 included one Cesium Frequency Standard (CFS), also with a back-up high performance voltage-controlled crystal oscillator (VCXO).

All GPS production vehicles, starting with GPS-13 and ending with GPS-40, include two Rubidium Frequency Standards and two Cesium Frequency Standards, each still with a back-up VCXO mode. The CFS are considered primary because of their degree of radiation hardness and their extremely low frequency drift rate or aging.

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The actual on–orbit GPS Frequency Standard operating history (shown in Figure 1 for still operating Block I satellites, Figure 2 for Block II satellites and in Figure 3 for Block IIA satellites) illustrates the results of these hardware implementations.

ON–ORBIT PERFORMANCE

The operating summary and life history of the two production models of Cesium Frequency Standards from Frequency Time System (FTS) are shown in Tables 1 and 2. All three of the first production models, P/N1, had successful operations on GPS–8, 9 and 10 as depicted in Table 1 for a total of 270 months or 7.5 years of operations per clock. The operating life history of the production model, S/N 4, P/N 1, Cesium Frequency Standard, on GPS–9 was very impressive. This particular clock was turned on 06/28/84 with no C–field tune necessary for its entire life of 9.3 years. There are several reasons why this particular clock was turned off on 10/01/93 before it had a catastrophic failure. These included poor stability, large frequency offsets, low cesium beam current, end–of–life testing on such an old clock, untried RFS's and limited projected vehicle life–time all of which will be discussed in more detail in the cesium trending section.

The differences between P/N 1 and P/N 2 CFS are the amount of cesium fill (1.0 grams to 1.5 grams) and a stricter quality control and inspection point program. All of the Block II vehicles currently have P/N 2 cesium clocks from FTS. As can be seen from Table 2, the two clocks that have failed without hope of continued operation are, GPS–14 and 15, and the one cesium clock on GPS–19 has questionable operation which may be given a second chance for use in the future. The two failures had an average lifetime of 2.75 years with the suspect clock having a life of 2.7 years. This is a far cry from the P/N 1 lifetimes. So much for stricter quality control on Cesium Frequency Standards. Of course the sample size is very small for any real conclusions.

There are several ways to acquire the exact performance characteristics of on–orbit frequency standards. The best way is to have a direct monitor point on the 10.23 MHz clock output. Since this is not available, the next performance evaluation is through the L–band signal which is affected by the FSDU and NDU trickery, atmospheric effects, ephemeris unknowns, monitor station variations and other factors. All of these factors are fed into the Kalman filter, a computer algorithm for processing discrete measurement data in an optimal fashion.

Two parameters that are helpful in evaluating the operating performance of the frequency standards are read off of the daily and/or weekly Kalman filter drift state residual plots. The first is frequency offset in sec/day, a_1 term. This is the filter's estimate of the frequency difference or offset between each satellite frequency standard and the GPS composite clock (a nominal frequency). This is a continuous absolute value. Typical values of a_1 are 1 X 10^{-8} to 1 X 10^{-6} sec/day (1 X 10^{-13} to 1 X 10^{-11} sec/sec) depending on cesium or rubidium data, respectively. Another parameter, $A1$, that has more movement and possibly more trending signature, is calculated by taking the daily average of the difference between the minimum and maximum values of a1. These values vary from 1 X 10^{-13} to 4 X 10^{-13} sec/day.

Another parameter is the motion or frequency drift in sec/day^2, (a_2 term). This is the difference between the maximum and minimum value of Kalman data averaged over a one week period. (a relative value). These values vary from 0.8 X 10^{-9} to 20 X 10^{-9} sec/day^2 (1 X 10^{-17} to 3 X 10^{-16} sec/sec^2) depending on whether a cesium or rubidium, respectively is operating.

Plots of these filter estimates provides us with a means of evaluating the performance or stability of each spacecraft's clock (Figures 4 through 6). Figures 4 and 5 depict typical a1 terms (the x–axis) for cesium clocks and very good drift rate term, a_2. Figure 6 shows the only RFS on orbit with its a_1 term and a very large drift rate term a_2 ($\approx$ 50 times greater than a typical cesium). Figure 7 through 9 shows the estimated range deviation (ERD) of three different performing satellite clocks for a particular week with excellent, good and fair performances, respectively. These performance ratings are very subjective and correspond to the following definitions: excellent performance = ERD are less than 4 meters per day, good performance = ERD are less than 8 meters per day and fair performance is when the cumulatively ERD are greater than 10 meters and require additional work by the MCS crew in the form of extra navigational uploads. One important criterion for the Kalman filter is to provide accurate continual measurement updates. Unfortunately there are periods when the spacecraft is not in view of a monitor station, and the filter must propagate aging, through the a_2 term, with no real measurement verification. In other words, some fraction of the total possible data is lost. Another factor in evaluating the filter results is that the data periods are retrieved by different monitor stations (MSs) with different clocks contributing errors into the filter estimation and subsequently the prediction process. Therefore, each MS's operational clock must have a drift plot generated daily for analysis to evaluate filter results. This becomes important for constellation analysis, i.e. when all SV clocks supposedly change when in view of the same monitor station. This would mean that the MS clock is actually drifting or that a switch from MS clock #1 to clock #2 had occurred.

The Second Space Operations Squadron (2SOPS) at Falcon Air Force Base at Colorado Springs, monitors the performance of the clocks via the daily and weekly Kalman filter estimate. From the Kalman drift state residuals plots, the continuous frequency offset from the GPS master clock is shown. Along with the clock movement in parts/day, the drift rate term (a_2) in sec/day^2 is also shown as a weekly value. Because this term is so small for the CFS, the a_2 term in the navigation message is set to zero.

Table 3 depicts the life history of the rubidium clocks on operational vehicles in 1993. (See Reference 2 for earlier history.) On the remaining operating Block I (experimental) satellites (GPS 9, 10 and 11), there are three RFS's operating in the primary mode. As can be seen, the final production model #12 RFS's have not acquired much on–orbit operating time lately since the cesiums clocks have been preferred over the rubidiums. This is because of the advantage of cesium over rubidium in terms of radiation hardness and autonomous operations (low, predictable drift rate) and no C–field tunes. Other reasons why cesiums are turned on first include the fact that there were no cesiums on the first four Block I's, only one cesium on the last six Block I's, and an equal number (2 of each) on Block II and IIA's. And now a reversal has taken place in that only one cesium is planned on Block IIR. There is one positive note on leaving the RFS's until last and that is to prove that rubidium clocks will not have any trouble turning on and operating successfully after six to nine years of radiation in space. There have been six turn–ons so far (five successes and one failure), with five more samples to test (Table 3). This is important because on the Block II and IIA's, the rubidiums will be turned on last with turn–on's expected from 1996 through 2000. There are already two vehicles on their last cesium (GPS 14 and 15) and three more vehicles with suspect cesiums (GPS 19, 22 and 23). This information is included in Table 4 "Navstar Mission Operations Status" along with a variety of performance parameters, such as a_1 and a_2 terms (discussed earlier), that help in determining the weekly operational status of each vehicle's clock.

FREQUENCY STANDARD ON–ORBIT TRENDING

One of the main objectives of performing trend analysis on a frequency standard is to prevent a long downtime of the satellite (unhealthy status). It is extremely hard to predict when a particular on–orbit cesium or rubidium clock will expire. Particularly elusive is the time frame–whether it be in days or weeks or months or the tolerance of the crews toward a clock that does not meet specification. It is the Air Force who will ultimately determine how burdensome to the MCS crew a particular clock, is based upon how many uploads must be performed to keep the estimated range deviation (ERD) under 10 meters. Multiply these extra daily uploads by two or three suspect vehicles plus the normal daily uploads to the other 22 or 23 healthy vehicles and the crew size will have to grow in number.

In order to predict the useful operating lifetime of either a cesium or rubidium, there are several parameters that must be examined. The most important performance parameter is the stability of the clock. This is what most affects the user. As seen in Figure 10, (Reference 1) the stability of GPS–9 slowly degrades with time, to the point where the user error becomes to large to comfortably handle. Frequency offset is another parameter that could affect the user to the extent that additional uploads are needed to correct the a_0 and a_1 terms (usually scheduled uploads suffice as the Kalman updates these terms continuously).

Of all the telemetry monitors on the clocks, there is only one on the cesium clock that has character or an individuality. This trending parameter is the cesium beam current telemetry monitor. It is also a fore–teller of failure. What makes this monitor hard to interpret, is that each clock starts off at a different absolute value, each has a different rate of decline and each has a different final plateau. This can be seen in Figures 11 through 14. Examining Figure 15 which depicts GPS–9 beam current over the last three years, a definite slope change can be seen in the last two months, along with poor stability and extra uploads each day. These last two correlations are important. Because if day 400 (mid–February of 1992) is taken as an example, there is also a large slope change in current but there was no correlation with poor stability or large frequency offsets or large ERD's (Figure 10). These declines were similar to the signatures of the cesiums on GPS–8 and GPS–10 just before catastrophic failure occurred (cesium depletion). Another example is GPS–15, turned off because of very unstable frequency, which had an initial beam current of 20 nano–amps and a value of two nano–amps at the end. This ratio of 20/2 or 10 to 1 relates to a reduction in loop gain, which can also be inversely correlated to another trending parameter, the loop time constant. Unfortunately, in order to measure the loop time constant of a clock, the vehicle must be set unhealthy, which the Air Force will only do under dire circumstances. If the telemetry interpretation is correct, that the beam current is really dropping, then the ratio of the original time constant ($\approx$ 12 seconds) to the final or measurement time constant (GPS–10 was equal to 120 seconds) will also be 10 to 1 (same as the ratio of original beam current to final beam current). This does not necessarily mean that a cesium depletion problem is imminent but that changes in other cesium tube parameters such as electron multiplier gain, pre–amp gain or about 10 other tube parameters may have effected the telemetry monitor value. And while the satellite is unhealthy, other tests such as Ramsey pattern retrace (should not be a flat line) and modulation tests (should be greater than 30%) should be performed, in order to determine a good or bad tube .

The rubidium clocks have only three telemetry monitor points. If the two control voltages start to change abruptly, it will be a direct and obvious verification of clock movement. Very small and gradual voltage changes are expected because of crystal aging. For example, the rubidium control voltages, 10 MHz and 10.23 MHz, on GPS–3 after 12 years of operation rose from 5 V to 13 V and 7 volts to 9 volts, respectively. In other words when the circuitry of the clock would degrade or the crystal would age, the control voltages would change in order to output the same frequencies, 10 MHz or 10.23 MHz. These voltage movements were still within the control region of both oscillators. The lamp voltage dropped from 7.6 V to 7.3 V over the 12 years with the final days of operation from 7.3 to 7.0 V (typical signature of rubidium depletion).

Another trending parameter that effects the performance of both clocks, in particular the RFS, is on–orbit temperature of the spacecraft. Studying Figure 16, prediction of temperature changes (and power constraints on aging Block I vehicles) can be made and incorporated into the trend analysis. [This eclipse data can also be used to calculate when the spacecraft's first eclipse season occurs so as to beware of the infamous bump–in–the–night phenomena. This is a known (but not completely understood) ephemeris issue and not a clock jump].

SCHEDULES

The last of the Block I satellites, Navstar 11, was launched on October 8, 1985. Of these 10 spacecraft, three satellites are currently providing good to excellent data to ground users and are situated in two orbital planes, one, GPS–10, in the 120 degree plane A/, and two, GPS–9 and GPS–11 in the 240 degree plane C/.

The last of the larger Block II satellites Navstar 15, was launched on October 1, 1990. Of these nine satellites, all nine are providing continuous service to all ground users.

These satellites have the same clock configuration of two CFS's and two RFS's. The most recent Block IIA satellite, Navstar 34, was launched on October 26, 1993, with the next scheduled for launch in March, 1994. This will complete the Block II and IIA constellation for fully operational capability (FOC) requirements. Besides the more sophisticated payloads on GPS–22 et al, GPS–29 through 34 each have a different manufacturer of cesium clocks. GPS 29, 30 and 34 have a second source cesium clock developed by Kernco which is similar to the future Block IIR clock. The performance of GPS–29, is excellent at one day, $< 1 \times 10^{-13}$ $\Delta f/f$, and is only suppassed by the only operating Block II/IIA rubidium on orbit, GPS–25. For 10–day stability and longer, this cesium is far superior, $< 3 \times 10^{-14}$. This data and more are included in the GPS Block I/II/IIA clock status charts (Table 4).

The total on–orbit times for both rubidium and cesiums are staggering for the first operational satellite system ever to utilize both types of production frequency standards. The on–orbit times for all rubidiums exceeds 600 months or 50 years of operation. The longest operating time on a RFS was 12 years and 5 months on GPS–3. The oldest operating RFS is on GPS–11, 4 years and 11 months, and still glowing.

The cesium on–orbit times are more impressive with figures of 1040 months or 86.6 years. The longest operating CFS was on GPS–9 for a total of 9 years and 3 months. The oldest operating Block II/IIA CFS, on GPS–13, was turned on June 17, 1989 and is still ticking.

Tabulation of all the individual operational hours on–orbit for frequency standards on Block II and IIA vehicles are included in Table 5.

CONCLUSION

As verified by on–orbit performance data, most of the corrective actions taken to eliminate problems in the clock, especially the rubidiums (lamps), have been very effective. Not only have these frequency standards demonstrated their combined five–year specified operating life but they have extended the operating time past the 7.5 years time frame. The usefulness of the back–up mode concept in each clock is greatly diminished because of the total success so far of the GPS constellation both in terms of numbers and performance.

The more data that are collected each day and the more clocks that are turned on, the easier it will be to predict and trend the performance and lifetime of the clocks through analysis. A total (all clocks) of 1640 months (136 years) of on–orbit time has accumulated in the primary mode.

For the more managerially inclined, instead of sifting through all the Kalman drift rate residuals, Allan variances, temperature coefficients, the ERD's, PRR's and SPR's, then Table 6 is for your review. These little quirks and idiosyncrasies of each vehicle combined with clock performance (in more detail in Table 4) are for management eyes only.

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- Aerospace
- Rockwell International (RFS Manufacturer)
- Frequency and Time System (CFS Manufacturer)
- Frequency Electronics Inc., and Kernco (CFS2 Manufacturers)

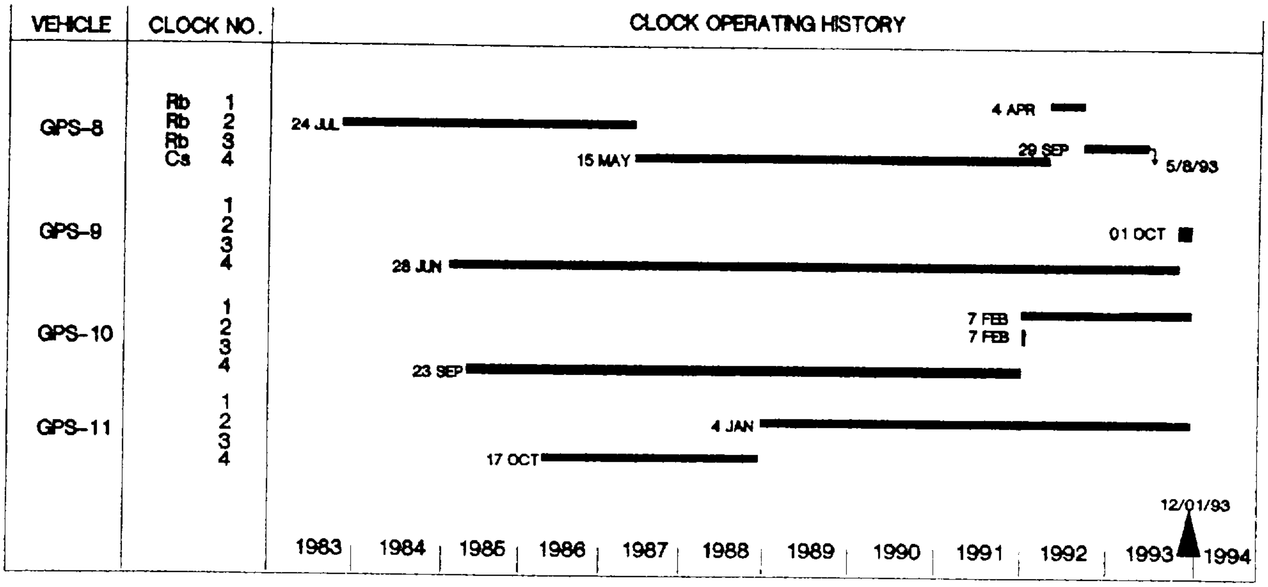


FIGURE 1: BLOCK I FREQUENCY STANDARD CONFIGURATION

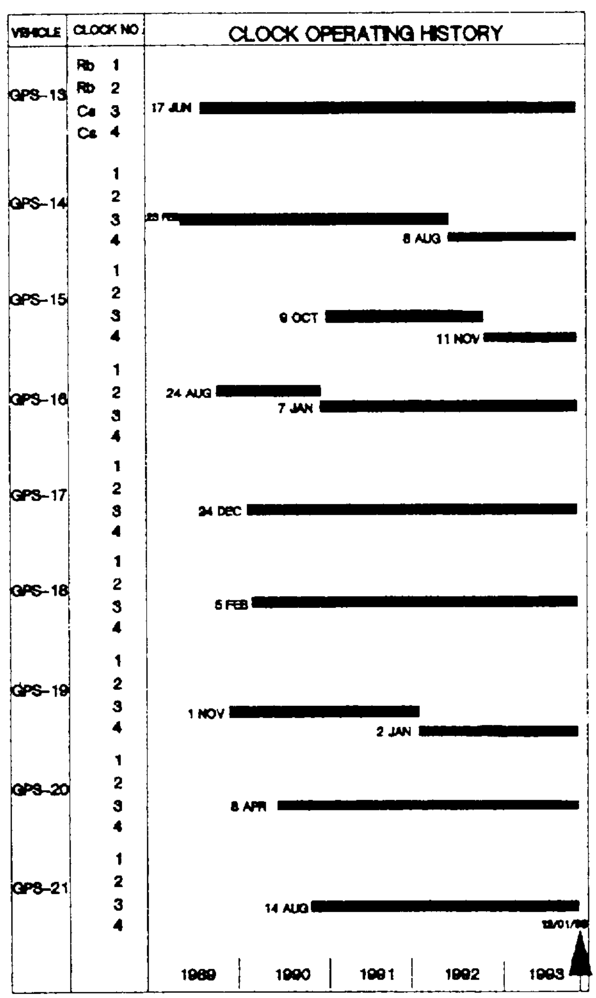


FIGURE 2: BLOCK II FREQUENCY STANDARD CONFIGURATION

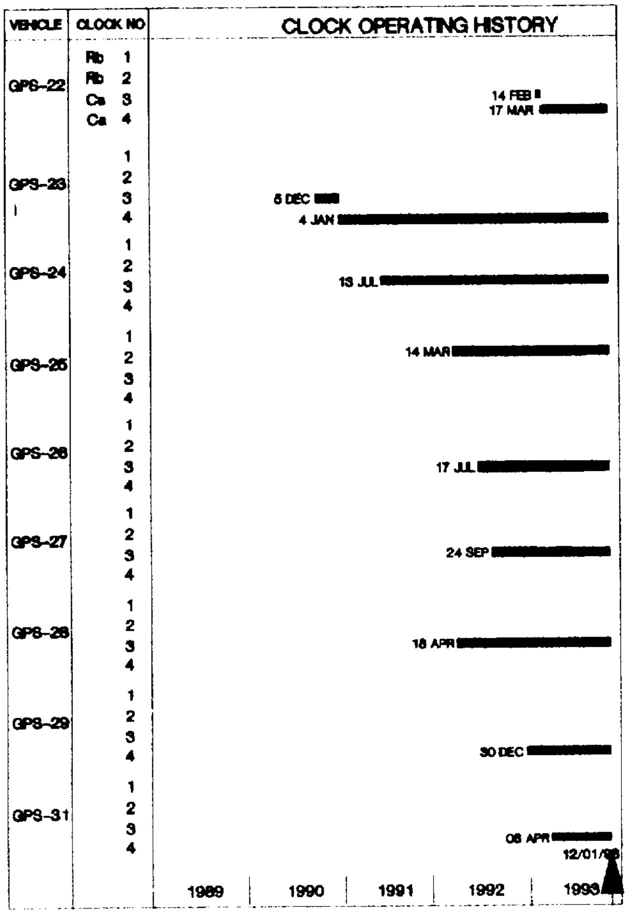


FIGURE 3: BLOCK IIA FREQUENCY STANDARD CONFIGURATION

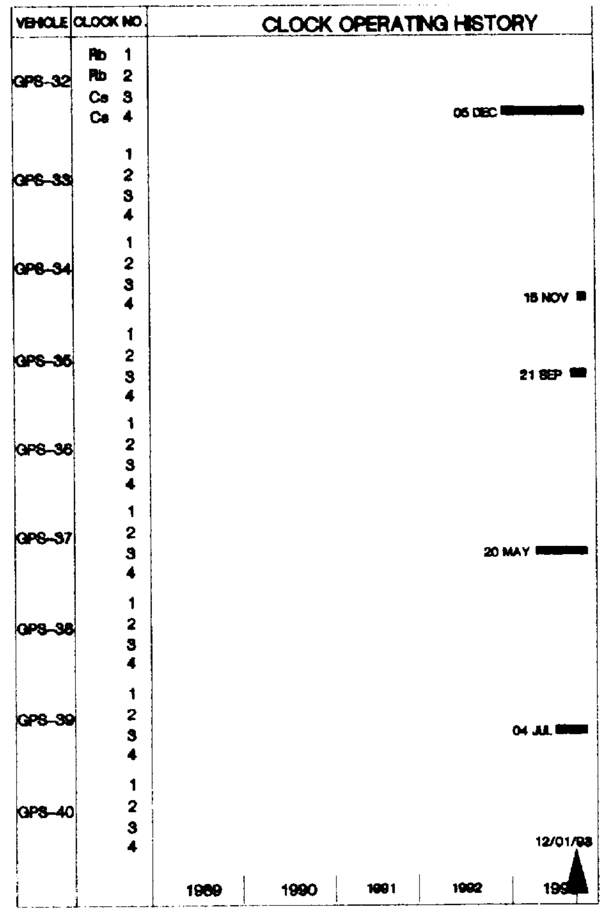


FIGURE 3 (CONT) BLOCK IIA FREQUENCY STANDARD CONFIGURATION

TABLE 1: ON-ORBIT LIFE TIME OF BLOCK I CESIUM FREQ. STD. Dec. 1993

BLK I	GPS	TIME		PROBLEM	MODEL
		YEARS	MONTHS		
	4	0 YEARS	12 HOURS	H. V. POWER SUPPLY	EDM
	11	3 YEARS	3 MONTHS	STABILITY AND DROP IN FREQUENCY	PPM
	6	3 YEARS	9 MONTHS	Cs DEPLETION	PPM
	8	5 YEARS	11 MONTHS	Cs DEPLETION - LOW CBI & Lo FREQ. VARIATIONS	1
	10	7 YEARS	4 MONTHS	Cs DEPLETION	1
	9	9 YEARS	3 MONTHS	STABILITY > 3×10^{-13}; EXTRA DAILY UPLOADS LOW CBI	1

TABLE 2: ON-ORBIT LIFE TIME OF BLOCK II CESIUM FREQ. STD. Dec. 1993

BLK II & BLK IIA	GPS	TIME		PROBLEM	MODEL
		YEARS	MONTHS		
	23	0 YEARS	1 MONTH	FREQUENCY JUMPS	2 *
	22	0 YEARS	1 MONTH	SOLAR COEFFICIENT PROBLEM WITH THE KALMAN FILTER, CBI DROP FROM 15 - 10 na	2 *
	15	2 YEARS	1 MONTH	NOISY, LARGE LOOP TIME CONSTANT	2
	19	2 YEARS	2 MONTHS	SAWTOOTH FREQUENCY OFFSET	2 *
	14	3 YEARS	6 MONTHS	FREQUENCY FLUCTUATION & LOOP CONTROL FLUCTUATION	2

* CANDIDATE FOR REUSAGE

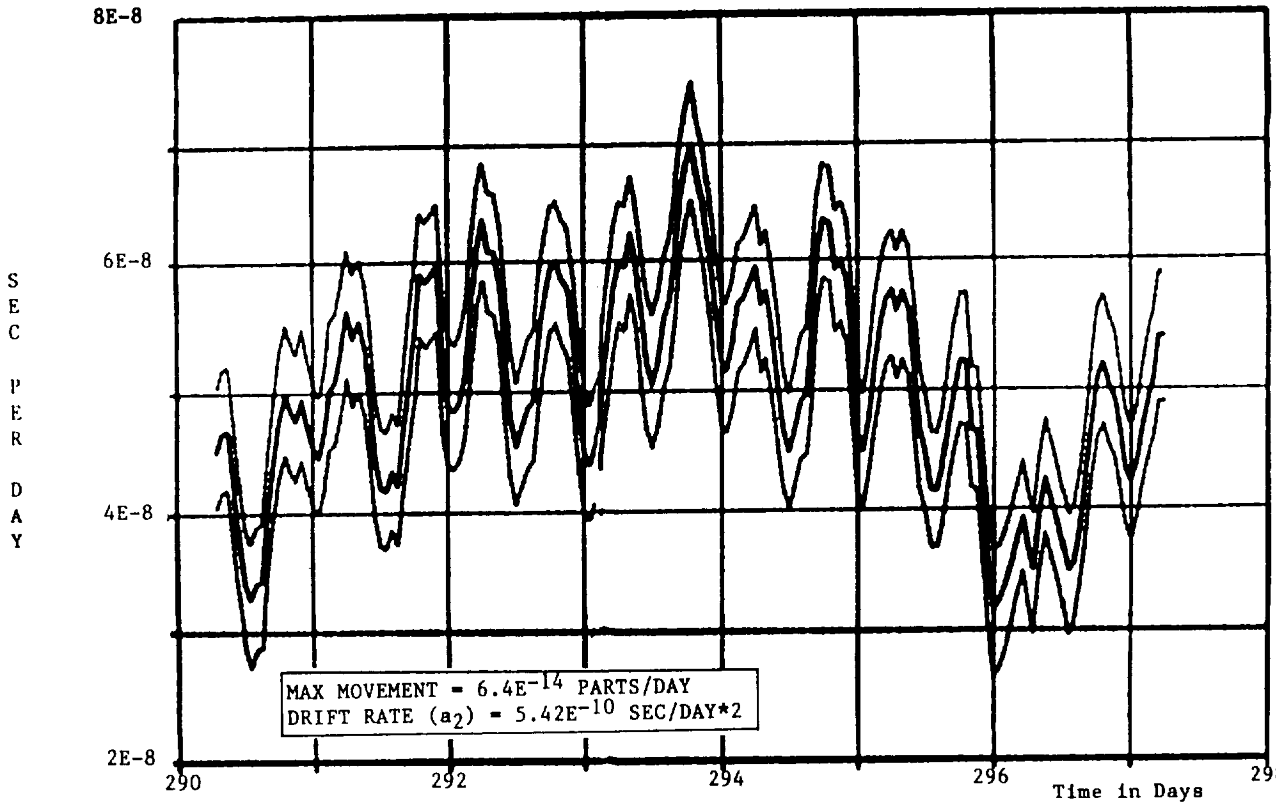


FIGURE 4: DRIFT STATE RESIDUAL FOR NAV 29

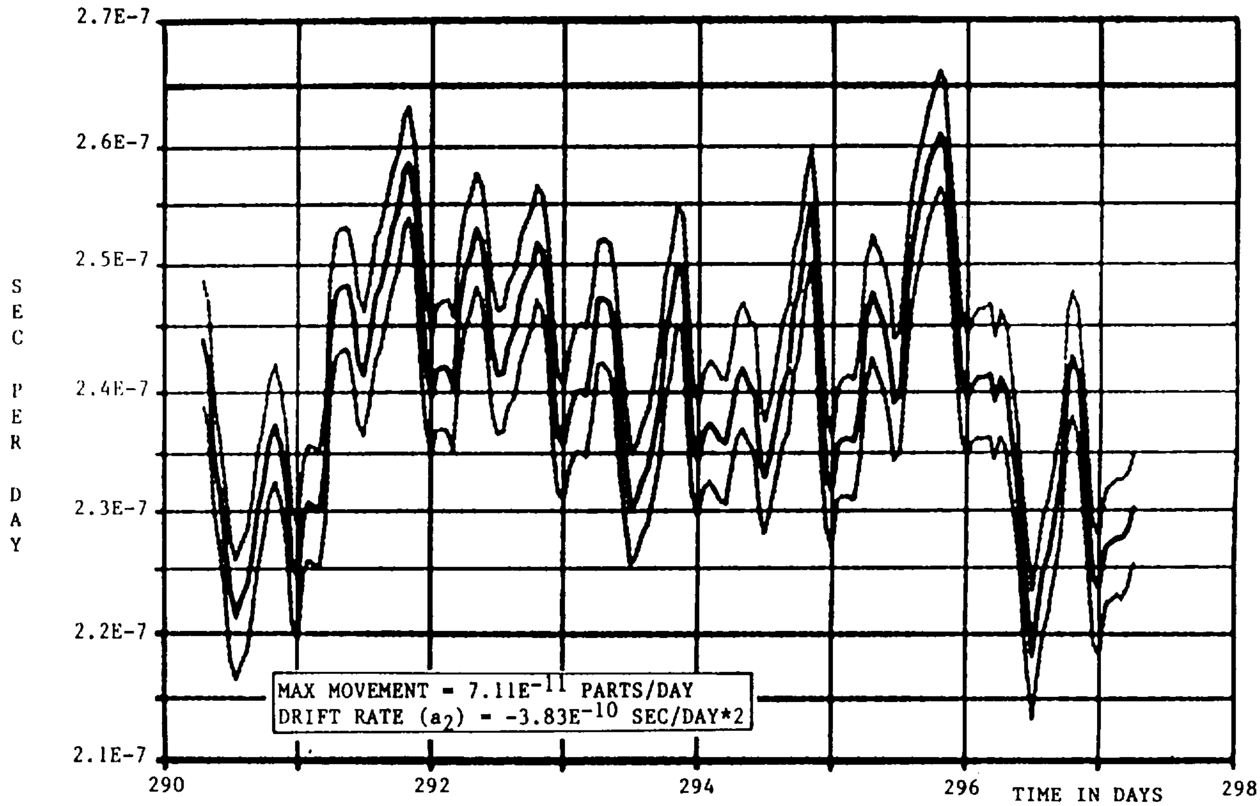


FIGURE 5: DRIFT STATE RESIDUAL FOR NAV 31

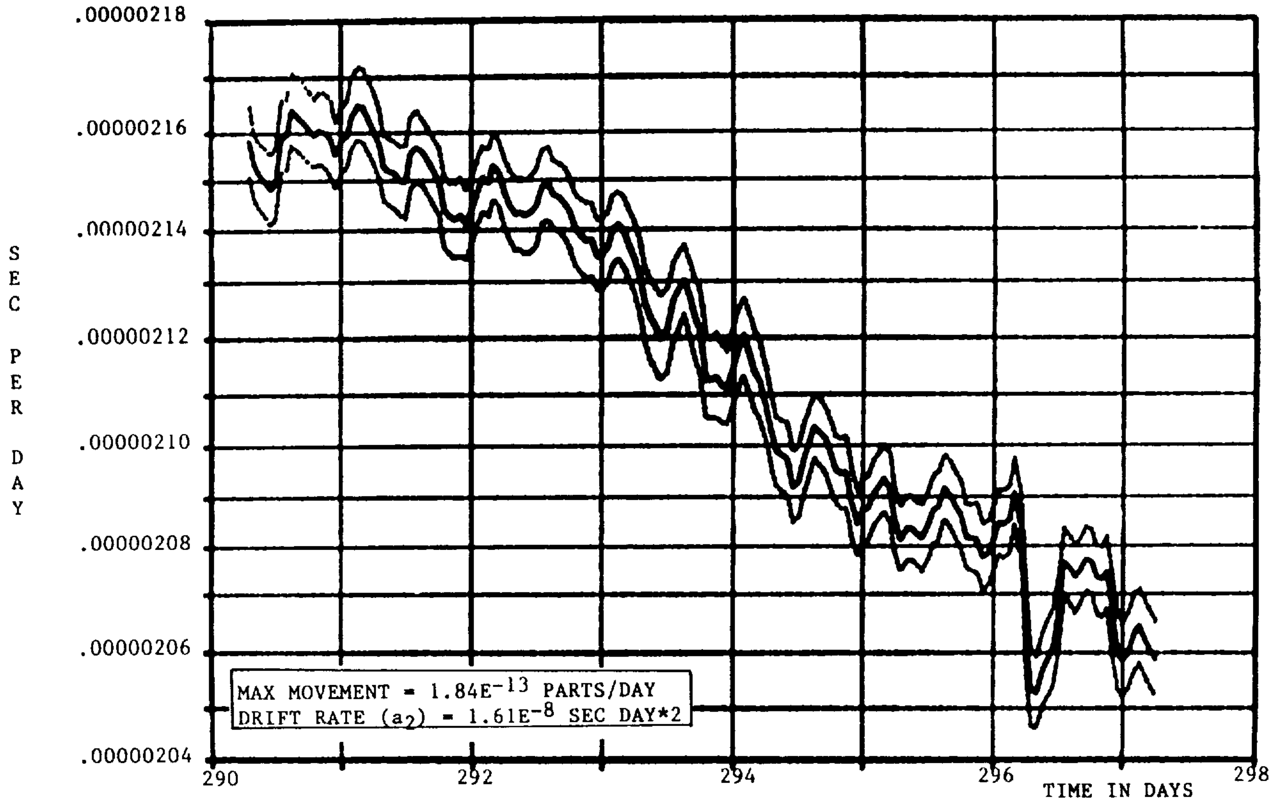


FIGURE 6: DRIFT STATE RESIDUAL FOR NAV 25

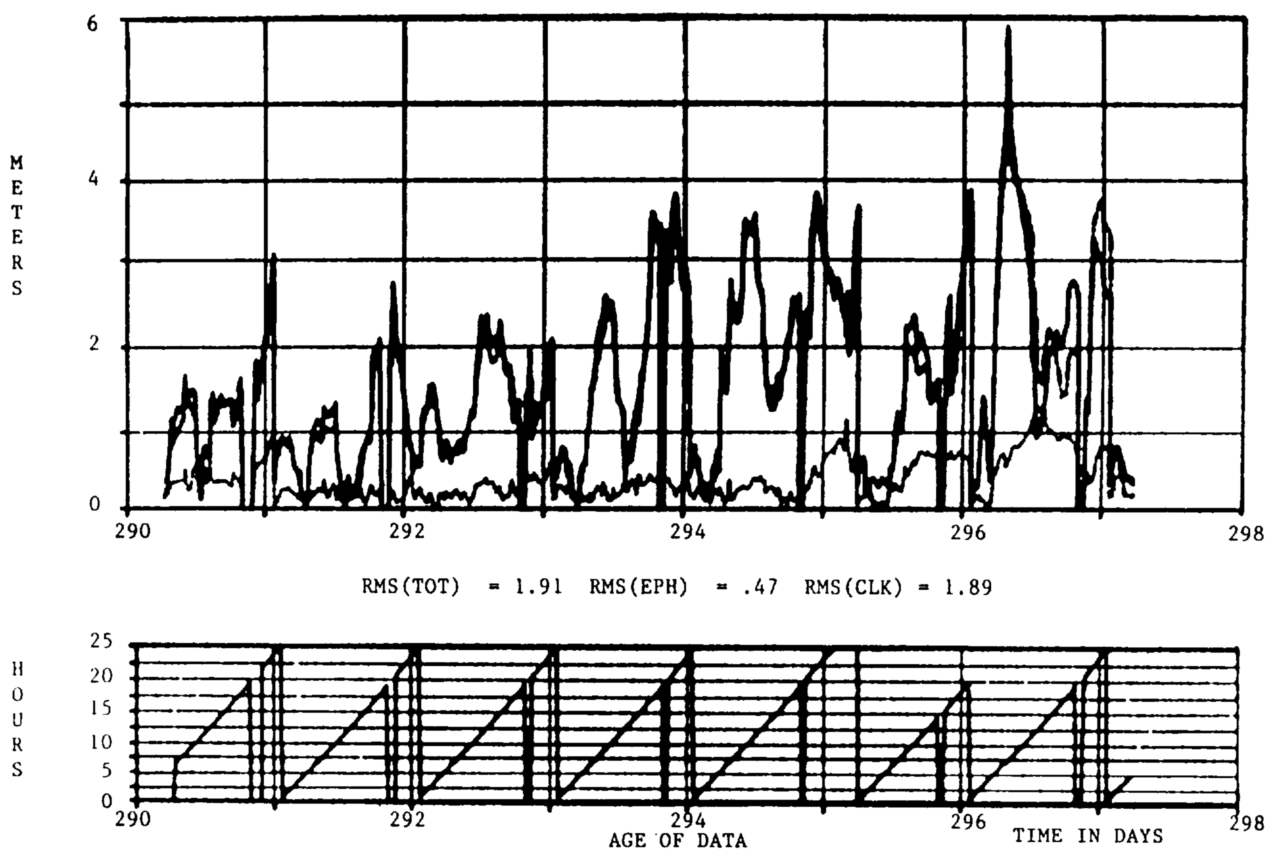


FIGURE 7: RMS-ERD FOR NAVSTAR 25

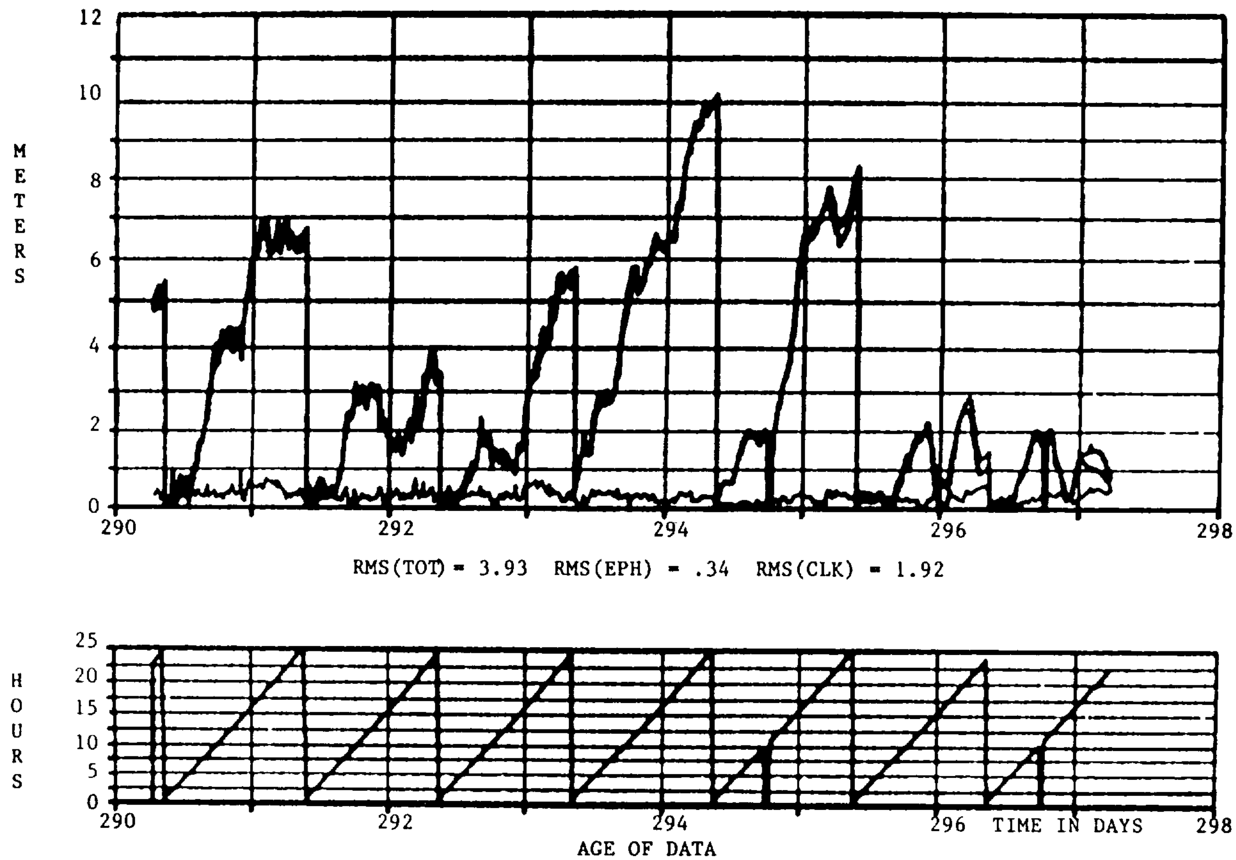


FIGURE 8: RMS-ERD FOR NAVSTAR 27

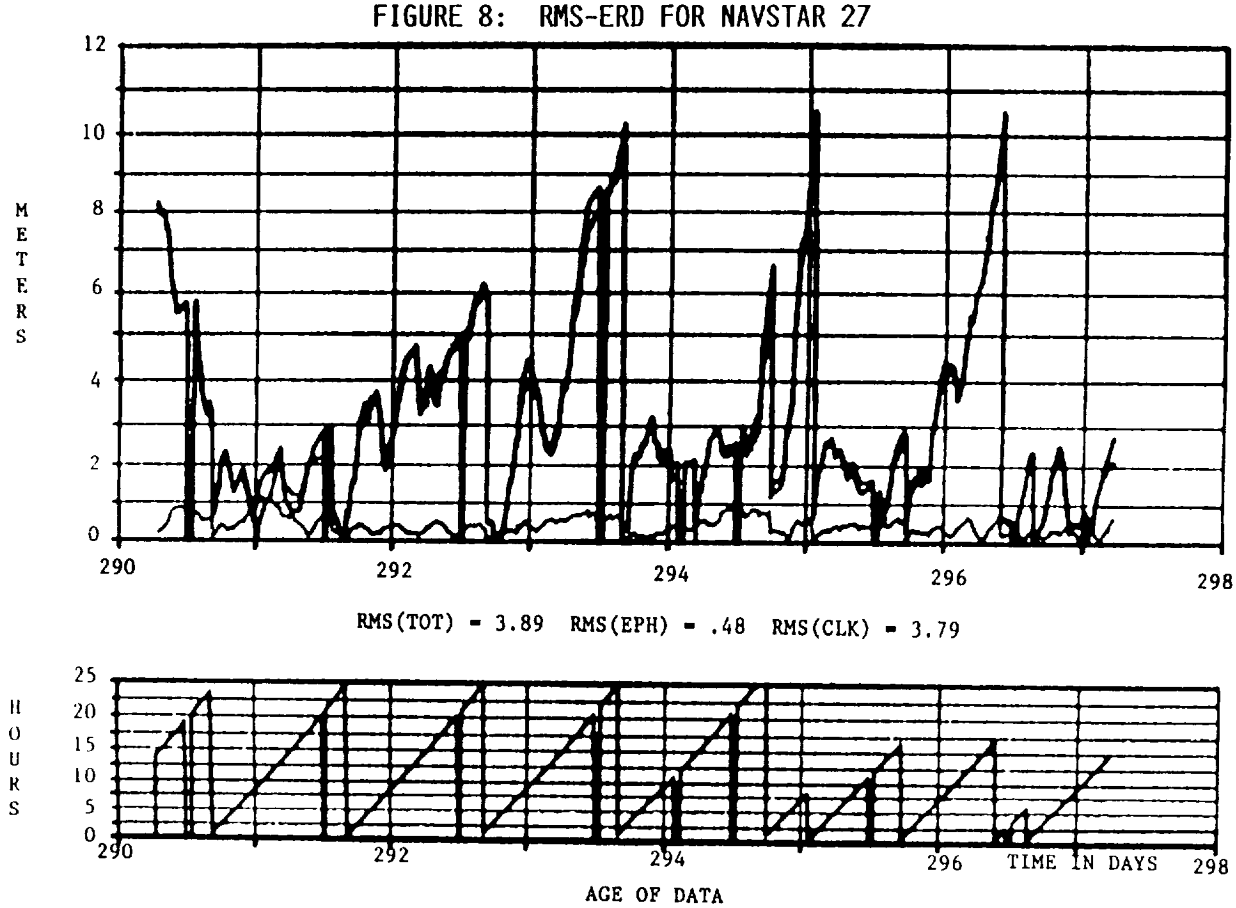


FIGURE 9: RMS-ERD FOR NAVSTAR 16

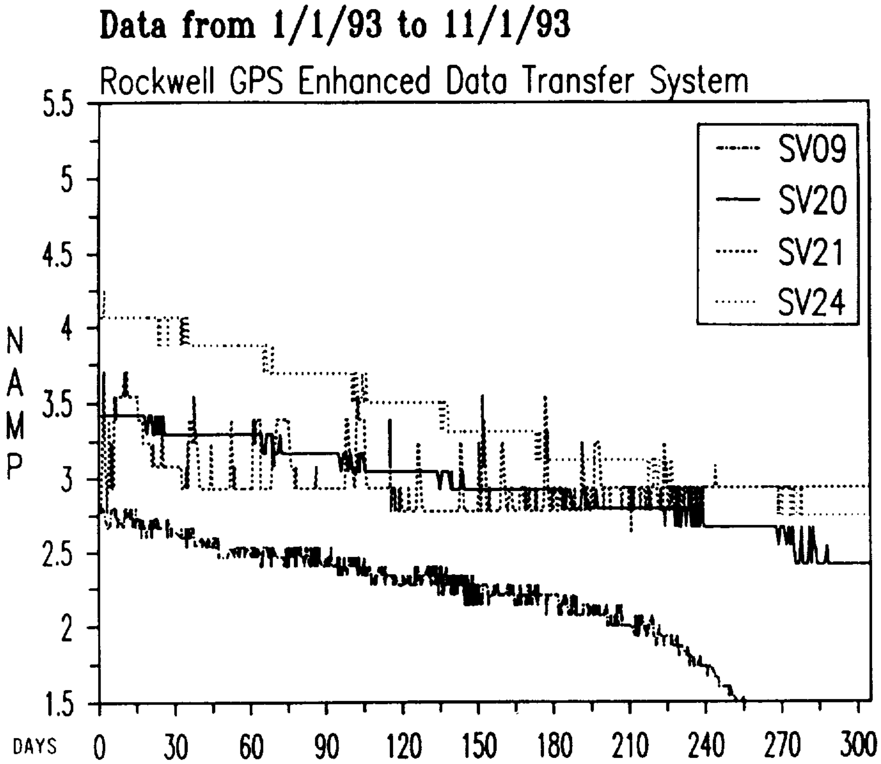


FIGURE 11: LOW CESIUM BEAM CURRENT VALUES

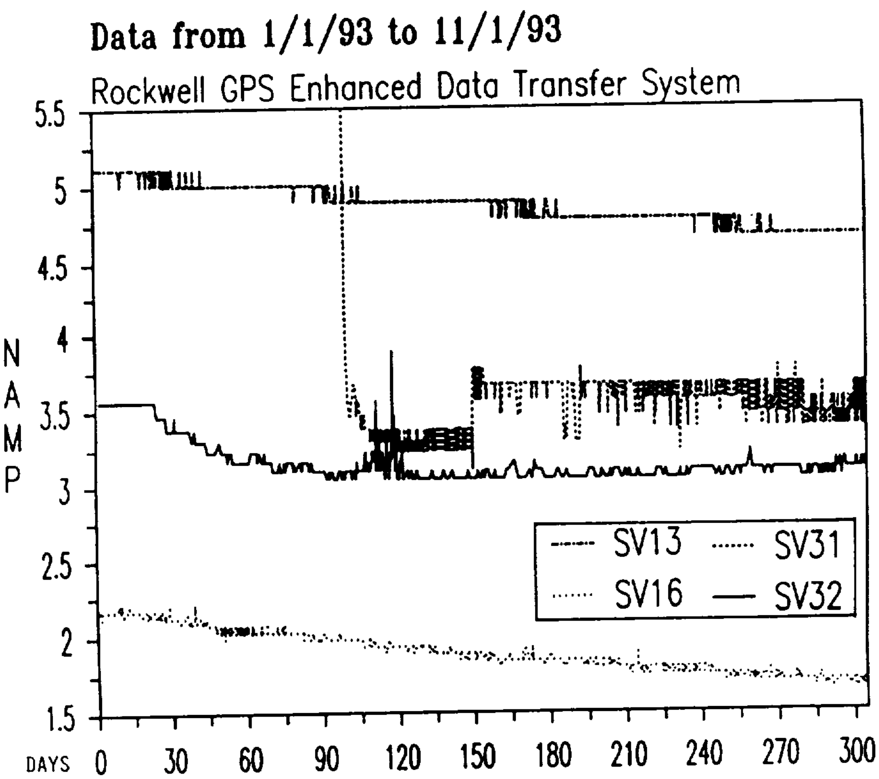


FIGURE 12: LOW CESIUM BEAM CURRENT VALUES

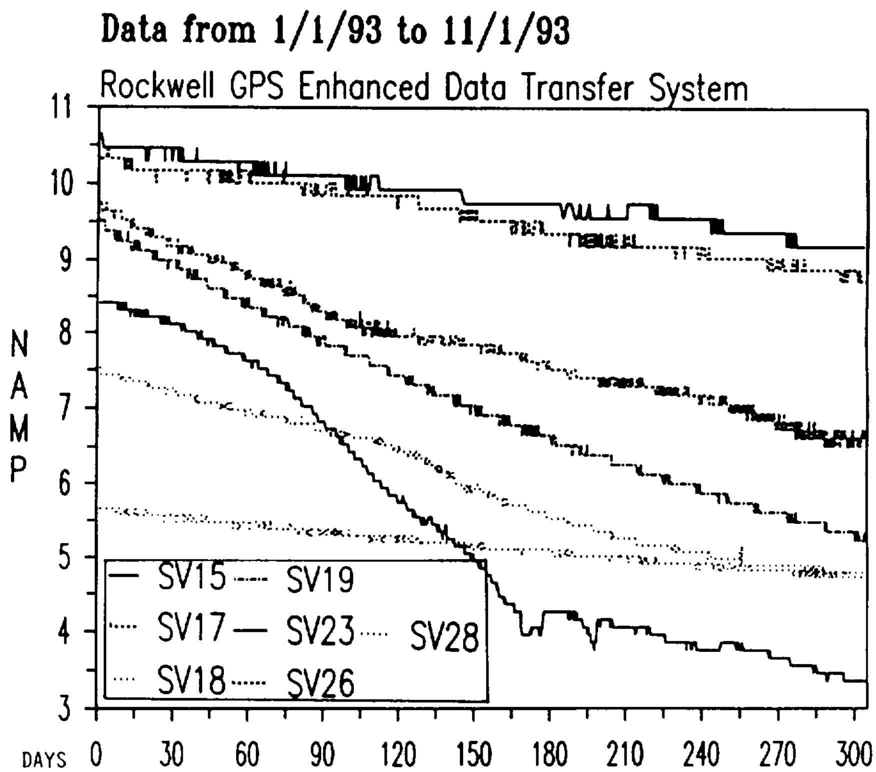


FIGURE 13: MEDIUM CESIUM BEAM CURRENT VALUE

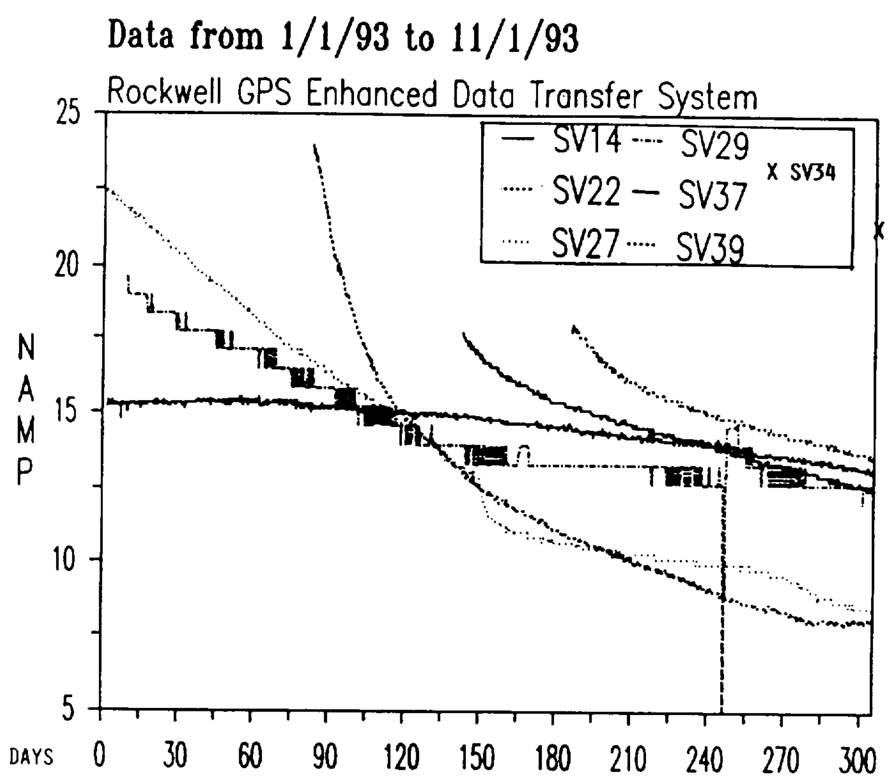


FIGURE 14: HIGH CESIUM BEAM CURRENT VALUES

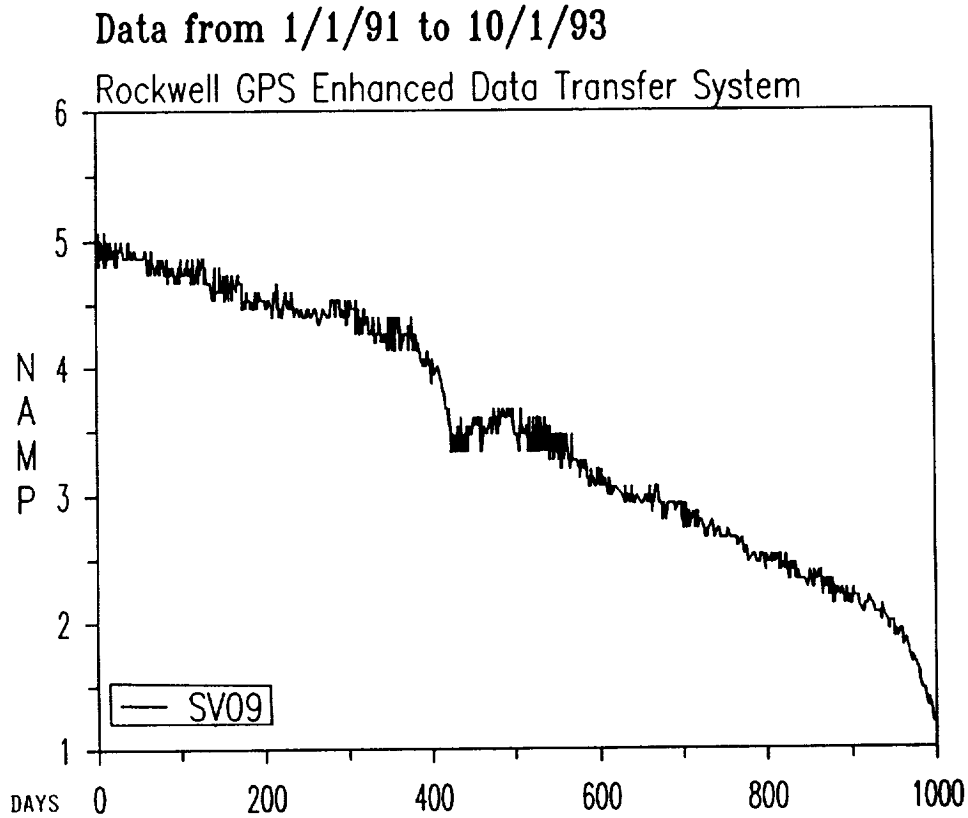


FIGURE 15: SVN 9 CESIUM BEAM CURRENT

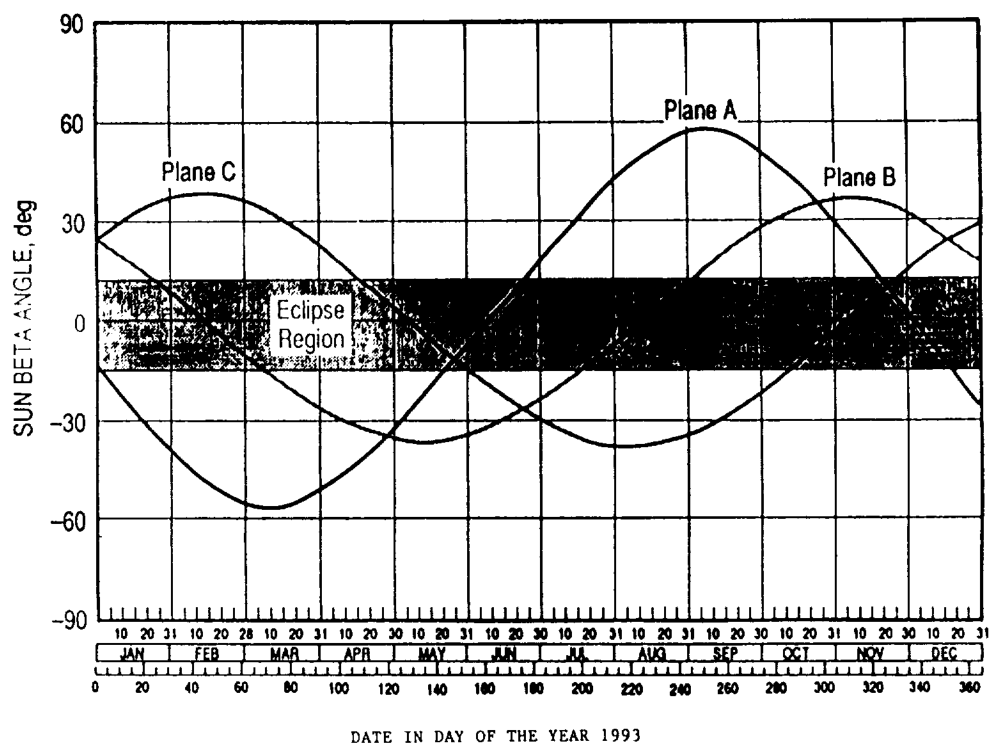


FIGURE 16: BLK II SUN BETA ANGLES AND ECLIPSE REGION

TABLE 5: TOTAL OPERATION HOURS OF BLOCK II/IIA CLOCKS

HOURS OF OPERATION

GPS VEHICLE	CESIUM 3	CESIUM 4	RUBIDIUM 1	RUBIDIUM 2
13	39054			
14	_30806_	109499		
15	_18396_	5270		
16	25403			_11972*_
17	34528			
18	33506			
19	_18980**_	16789		
20	31973			
21	27907			
22	_744**_	6280		
23	_730*_	25476		
24	20877			
25				15037
26	12044			
27	11365			
28	14234			
29		8056		
31		5728		
32		8680		
34		340		
35	1704			
37	4720			
39	3624			
SUBTOTAL	394943	91568		27009
TOTAL	486511 (55.54 Yrs.)		27009 (3.1 Yrs.)	

LEGEND:

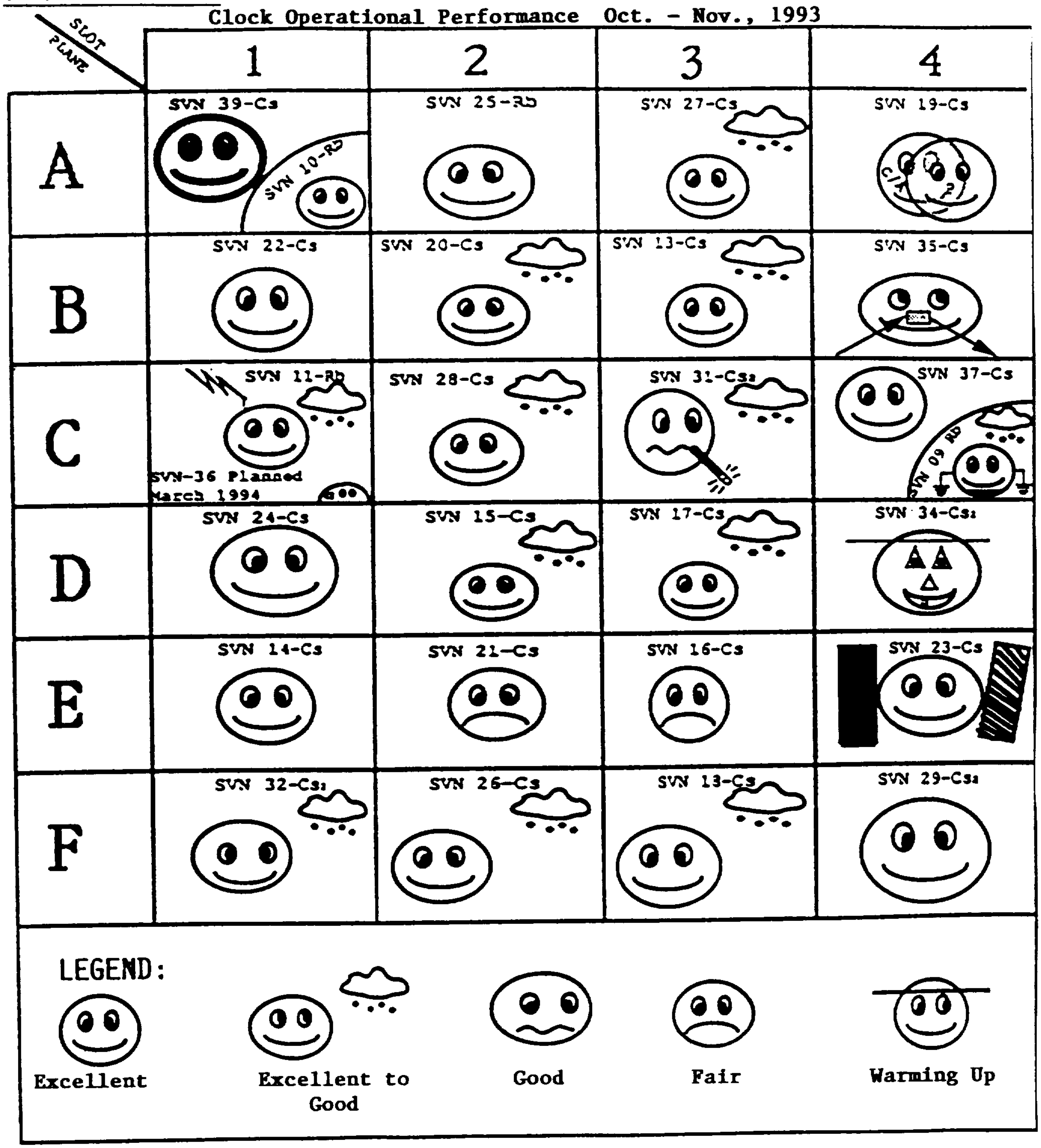
_00000_ = Mortified Clock
* = Powered down for Desert Storm; will power up after all clocks have failed
** = Suitable for degraded operation
8760 Hours = One year

TABLE 6: NAVSTAR MISSION OPERATIONS STATUS

DECEMBER 1, 1993

On-Orbit Vehicles

Clock Operational Performance Oct. - Nov., 1993



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Hydrogen Masers and Cesium Fountains at NRC

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Abstract

The NRC masers H-3 and H-4 have been operating since June/93 with cavity servo control. These low-flux active H masers are showing stabilities of about 10^{-15} *from 1 hour to several days. Stability results are presented, and the current and planned uses of the masers are discussed.*

A cesium fountain primary frequency standard project has been started at NRC. Trapping and launching experiments with the goal of 7 m/s launches are beginning. We discuss our plans for a local oscillator and servo that exploit the pulsed aspect of cesium-fountain standards, and meet the challenge of $10^{-14}\tau^{-1/2}$ *stability [1] without requiring masers.*

At best, we expect to run this frequency standard initially for periods of hours each working day rather than continuously for years, and so frequency transfer to outside laboratories has been carefully considered [2]. We conclude that masers (or other even better secondary clocks) are required to exploit this potential accuracy of the cesium fountain. We present and discuss our conclusion that it is feasible to transfer frequency in this way with a transfer-induced uncertainty of less than 10^{-15}*, even in the presence of maser frequency drift and random walk noise.*

Introduction

NRC has been building and operating frequency standards (Cesium beam tubes and hydrogen masers) for more than 25 years[3]. One NRC maser, H-1, has been operating since 1967, and is still in operation. Two newer masers, H-3 and H-4 began operation as clocks, with cavity servo contol, in June 1993. They have a better long term stability as well as a better short term stability, due to the improvements made to the design. Despite the inaccuracy inherent to the wall shift problems preventing their use as primary frequency standards, hydrogen masers are still the best widely used timekeepers in the range of hours to weeks.

In parallel with the development of hydrogen masers, cesium clocks were built at NRC[4][5]. Cs-V, a 2.1 metre primary cesium beam frequency standard, has been operating for more than twenty years and two of the three Cs-VI, one metre beam tubes built in 1978, are also in operation. The

[0]Retired

development of these cesium beam tubes had been facilitated by the availability of the hydrogen masers. By increasing the intensity of the cesium beam, the short term stability of these clocks from $3 \times 10^{-12}\tau^{-1/2}$ can be pushed to better than $8 \times 10^{-13}\tau^{-1/2}$. The good medium term stability of the hydrogen maser can then be used to measure various parameters of a cesium clock at 10^{-14} level of accuracy in several hours.

But these old laboratory cesium frequency standards are on the verge of being obsolete when compared to the possibilities of the cesium fountains due to the advance in magneto-optical trapping. We have started experiments aimed at building a cesium fountain frequency standard. We are planning to use the hydrogen masers in various ways to help develop, operate and use these new frequency standards, which should give an accuracy better than 10^{-15}. Our plans are to build a tall fountain, with a launch velocity of 7m/s or more. This can minimize the density shift[6] and allows enough room for magnetic focusing and adiabatic fast passage between Zeeman levels. The method of interrogation which was proposed in 1992[1] should allow us to use a one second cycle quasi-continuous fountain.

The main role of our hydrogen masers will be to allow intercomparison of frequency between cesium fountains at various sites and operating at different times. They will probably be our only reliable link between laboratories and BIPM at a level of accuracy of 10^{-15} until the fountains will be operating continuously for months at a time.

Hydrogen masers

The design of the two hydrogen masers, H-3 and H-4[7] [8], has been based partly on experience gained at NRC[3] and at Laval University[9] in Quebec City. In order to operate these masers as clocks, special attention has been paid to minimize the effects of external influences, such as vibration, magnetic field changes and changes in atmospheric pressure and ambient temperature. Five layers of magnetic shielding are used. Their design is the same as the one used in the Laval University masers[9], for which a magnetic shielding factor of 100 000 was measured. This means that a 10% fluctuation in the earth's field should cause a frequency change of less than 10^{-15}. Three concentric ovens are used outside the vacuum enclosure for active temperature stabilization. Two thermal shields have been added inside the vacuum housing, enclosing the resonant cavity. The supports of these shields also serve to decouple mechanically the resonant cavity from changes in atmospheric pressure. The resonant cavity is made of fused quartz, silvered internally. A reentrant aluminum disk is mounted in such a way to compensate the difference in dimensions due to relative thermal expansion of the quartz and aluminum. The loaded Q of the cavity is 38 000. A spherical storage bulb 18 cm in diameter is symmetrically located in the cavity. The bulb in H-3 has been coated internally with FEP-120 Teflon. Since April 1992, a bulb coated with the Russian Fluoroplast F-10 material has been used in H-4. All vacuum seals on the masers use metal rings or wires (either copper or indium). A thin-walled tube of palladium-silver alloy is temperature controlled to control the hydrogen pressure in the discharge tube. The masers are operated in low-flux mode.

The masers have been operated experimentally in different modes: free-running and with external spin-exchange auto-tuning. Now in clock operation, they operate with stand-alone cavity frequency servos employing injected square wave FM signals[10]. Figure 1 shows the relative stability of the two masers over a period of more than two months. Over the same period, the Allan deviation of Cs-VIC and HP234 (Hewlett-Packard cesium beam standard model 5071 with high stability option) against NRC ensemble (based on a Kalman filter algorithm[11]) are also shown. It is obvious that the hydrogen masers have a definite advantage in stability, making them the best candidates to keep memory of frequency calibrations by a cesium fountain running shortly (less than a day) from time to time. It is still too soon to see if there is really any improvement to the drift rate by using the Russian coating. Periods of one to two months without any relative drift between the masers are followed by periods with a relative drift of about 5×10^{-16}/day. It seems that most of the drift is due to H-3. The drift against the ensemble of Cesium clocks appears smaller for the bulb coated with Fluoroplast F-10. (The apparent degradation of stability of H-3 and H-4 against the ensemble (three hydrogen masers, four cesium clocks) in the range of 2×10^4 to 10^6 seconds, is due to the algorithm: no clock is allowed a weight greater than 50%. This puts too much weight on the cesium clocks in the considered range, where they start to compete with the hydrogen masers. It is also in this range where H-1, not shown here, suffers from changes in atmospheric pressure. It does degrade the ensemble, grabbing too much weight from the two better hydrogen masers.)

Cesium fountain

We are currently building a magneto-optical trap which will allow us to laser-trap, laser-cool and laser-accelerate cesium atoms to velocities greater than 7 m/s (see Figure 2). The basic characteristic of our trap is that no laser beam lies along the launch direction. This is done in order to allow preparation of an ensemble of cold atoms while another one is already on its ballistic trajectory. Two choppers acting synchronously let the ensemble of atoms go up along the tube and stop the diffusion light from the trap which could perturb the atoms in the fountain. The Ramsey phase discriminator[1] will be used to interrogate the atomic ensemble. It is a quasi-continuous phase measurement of the local oscillator (a quartz oscillator) with respect to the hyperfine phase of the ensemble of cold cesium atoms. Using the shortest possible dead time τ, relative to the Ramsey interrogation cycle t_a, or active time, we can expect to measure the phase of the local oscillator with an accuracy level of $10^{-14}\tau^{-1/2}$[1]. Post-processing of these measurements makes it possible to calculate a correction relative to the time-scale of the local oscillator. Such a correction can probably be done within a few seconds of the actual measurements.

Optics of the Magneto-Optical trap

The master laser, an extended-cavity diode laser is locked to the saturated absorption crossover resonance peak $6S_{1/2}, F = 4 \rightarrow 6P_{1/2}, F' = 4/5$, which is 125.7 MHz lower than the $6S_{1/2}, F = 4 \rightarrow 6P_{1/2}, F' = 5$ transition used to cool the cesium atoms. The locking is done through an acousto-optic modulator scanning the crossover transition, allowing a modulation free locking of the master laser. Third harmonic detection is used to remove the slope of the saturated absorption profile. A slave laser (>100 mW) is locked to the master laser by optical injection and is split in five beams to create the appropriate trap configuration. Acousto-optic modulators are used to shift the frequency of each beam to create the trapping, the cooling and the acceleration of the atoms. The power per beam is about 10 mW, with a diameter of 1.5 cm. The repumping laser, tuned to the transition $6S_{1/2}, F = 3 \rightarrow 6P_{1/2}, F' = 4$, is locked to the Doppler profile of Cesium absorption. Plans to lock it to the master laser by detection of the beat period at 9.1926 GHz are under development. The repumping laser is added to the horizontal pair of arms. It can also be added to the other four arms.

Vacuum System

The current system is built in two main parts: the trap and the 'clock'. The magneto-optical trap is stainless steel with six viewports on arms aligned in pairs for the three orthogonal laser beam axes. One axis is in the horizontal plane, and the other two are at 45° to the vertical launch axis. The anti-Helmholtz pair of coils are wound around the horizontal arms. The viewing ports are of the Housekeeper type, non-magnetic AR coated glass windows, with a clear aperture of over 2 cm. This allows quasi-continuous trapping. On a one second cycle, it is expected to trap at least 10^7 atoms with laser beams of 1.5 cm diameter, and 10 mW per beam. The preparation of the polarization of the atoms can be made at this level by laser pumping.

The 'clock' part is separated from the trap by a valve, allowing fast modification to the whole system, without having to destroy the vacuum of the trap. The lower section of the clock encloses the choppers to let the atoms get through, but not the light. The middle section contains the quadrupole magnets, and the adiabatic fast passage systems. These will allow us to switch atoms from one Zeeman state to the other allowing for a clock transition from the $F = 4$ to the $F = 3$ levels. The quadrupole magnets could be used to eliminate the atoms in states other than $F = 4, m_F = 0$. The first use of these magnets is to control the transversal dispersion of the moving ensemble of atoms. The upper section houses the detection region, the microwave cavity and the drift region with the C-field.

Microwave System

The microwave cavity is a section of wave guide in the mode TE_{01}. The magnetic and microwave fields will be perpendicular to the beam, as in our classical cesium beam tubes. To select only the clock resonance with a pulsed system, the Ramsey beat-period polarization might be used in addition to the C-field splitting and optical pumping depopulation of undesired levels. For large-diameter detected beams, since $\nabla \cdot B = 0$, transverse-field systems offer some important advantages over axial-field system, and we propose to use a transverse-field system in our initial experiments.The interrogation scheme[1] is a new type of servo: the phase of the atomic ensemble is the reference for evaluating the local oscillator phase. The local oscillator is not providing a reference frequency to evaluate the performance of the locking system to the center frequency of the clock transition. The transition is used to evaluate the phase difference accumulated over the time of flight of the atomic ensemble between the two Ramsey passages in the cavity. For this reason, it is important to minimize the dead time between two cycles. The overall stability does not depend[1] on the stability of the local oscillator over the time of a Ramsey cycle, as in a conventional

[1] To some extent only; the phase error accumulated during one cycle must still be less than $\pi/4$, i.e. a stability of about 10^{-11}.

servo. It depends only on the stability of the local oscillator during the dead time. Depending on the type of noise dominating such a time interval, the long term stability can be dramatically improved over a conventional servo using the same local oscillator.

Detection of the Atomic Polarization

The detection is one of the major problem for delivering the full accuracy of a cesium fountain. It is mandatory to evaluate the atomic polarization of the ensemble of atoms with the highest accuracy possible. We will need to measure the atomic polarization errors at the 10^{-5} level. Since the total number of atoms trapped is not a constant, the ratio of atoms which have undergone a transition to those not having done so is the real parameter to evaluate. We will use a double detection region, where atoms in the $F = 4$ state are first detected by the fluorescence of the cycling transition $6S_{1/2}, F = 4 \rightarrow .6P_{1/2}, F' = 5$, then a second region where atoms in the $F = 3$ state are pumped in the $F = 4$ and detected. The disadvantage of this method is the non-uniformity of detection over the probed volume of the returning atomic ensemble and the difficulties in evaluating perturbations of nearby atoms from the fluorescence.

Another technique we are considering for use is multi-step, multi-photon excitation to high Rydberg states where atoms can be ionized and counted. The advantage of this method is the possibility to have a more uniform detection region. It is also possible to put to use old techniques too. A magnetic detection, using dipole magnet to separate the various Zeeman states could allow direct measurement of the polarization of atoms.

Evaluation of the System

The main advantage of a fountain over a conventional thermal cesium beam tube is the long interrogation time which gives a much narrower line-width, roughly an improvement of 100. In order to get the most out of these new devices, each still has to be evaluated for all the parameters which can affect their potential accuracy. Some new effects, negligible or unheard of in the old standards, might arise. Here are the parameters important to evaluate, in order to reach an accuracy of 10^{-15} or better, and the solutions we intend to apply.

- The second-order Doppler effect can be estimated to much better than 10^{-16}. In the thermal-beam Cs clocks, it can be evaluated to 10^{-15}[12] and the velocity of the atomic ensemble is reduced by close to two orders of magnitude, the second order Doppler effect is reduced by about four orders of magnitude. Also, the velocity distribution is much easier to define than with a classical clock with magnets. This should give another order of magnitude in accuracy on the second order Doppler effect.
- Frequency pulling by neighboring transitions can be eliminated first by depleting the neighboring Zeeman states and second by careful alignment of the cavity microwave field and C-field. To study this last effect, we will use a transverse-field and a six-rod structure for the C-field generation. One pair of opposing rods will be used to controlled the rotation of the C-field. By rotating the C-field respect to the microwave field, Ramsey pulling can be

studied. The long travelling time between the two passages into the cavity will permit to rotate the C-field with constant amplitude and push further the study of this effect.

The easiest way to eliminate some of the frequency pulling is still to operate the frequency standard in the Ramsey phase discriminator mode. If the local oscillator's offset is kept small enough, it eliminates virtually all the pulling effects due to the distortion of the baseline.

- The C-field inhomogeneities can be studied in different ways. Since the atoms are spending most of their time above the cavity in the top part of their trajectory, by varying the height above the cavity, it is possible to sample the C-field effectively. Based on our experience with cesium beam tubes, with proper care, it is possible to build a transverse field with 0.02% uniformity[9], reducing the error associated to less than 10^{-15} for fields smaller than 10 mGauss. Using a cold, superconducting, drift region for the fountain part, it is also possible to have a calculable magnetic field.
- Spectral impurities, cavity pulling and microwave power effects can be reduced to less than 10^{-16} with proper electronics design and the mode of operation in phase modulation instead of frequency modulation.
- The spin-exchange effects are likely to be one of the dominant effect on the frequency pulling. Operating the clock at a low density of atoms is then very important to reduce the uncertainty due to this effect. Very careful measurements of the real density and polarization of each ensemble of cold atoms will probably be a necessity to break the 10^{-15} limit. First measurements made by Gibble and Chu[6] are already giving an order of the magnitude of the problem.
- The cavity phase shift due to different phase between two cavities in the Ramsey beam configuration may still be present in a different form. The power absorbed by the atoms is likely to be different on the going up trajectory than on the going down trajectory. The density of atoms will likely be lower on the second passage, loading the cavity at a lower level but for a longer time. Using a variable quadrupole focusing magnet, we will measure the effect of the ratio of densities between the two passages. There is still the problem of trajectories through the cavity, sampling different phases of the microwave field. A superconducting cavity would alleviate this problem.
- The black body radiation will have to be measured very accurately. Being of the order of 1.5×10^{-14} at room temperature, it needs to be measured at various temperature, including very low temperature, in order to get the required accuracy to compensate for any bias at room temperature. The best solution is to compare two fountains, one at liquid helium temperature[2], one at room temperature.

There is still a lot of work to be done before assessing an accuracy of 10^{-15} or better to the cesium fountains. For this reason alone, it is unlikely that such a device would be operated continuously in the near future. So many experiments need to be done that it is likely a cesium fountain would be operated only for short periods at a time between experiments.

[2]This would be a real Zacharias fountain.

Frequency transfer

The International Bureau of Weights and Measures (BIPM) is always in need of better accuracy. Hence it is imperative to transfer the improved accuracy of the cesium fountains as soon as possible. It will also be most interesting to compare implementations of these new frequency standards by various groups[6] [13] [14] as early as possible. Hydrogen masers appear to be most attractive as frequency transfer standards until the fountains can be operated in the clock mode, i.e. periods of continuous operation of months or more. The uncertainty in any proposed frequency transfer process is likely to be the dominant term in the uncertainty budget, and so we developed a reliable method[2][15] for evaluating this uncertainty, which has its origins in the random-walk frequency noise and the frequency drift of the maser.

We used the following hydrogen maser characteristics which includes white phase noise ($\alpha = 2$) contributed by the maser and phase measurement system and typically $h_2 = 6.7 \times 10^{-23}$, flicker phase noise ($\alpha = 1$) with $h_1 = 2.9 \times 10^{-30}$, white frequency noise ($\alpha = 0$ - shot noise on the atomic beam of the fountain also contributes noise of this form) with $h_0 = 2.9 \times 10^{-27}$, flicker frequency noise ($\alpha = -1$) with $h_{-1} = 7.2 \times 10^{-31}$, and random walk frequency noise ($\alpha = -2$) with $h_{-2} = 4.9 \times 10^{-37}$. The frequency stability described by this random noise model is shown in Figure 3 (thick line) as the two-sample deviation (Allan deviation) of the average frequency vs averaging time τ.

The light straight line on Figure 3 is the cesium fountain noise with a frequency uncertainty of $3 \times 10^{-14}\tau^{-1/2}$. This is what could be expected from a pulsed cesium fountain with a 1 s cycle time (0.5 Hz Ramsey line-width) with 1% dead time per cycle [1], with an ideal atomic shot noise of about 4×10^5 detected atoms per second (assuming ideal atomic polarization detection, without background or detector noise). The curved lines, labeled $t_a = 3000s$ and $t_a = 10000s$, tangent to the maser curve at large τ, are the expected uncertainty limits of the frequency transfer for a single calibration of the hydrogen maser for a time t_a (the active time of the cesium fountain) centered in the interval time τ between time transfers. It can be seen that we gain a factor of two on the maser stability alone at large τ.

The dotted lines are the expected frequency transfers for multiple calibrations, each one done once a week. Using a multiple calibration to remove the drift rate of the hydrogen maser, we can improve in the long run the frequency transfer. For a cesium frequency standard running less than an hour per week, four weeks are needed to transfer the frequency to an accuracy of 10^{-15}. If the fountain is running nine hours once a week, two weeks only are needed to reach the same accuracy.

Interlaboratory Frequency Transfer

The above discussion applies only to frequency transfer in the confines of the laboratory, where phase resolutions of less than 1 ps and longer term stabilities of the order of 10 ps are possible. The accuracy of interlaboratory frequency transfer can probably best be achieved by two-way time transfer (TWTT) via common-view geosynchronous communications satellites, preferably at Ku band, or with GPS (Global Positioning System) satellites if time calibrators are used for the receivers to measure the carrier phase. The current state of the art of TWTT shows time transfer precisions of 2 ns (long-term) with short-term precision of 0.2 ns. With dynamic calibration, it is expected to get a long-term precision as good as the short-term calibration.

Figure 4 shows the trend line for the frequency uncertainty within a laboratory for a calibration time $t_a = 3000$ seconds, the maser characteristics (thick curve) and the frequency uncertainty that might be delivered to a remote laboratory by two-way time transfer, with a full time transfer precision for each transfer of $\delta t = 2$ ns and 0.2 ns. In remote calibrations, we need only to add in quadrature the standard uncertainty of the second cesium fountain's frequency to get the full frequency transfer uncertainty delivered to a second time laboratory. For comparisons with the frequency of a second laboratory's cesium fountain, the effects of their hydrogen maser (or local oscillator used for the frequency transfer) must also be added. With the present two-way time transfer precision of 2 ns, the intercomparison uncertainties for weekly calibrations would require more than nine weeks to reach the level of 10^{-15}. At the 10 day reporting interval used by TAI, the intercomparison uncertainty is better than 5×10^{-15} for the weekly trend line.

Conclusion

We presented the latest results from our hydrogen masers H-3 and H-4. The Fluoroplast F-10 coating appears to be an improvement over the FEP-120 Teflon. We also presented our activity on the cesium fountain project. Although we are not planning to use our hydrogen masers as local oscillators, they show they have the stability required to provide the proper timekeeping capacity for interlaboratory comparison in the early age of cesium fountains.

Two-way time transfer or perhaps GPS carrier-phase based (geodetic) time transfer are able to achieve interlaboratory frequency transfer accuracies of better than 10^{-15} over periods of many weeks. To keep in pace with the expected development of the cesium fountain's frequency standard, an improvement in the transfer techniques, or in the transfer oscillators, is needed to achieve comparable frequency transfers in a shorter time.

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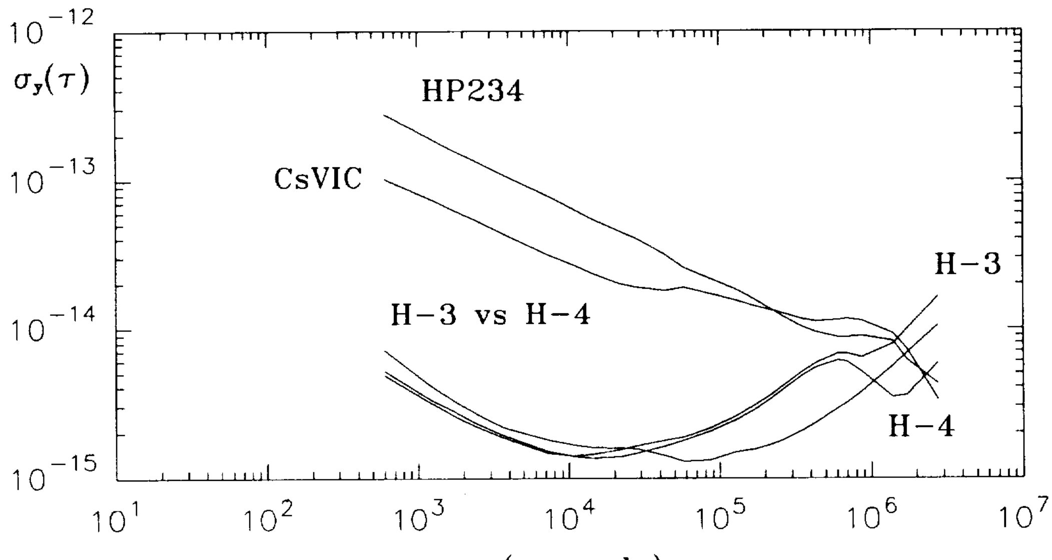
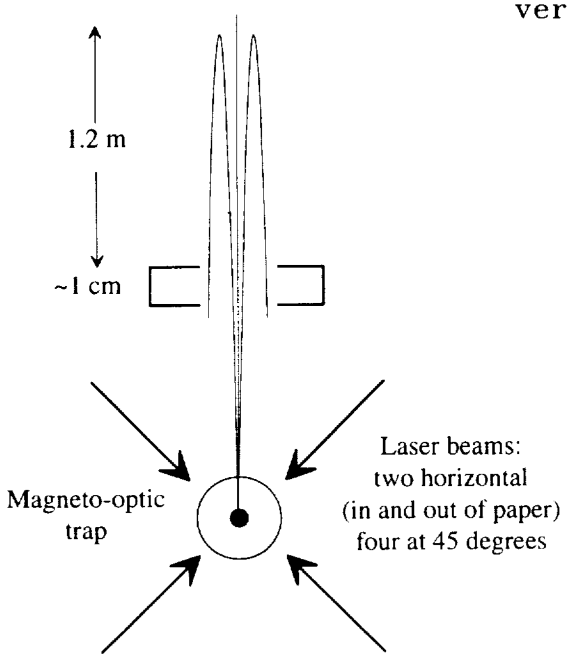


Figure 1
Stability of H−3, H−4
and cesium clocks at NRC
versus the ensemble.



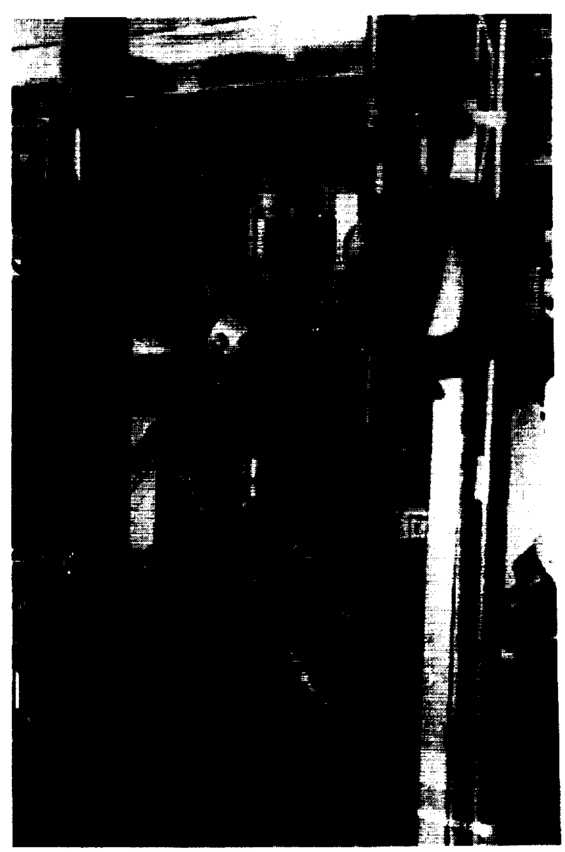


Figure 2
The tall cesium fountain. The picture at right
is the magneto-optical trap already built.

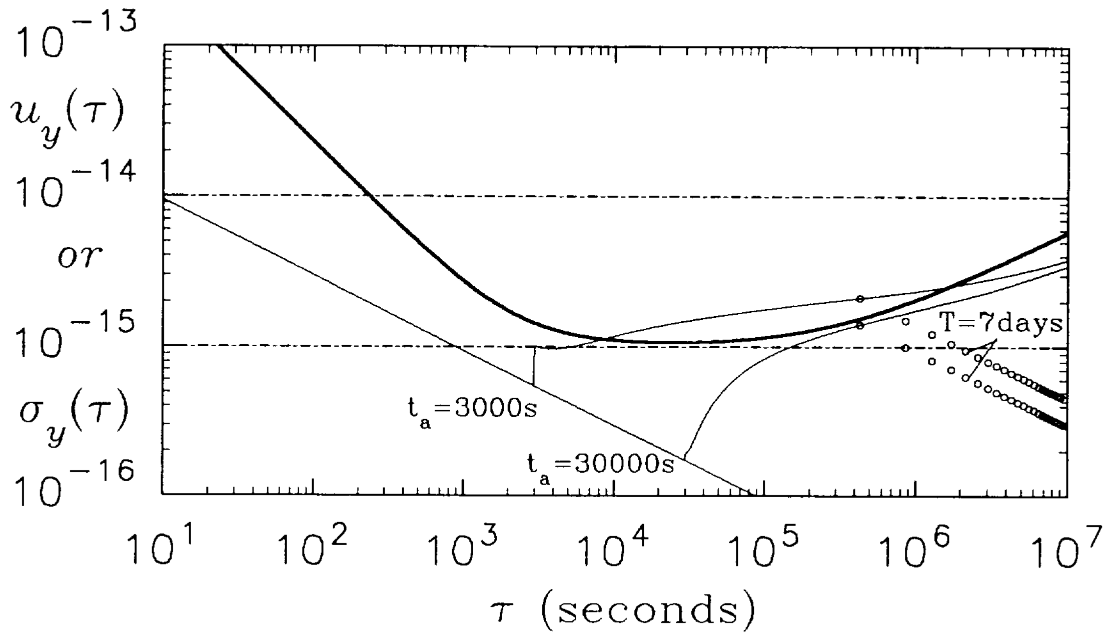


Figure 3
Frequency transfer uncertainty with a hydrogen maser.

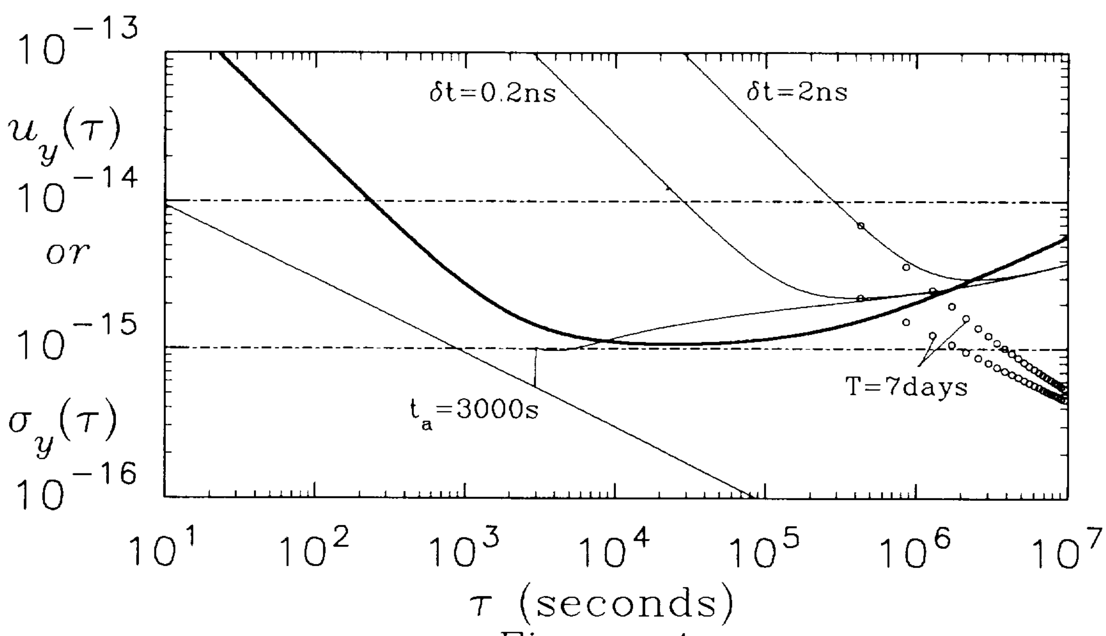


Figure 4
Frequency transfer uncertainties with a hydrogen maser and two-way time transfer

COMPARISON OF LASSO AND GPS TIME TRANSFERS

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Abstract

The LASSO is a technique which should allow the comparison of remote atomic clocks with sub-nanosecond precision and accuracy. The first successful time transfer using LASSO has been carried out between the Observatoire de la Côte d'Azur in France and the McDonald Observatory in Texas, United States. This paper presents a preliminary comparison of LASSO time transfer with GPS common-view time transfer.

1. INTRODUCTION

The idea of using satellite laser techniques for the comparison of remote atomic clocks, known as LASSO (Laser Synchronization from Stationary Orbit), was conceived by M. Lefebvre and J. Gaignebet in 1972. The first successful tests were accomplished in 1989[1]. The first LASSO experimental link was established in 1992 between Observatoire de la Côte d'Azur (OCA) in Grasse, France, and McDonald Laser Ranging Station (MLRS) located at the McDonald Observatory in Fort Davis, Texas[2,3]. LASSO involves very simple physics, light travelling through space, and should easily allow sub-nanosecond time transfer.

At present, the use of the GPS common-view technique permits the comparison of remote atomic clocks at their full level of performance. We already know, however, that over the next few years new and better clocks will become available and that the GPS, as practiced now, will not then provide a system of adequate resolution. The estimated accuracy of intercontinental GPS time comparisons is of several nanoseconds[4,5], but, up to now, this has not been verified by an independent method of comparable or better accuracy. In this context LASSO appears to be an outstanding tool for the evaluation and calibration of the GPS time transfer and other time transfer techniques.

During an experiment covering the period from 8 December 1992 to 28 January 28 1993, two remote atomic clocks, separated by about 8000 km, were compared by independent space links, LASSO and GPS common-view. On each site a laser and a GPS receiver were connected to a single clock, a commercial cesium standard (Fig. 1).

The principal difficulty of this experiment was to obtain weather conditions under which LASSO measurements could be carried out. Unfortunately, throughout the experiment the sky was often covered and only in last week were five LASSO measurements accomplished. The experiment has now ended since the geostationary satellite Meteosat 3/P2, on which LASSO package is placed, has been moved to a location not visible from the OCA.

This paper, after giving a brief description of the GPS common-view and LASSO time transfers, reports the preliminary results of the comparison of these two methods.

2. GPS COMMON–VIEW LINK

In common–view time transfer, two remote stations receive signals from the same satellite at the same time and exchange the data to compare their clocks (Fig. 2). The main advantage of this method, introduced in 1980 for GPS[6], is that satellite clock error contributes nothing (satellite time disappears in the difference). Also over distances of up to a few thousands of kilometres the impact of other errors, such as poor estimation of ionospheric delay or broadcast ephemerides, is diminished. During our experiment, time transfer were carried out over a distance of 8000 km. In this case the modelling of the ionospheric delay applied by GPS time receivers should be replaced by measurements of ionosphere and broadcast ephemerides should be replaced by post–processed precise ephemerides. Both improvements will be incorporated in the next report on this experiment.

By using the same type of receiver at each site the consistency of the clock comparison is ameliorated as possible software errors are removed by the common–view approach. In the present study, GPS C/A Code time receivers were of the same type, AOA TTR5 at OCA and AOA TTR6, on loan from the BIPM, at McDonald.

In addition to single frequency GPS time receivers, double frequency GPS receivers providing ionospheric measurements were installed on both sites: a NIMS (NIST Ionospheric Measurement System) at OCA and a Trimble 4000 SST at McDonald.

The coordinates of the GPS antennas were expressed in the ITRF88 reference frame at OCA and the ITRF91 reference frame at McDonald, and were provided by the geodetic link with laser points at each site[7]. The estimated uncertainty of coordinates at each site is 5 cm. The uncertainties of the GPS ground antenna coordinates can have only a sub–nanosecond impact on the accuracy of this GPS common–view link.

The GPS common–view time transfer was realised from the about fifteen daily tracks of Block I and Block II satellites, following a special schedule (Fig. 4). During this experiment, the Block II satellites were subject to Selective Availability, so strict common views were required[8].

A Vondrak smoothing[9], which acts as a low-pass filter with a cut-off period of about five days, was performed on the raw GPS common-view values. The precision of this GPS link, estimated from the residuals of the smoothed values, is about 10 ns and should fall to about 4 ns after application of the measurements of ionosphere and post-processed precise ephemerides[4].

3. LASSO LINK

The LASSO link was realized through quasi-simultaneous laser firing to the METEOSAT 3/P2 geostationary satellite which was located at longitude 50° West[2,3]. The on board LASSO payload comprises a laser pulse detector, an event timer monitored by quartz oscillator, a retroreflector and uses telemetry downlink transmitter of the meteorological par of the satellite. A laser pulse departure is recorded on the ground station clock, its arrival at the satellite is recorded on the on board-clock and the time of returning pulse is then recorded on ground station clock (Fig. 3). A set of these three epochs is called a triplet. The same scheme is repeated quasi-simultaneously on the second ground station. The recorded arrival times at the satellite are sent back to the Earth. Atomic clocks located in two laser stations are compared using pairs of triplets. A detailed description of the LASSO observation and data processing is given in [2] and in [3] in these proceedings.

Bad weather conditions at the OCA and McDonald prevented simultaneous laser observations for almost the entire period of this experiment. Only during the last week did three cloudless nights at both sites allow LASSO time transfer. The results are given in Table I and Figure 4. The estimated precision of each of the five LASSO comparisons is better than 100 picoseconds[2,3].

4. CALIBRATION OF GPS AND LASSO TIME LINKS

The GPS TTR6 receiver was returned from McDonald back to France at the end of the experiment, where it was compared with the OCA TTR5 receiver. This differential calibration was performed according to the method described in [10]. The estimated uncertainty for the calibration of the GPS equipment is 2 ns.

To calibrate the laser equipment a portable laser station belonging to the ESA was compared in May 1993 with the OCA on-site laser equipment. In July 1993 the portable laser was transported to McDonald, where it was compared with on-site laser equipment. This exercise is described in [11] of these proceedings. As this report was being prepared the results of the calibration of laser equipment were not available. These will be given in future reports on this experiment. We know already that the precision of the calibration at the OCA is estimated at about 100 ps and that at McDonald at a few nanoseconds. This very large uncertainty in the calibration of the McDonald laser is linked to a particular configuration of the timing equipment at this station, which was not designed for ultra-precise time transfer, a problem which was not understood at the beginning of the experiment.

Particular attention should be paid to the link between the timing marks obtained by GPS and by laser timing equipment. In particular GPS receivers treat a stream of 1 Hz pulses provided by local clock, and laser timing equipment treats 5 MHz zero–crossing pulses.

5. COMPARISON OF GPS COMMON–VIEW AND LASSO TIME TRANSFERS

As the GPS common–view link between the OCA and McDonald was calibrated, and its estimated uncertainty is about 10 nanoseconds, it serves as a good reference for a preliminary evaluation of the LASSO link.

For this experiment, the smoothed GPS values were interpolated for the times of occurrence of LASSO observations. Comparisons of the two techniques are given in Table I and Figure 4. Note that the GPS and LASSO results differ by a fairly constant bias with peak–to–peak discrepancy of about 15 ns. The mean of these differences is 192 ns. The root mean square of the residuals to the mean, which is taken as an estimation of the confidence of the mean, is 6 ns.

Table I. Comparison of GPS common–view and LASSO time transfers

1993 Jan.	Epoch h	m	s	OCA-MLRS byLASSO ns	OCA-MLRS by GPS ns	GPS - LASSO ns	GPS - LASSO -192 ns ns
21	2	15	14.4	9933.56	10133	199	7
22	1	41	54.9	9990.05	10175	185	-7
22	1	56	12.1	9990.58	10176	185	-7
26	1	52	01.4	10154.26	10349	195	3
26	2	17	59.4	10155.96	10350	194	2

The bias of about 192 ns between the GPS common views and the LASSO is certainly due to the lack of calibration of laser equipment. In the last column of Table I the 192 ns bias has been removed.

6. FUTURE OF LASSO EXPERIMENT

The experiment described in this paper ended when the geostationary satellite Meteosat 3/P2, on which LASSO package was mounted, was moved to a location not visible from the OCA (75° West). Its mission was scheduled to end some time in 1993.

After this first successful LASSO time transfer experiment, the timing community considered future LASSO missions; a new LASSO generation could be able to reach a 10 ps accuracy of time transfer. One possible carrier of a LASSO payload would be the Russian satellite METEOR 3M during a joint experiment with the European Space Agency "Hydrogen Maser/Meteor 3M Mission"[12]. Other possible spacecraft which might carry LASSO equipment are the GPS

C-5

and GLONASS satellites. GPS Block II satellites are now equipped with laser reflectors; all GLONASS satellites have always been equipped with such reflectors. As these navigation satellites are equipped with atomic clocks very few additional elements would be required to complete the LASSO payload. A detailed description of a possible LASSO implementation on GLONASS satellites is given in[13].

7. CONCLUSION

This comparison of GPS common-view and LASSO time transfers between Western Europe and North America shows consistency within stated uncertainties and a bias of about 192 ns. The bias is certainly due to non-calibration of the laser equipment.

After ameliorating of GPS link by inserting measurements of ionosphere and post-processed precise ephemerides, and after differential calibration of the lasers, the agreement between two techniques should be improved.

Although LASSO, because of its sensitivity to weather conditions, is inherently unsuited for operational duties, it is certainly an excellent tool for the assessment of the accuracy of GPS, GLONASS and Two-Way time transfers. The implementation of LASSO on new satellites is a challenge for coming years.

Acknowledgements

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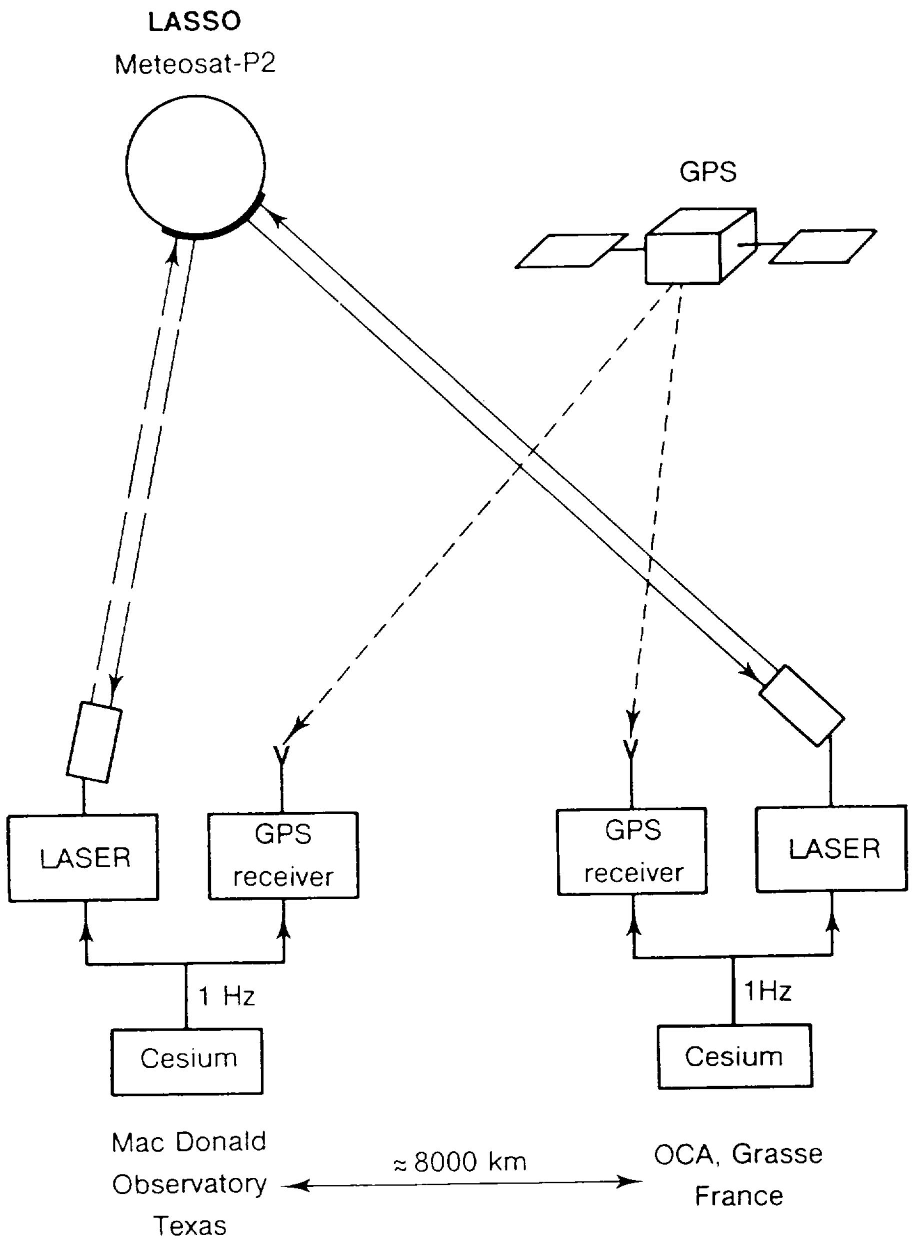
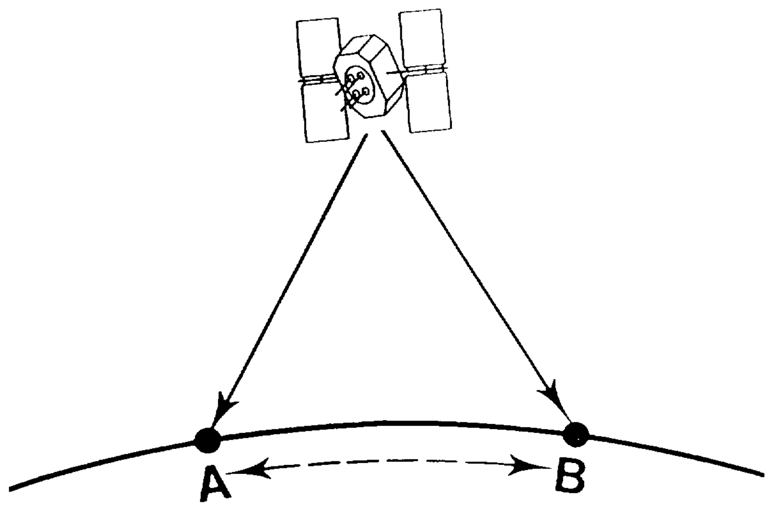


Figure 1. The experiment configuration.



$$\text{clock A} - \text{clock B} = [\text{clock A} - \text{sat. clock}] - [\text{clock B} - \text{sat. clock}]$$

Figure 2. GPS common-view time transfer.

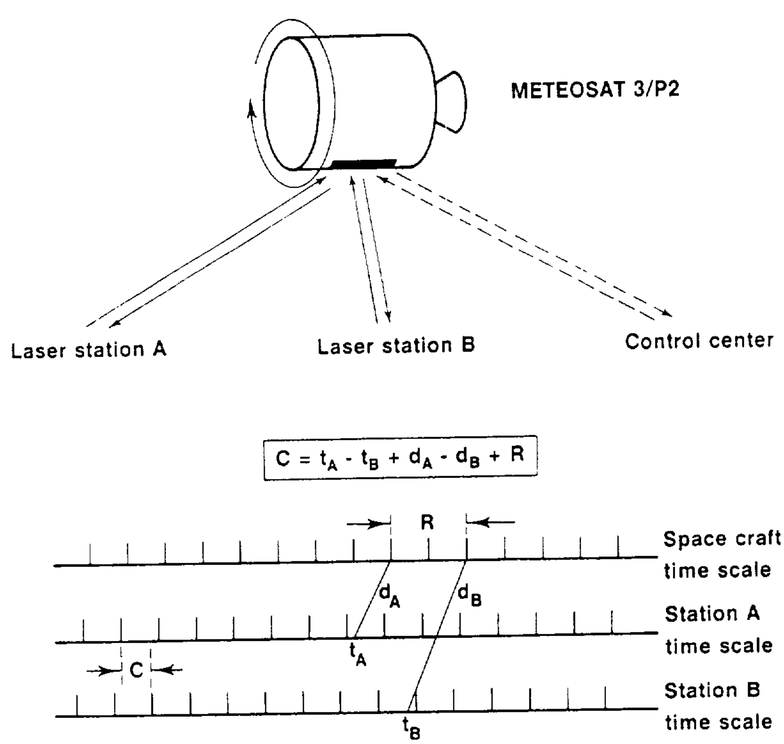


Figure 3. LASSO time transfer.

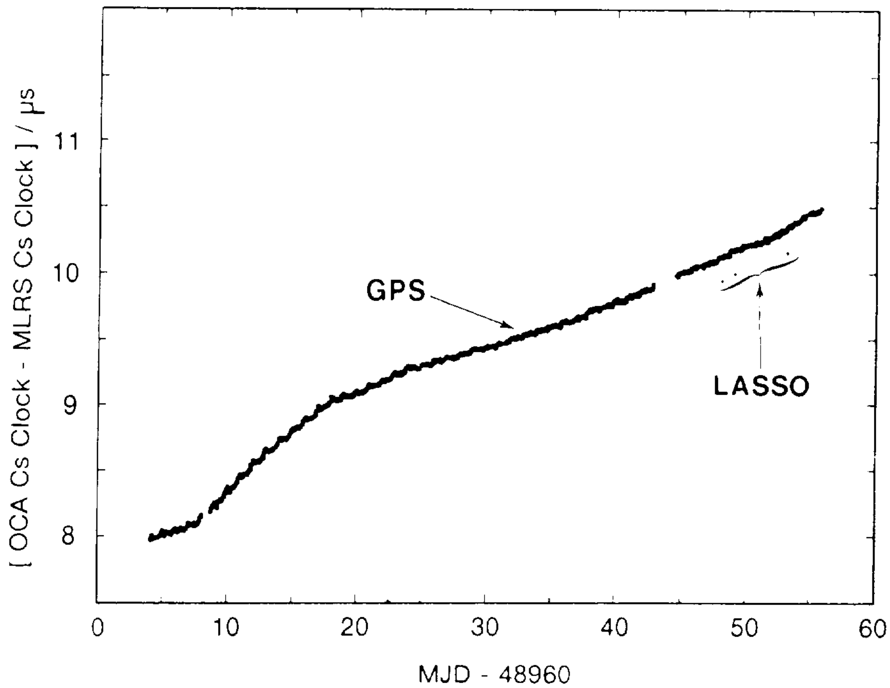


Figure 4. [OCA Cs Clock - MLRS Cs Clock] by GPS common-view and by LASSO.

Done

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LASSO EXPERIMENT: INTERCALIBRATIONS OF THE LASSO RANGING STATIONS

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I. LASSO PRINCIPLE — Fig 1–2

Let assume a satellite S fitted with laser retroreflectors associated to a light detector and an event timer. The time scale of the satellite is HS.

Let assume two laser ranging stations L1 and L2 with their own time scales H1 and H2 and their own event timers. (The event timer could be replaced by an intervalometer and a chronometer).

L1 sends a laser pulse towards the satellite at the epoch TE1 in the time scale H1. The laser pulse is detected on board at the epoch TS1, in the time scale HS, and, at its return at the laser station at the epoch TR1 in the time scale H1. The two way flight time tF1 could be expressed in two different manners.

tF1 = TR1-TE1 = tg1+tr1 where tg1 and tr1 are the flight times of the laser pulse from the station to the satellite and from the satellite to the station.

Neglecting aberration and relativistic corrections:

tg1 = tr1 = tF1/2.

In the same way one can define the epochs TE2, TS2, TR2, and flight delays tF2, tg2, tr2.

We can write the following relations:

TS1 = TE1 + tg1 (H1)

TS2 = TE2 + tg2 (H2)

TS2 = TE2 + (H02-H01) + tg2 (H1).

We can deduce:

TS2 - TS1 = TE2 - TE1 + tg2 - tg1 + H02 - H01,

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TS2 - TS1 = TE2 - TE1 + tg2 - tg1 + H02 - H01,

or

H02 - H01= TS2 - TS1 + TE1 - TE2 + tg1 - tg2.

If the satellite sends by telemetry TS1 and TS2 (HS) or TS2 - TS1 we can compute the time difference between the two time scales H1 and H2.

One can also monitor, from one of the laser station, the behavior of the satellite clock.

TS1 H1 = TE1 H1 + tg1 H1 = TS1 HS + (H0S-H01) H1,

then:

(H0S - H01) H1 = TE1 H1 -TS1 HS + tg1 H1.

II . DEFINITION OF THE CALIBRATIONS — Fig 3

In the following we assume that the laser ranging stations are provided with event timers. The epochs TE1 TR1 TE2 TR2 TS1 TS2 are related to marks called "reference points". For laser stations this point is defined as the first invariant point of the return path and the last invariant point of the emission path. In general the point is the crossing point of the two axes of the mount. (For some station the two axes are not crossing and a correction computed from the direction of the mount is to be added). In fact the timing is always delayed by optical travel times, cable propagation delays and electronic delays.

Fig. 3 develops the diagram of a conventional laser ranging station and its symbolic representation.

T'E = TE + τg where τg = $\sum_1^n \tau$ gn,

T'R = TR + τr where τr = $\sum_1^{\diamond} n \leq \tau$ rn,

T'E and T'R being the event timer displayed times.

The same kind of relations are true at the level of the satellite but the equations of time synchronization include time differences only. By this the satellite delay t cancels. This is also true when following the on board oscillator frequency. But this delay must be taken into account to know the synchronization between ground and satellite times.

III. LASER RANGING STATION CALIBRATIONS

The equations leading to the determination of the synchronizations of the clock include for each station two kinds of measurements:

- Time intervals: measurements of the round trip times of the laser pulses at each station:

  The value tg1 - tr1 is the station ranging calibration constant. This constant has to be added to the difference of event timers readings to determine the true flight time of the light from the station to the satellite and back.

- Times TE1 and TE2 and more precisely the difference TE2 -TE1 between two different stations.

  In this case:

  $TE1 = T'E1 - \tau g1$ and $TE2 = T'E2 - \tau g2$,

  $TE2 - TE1 = T'E2 - T'E1 + \tau g1 - \tau g2$.

Therefore, it is enough in order to keep the same accuracy of the time synchronization to determine $\tau g1 - \tau g2$.

NB.: it has to be noted in that application of laser ranging to the time domain that we use directly the flight time without consideration to the medium crossed. The index correction necessary for range determination is not useful in time synchronization.

IV. CALIBRATION DETERMINATIONS

A: Ranging Calibration ($\tau g - \tau r$)

Several methods have been developed within the laser ranging community.

a) Target ranging

A target at a known distance is ranged by the station. The flight time from the reference point to the target and back is computed taking into account the meteorological parameters at the time of each session.

$\tau g + \tau r = T'R - T'E + \tau g - \tau r$.

b) Simple and double two way flight time, Fig 4

Simple ranging:

$\tau g + \tau r = T'R - T'E + \tau g - \tau r$

Double ranging:

$2(\tau g + \tau r) = T''R - T''E + \tau g - \tau r$

which allows us to determine

$\tau g - \tau r = T''R - T''E - (T'R - T'E)$ round trip time

$T''E$ and $T''R$ being the event timers displayed times for the double ranging.

$\tau g - \tau r = T''R - T''E - 2(T'R - T'E)$ ranging calibration constant:

c) Measurement of optical and electronical delays

This method let determine a value of the correction with good approximation but must be verified by a global method as some delays are rather tricky to determine.

d) Co-location

The co-locations do not by themselves measure the value of the ranging calibration constant. However they are the only way to verify that the measurements are consistant within to stations.

B: Lasso Intercalibration ($\tau g1$ - $\tau g2$) Fig. 5

The two methods are:

a) Co-location

Two co-located stations use the same time scale and range on the same target, it allows to determine the Lasso intercalibration constant. In practice most of the laser stations are not mobile and cannot be co-located.

b) Calibration station

The method requires a common reference for the different stations. This common reference is a highly mobile laser ranging station able to be set up next to the stations to be intercalibrated. The method is in fact a double co-location with a common station. This allows the determination of $\tau g1$ - τgC and $\tau g2$ - τgc and taking out τgc, $\tau g1$ - $\tau g2$.

Principle of the measurements Fig. 6

Two sessions will be organised ranging at the target T in the following configurations :

Session 1 :

The calibration station LC ranges the target, recording in its own time scale HC, the emission time T'E(C,C,C) the return time T'R(C,C,C) and the return time at the station to be calibrated L1 and with an additional delay h1C (delay of the link from station 1 to station C) T'R (C,1,C). At the same time L1 records the return in its own time scale T'R(C,1,1).

Session 2 :

The station to be calibrated L1 ranges the target. L1 and LC record the epochs T'E(1,1,1) T'R (1,1,1) T'R(1,C,1) T'R(1,C,C).

The format of these times is a follow :

T' Time displayed at the event timers

E/R Emission or return time

C/1 Emitting station

C/1 Receiving station

C/1 Event timer

We could express these times as follows: Fig 7

$$Session1:$$

$$\begin{aligned}
(1)T'E(C,C,C) &= TE(C,C,C) + \tau gC \\
(2)T'R(C,C,C) &= TE(C,C,C) + \tau rC + \tau gC + \tau rC \\
(3)T'R(C,1,C) &= TE(C,C,C) + \tau r1 + \tau gC + \tau r1 + h1C \\
(4)T'R(C,1,1) &= TE(C,C,C) + \tau r1 + \tau gC + \tau r1 + (H01 - H0C) \\
&= TE(C,1,1) + \tau r1 + \tau gC + \tau r1
\end{aligned}$$

$$Session2:$$

$$\begin{aligned}
(5)T'E(1,1,1) &= TE(1,1,1) + \tau g1 \\
(6)T'R(1,1,1) &= TE(1,1,1) + \tau r1 + \tau g1 + \tau r1 \\
(7)T'R(1,C,1) &= TE(1,1,1) + \tau rC + \tau g1 + \tau rC + h1C \\
(8)T'R(1,C,C) &= TE(1,1,1) + \tau rC + \tau g1 + \tau rC + (H0C - H01) \\
&= TE(1,C,C) + \tau rC + \tau g1 + \tau rC
\end{aligned}$$

We know that τgC = τrC = τC and τg1 = τr1 = τ1 and the difference τ1 - τC could be accurately measured (difference of the position of the two reference points related to the target).

From these relations we could compute the ranging calibration constants and their difference (τgC - τrC) - (τg1 - τr1). In the case of the calibration station: τgC - τrC = 0 - Fig 8 - we will determine immediately τg1 - τr1.

For the Lasso intercalibration τgC- τg1 different methods could be used:

1) Direct measure of the difference H01 - H0C of the time scales of the two co-located equipments. Inaccuracy arises by the fact that the internal delays of the event timers are not taken into account.

2) Use of known delay links between the two time reference points of the event timers. These reference points are in most of the cases the input of discriminators for the emitted and received signals. As these links are simple cables the measurements of their delays are quite simple. In practice we have two cables. Each cable carries the signal from one of the station to the second one in one direction only. The difference in their delays h1C - hC1 must be known.

3) Use of the same cables to intercalibrate the two fixed stations

$\eta 1C = \eta 2C$ $\eta C1 = \eta C2$

We consider that the cables with delays $\eta 1C$ and $\eta C1$ are part of the calibration station.

4) Use of the same cables for all the co-locations to carry the 1Hz and 5MHz signals. When the event timers have been started they need the 5MHz only. The 1Hz line could be used to time tag pulses at both event timers. At the end this will allow to determine H01 - H02 in the conditions used during the calibration session.

From equations 1 to 8, which are not fully independent, we could determine: the ranging calibration constant of station 1 $\tau r1$ - $\tau g1$, the gap between the two time scales H01 - H0C, the Lasso calibration constant $\tau g1$ - τgC.

N.B. : In the case of the calibration station the event timer has 4 channels and two inputs (Emission/Reception). We have implemented an emission delay Fig.3 $\tau' g$ which allows us to monitor the stability of the equipment. By conception the ranging calibration constant of the calibration station is equal to zero Fig. 8.

This delay is designed to be as stable as possible with an optical fiber link. As noted hereupon the ranging calibration is zero. The emission and reception paths are common after the reference point.

The difference of return levels could introduce some error. To minimize it we use very short laser pulses (13ps), light attenuators and constant fraction discriminators.

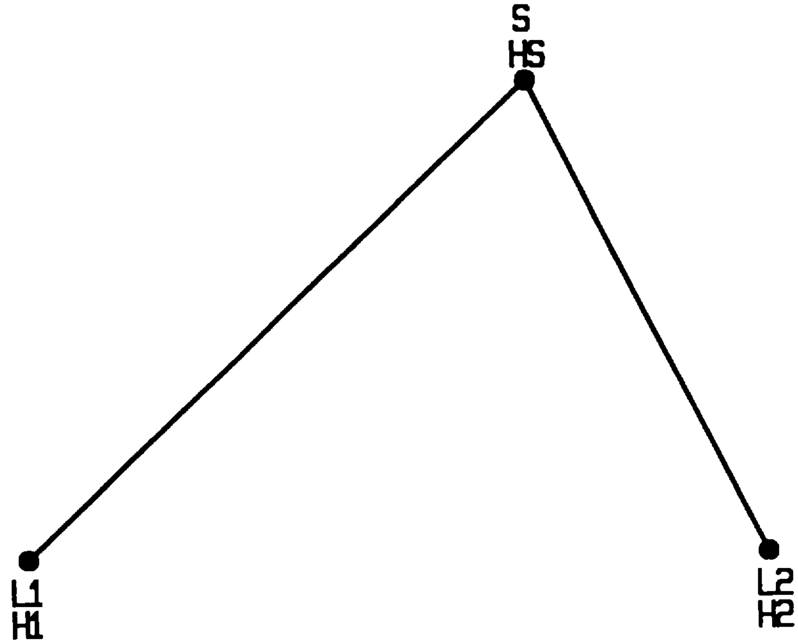

S
HS
L1
H1
L2
H2

Fig 1

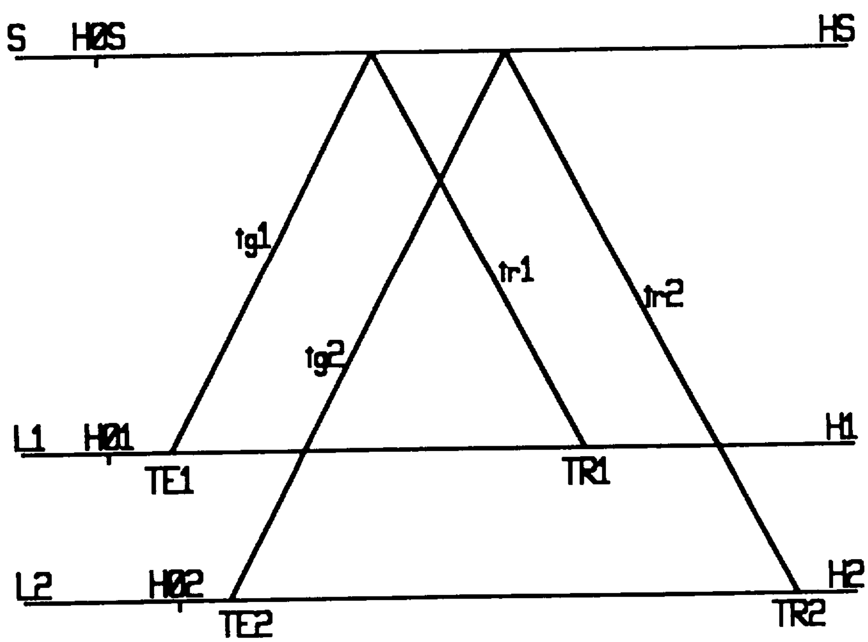

S
H0S
HS
tg1
tr1
tr2
tg2
L1
H01
H1
TE1
TR1
L2
H02
H2
TE2
TR2

Fig2

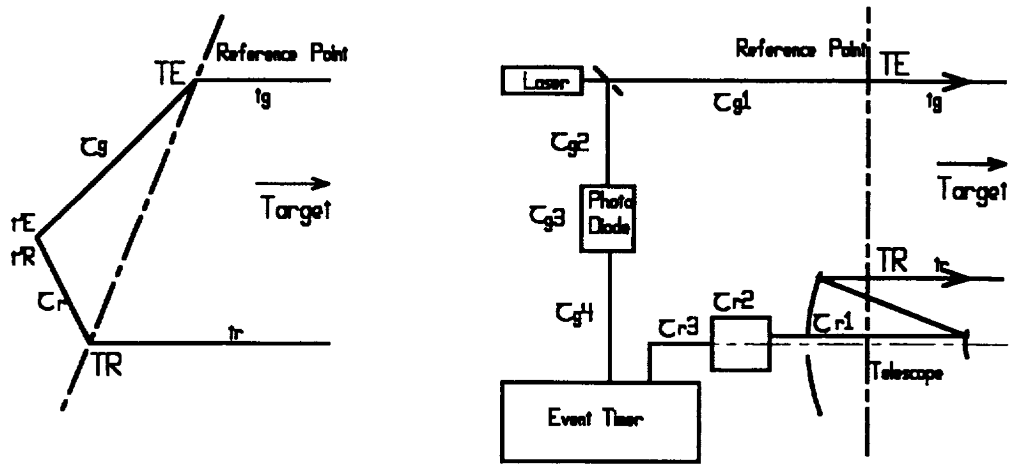

Reference Point
TE
tg
τg
Target
tE
tR
τr
tr
TR
Laser
Reference Point
τg1
τg2
τg3
Photo Diode
τg4
τr3
τr2
τr1
TR
Telescope
Event Timer

Fig 3

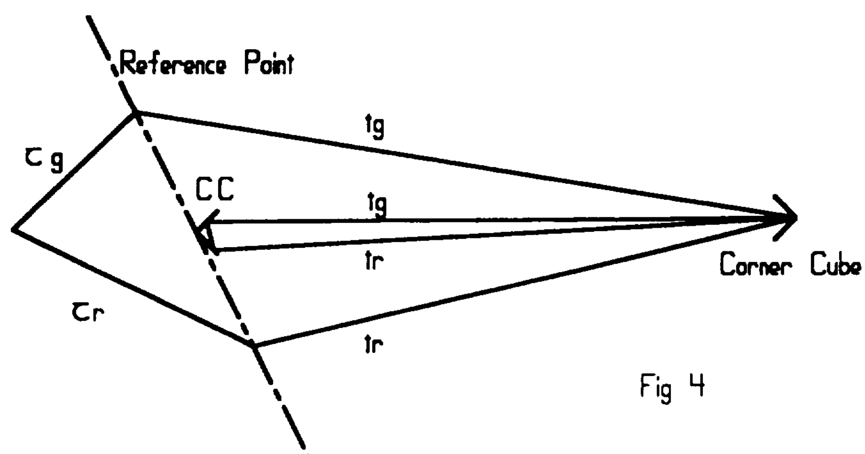
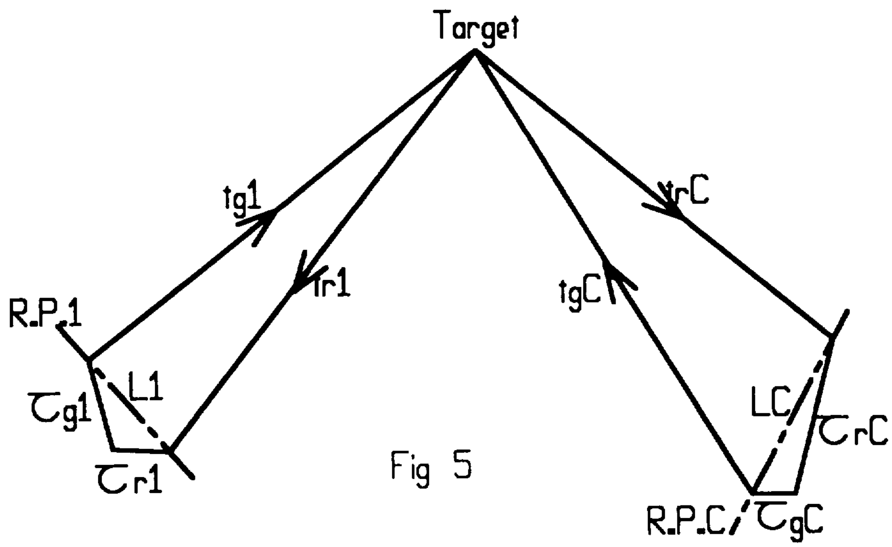
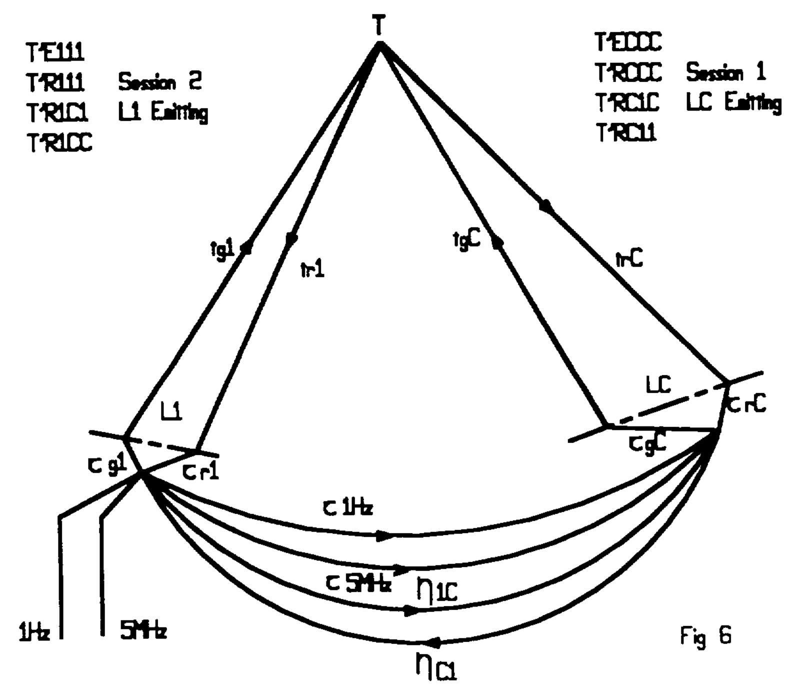

Reference Point
τ g
tg
CC
tg
tr
Corner Cube
τr
tr

Fig 4



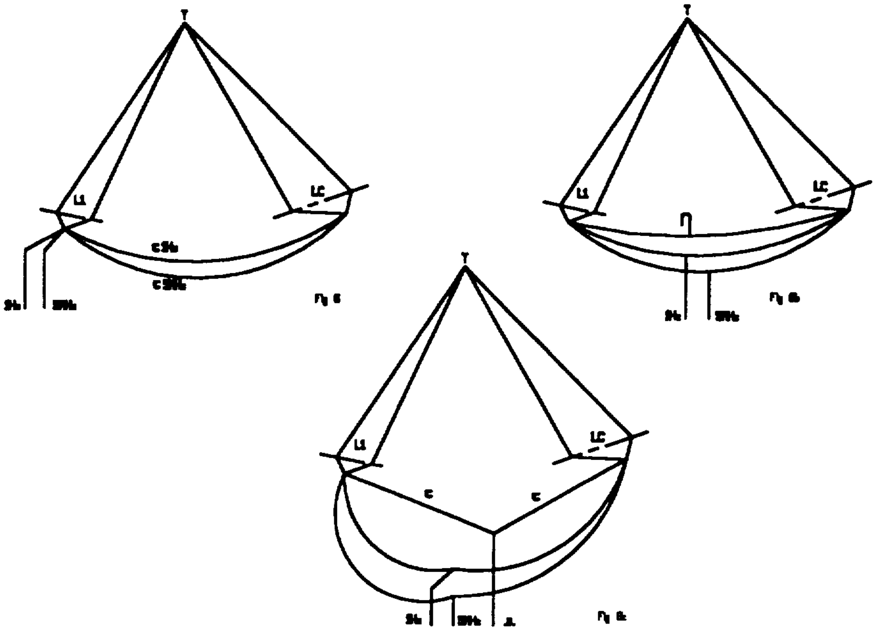
Target
tg1
tr1
tgC
trC
R.P.1
L1
τg1
τr1
LC
τrC
R.P.C
τgC

Fig 5



T
T'E111
T'R111 Session 2
T'R1C1 L1 Emitting
T'R1CC
T'ECCC
T'RCCC Session 1
T'RC1C LC Emitting
T'RC11
tg1
tr1
tgC
trC
L1
LC
τ g1
τ r1
τ gC
τ rC
τ 1Hz
τ 5MHz
η1C
ηC1
1Hz
5MHz

Fig 6



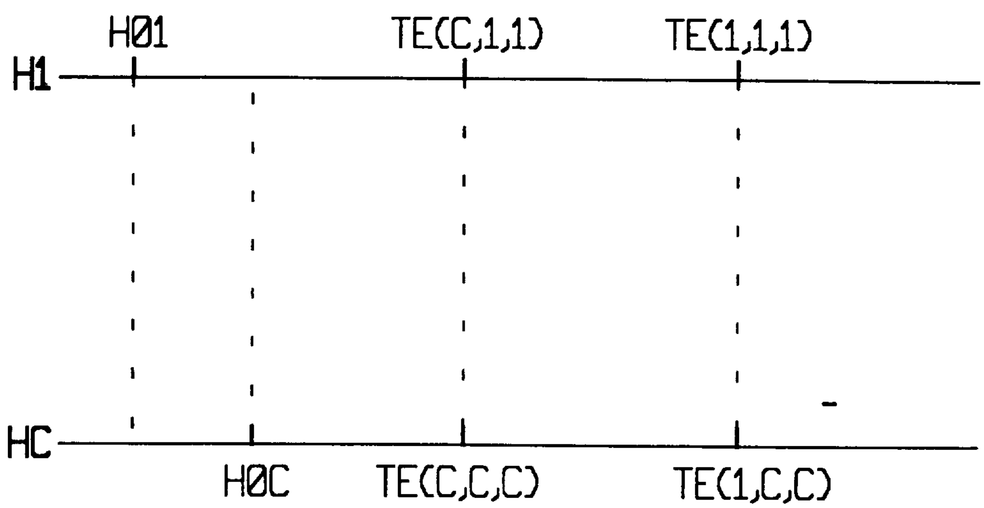


Fig 7

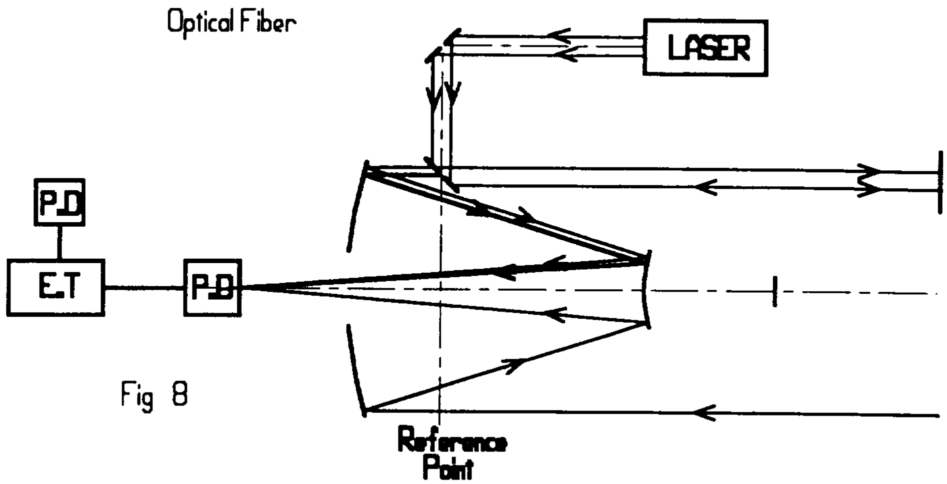


Fig 8

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NOISE AND DRIFT ANALYSIS OF NON–EQUALLY SPACED TIMING DATA

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Abstract

Generally, it is possible to obtain equally spaced timing data from oscillators. The measurement of the drifts and noises affecting oscillators, is then performed by using a variance (Allan variance, modified Allan variance, Time variance) or a system of several variances (multi-variance method[1, 2]).

However, in some cases, several samples, or even several set of samples, are missing. In the case of millisecond pulsar timing data, for instance, observations are quite irregularly spaced in time. Nevertheless, since some observations are very close together (1 minute) and since the timing data sequence is very long (more than 10 years), information on both short–term and long–term stability is available. Unfortunately, a direct variance analysis is not possible without interpolating missing data.

We used different interpolation algorithms (linear interpolation, cubic spline) to calculate variances in order to verify that they do neither lose information nor add erroneous information. A comparison of the results of the different algorithms will be given in the paper.

Finally, we adapted the multi–variance method to the measurement sequence of the millisecond pulsar timing data: we calculated the responses of each variance of the system for each type of noise and drift, with the same missing samples as in the pulsar timing sequence. An estimation of precision, dynamics and separability[1] of this method will be given in the paper.

INTRODUCTION

The time stability measurement of oscillators is well known in the case of signals composed of equally time–spaced data[1, 2, 3, 4]. However, in some cases, e. g. the millisecond pulsar timing data, the sequence of time error measurement is not regularly spaced. It is then necessary to reconstruct a sequence of equally time–spaced data from the original sequence. The aim of this paper is the study of different ways of sequence reconstruction.

1. DIFFERENT METHODS OF SEQUENCE RECONSTRUCTION

The goal of the reconstruction is to get N equally time–spaced data from M irregularly spaced data without losing information or adding information.

From M data we measure τ_0, the smallest interval between 2 consecutive timing data. This smallest interval τ_0 is the basic interval between all consecutive data of the reconstructed sequence. N, the new number of data, is then equal to the duration of the sequence divided by τ_0. Actually, in order to easily perform Fast Fourier Transform over the reconstructed data, we choose as N the first power of two greater than the duration of the sequence divided by τ_0. Let us define τ_0 the date of the first sample of the sequence and τ_{M-1} the date of the last sample of the sequence, N is given by the relationship :

$$N = 2^{\mathrm{int}\left(\log_2 \frac{(t-M-1-t_0)}{\tau_0}\right)+1} \tag{1}$$

Generally, the available data are time error $x(t)$ measurements between the oscillators and a reference oscillator. However, the time stability is mainly studied from the instantaneous normalised frequency deviation samples $\bar{y}_k$, obtained from the $x(t)$ data by the relationship:

$$\bar{y}_k = \frac{x(t_k + \tau) - x(t_k)}{\tau} \tag{2}$$

Reconstructing equally spaced data from the $x(t)$ data or from the $\bar{y}_k$ samples yields different ways of reconstruction.

1.1. Reconstruction by linear interpolation of the $x(t)$ data

This first method (see Fig. 1, left) keeps the same $\bar{y}_k$ samples as in the original irregularly spaced sequence. The only difference this method yields, is the division of each initial $\bar{y}_k$ sample into several τ_0–long samples with the same value. Thus, the added information is the constancy of the frequency deviation during the initial samples.

1.2. Reconstruction of the $x(t)$ data by cubic spline functions

Obviously, the real frequency deviation $y(t)$ is not constant over the time interval of each initial $\bar{y}_k$ samples. In order to avoid this hypothesis of constant samples within each initial sample, it is possible to fit the $x(t)$ data with cubic spline functions (see Fig. 2, right). The new τ_0–long samples vary smoothly while preserving the same average over the initial samples. The added information is then an hypothesis of continuity (and derivability) of the $\bar{y}_k$ samples, due to the continuous variation (derivability of second order) of $x(t)$.

Although the $x(t)$ samples are strongly correlated for the low frequency noises, the hypothesis of continuous variation of the $x(t)$ samples is completely wrong in the case of a white noise! Since the types of frequency noises can vary from f^{-3} (only in the case of millisecond pulsars[5, 6]) to f^{+2}, i. e. from f^{-5} to f^{0} phase noises, this method may be justified only for correlated $x(t)$ data, but not in the case of a white phase noise (f^{+2} frequency noise).

1.3. Reconstruction by linear interpolation of the $\bar{y}_k$ samples

On the other hand, it is possible to reconstruct directly the $\bar{y}_k$ samples by linear interpolation. The new yk sequence is then continuous but not derivable. The $x(t)$ sequence is obtained by the relationship :

$$x(t_k + \tau_0) = x(t_k) + \tau_0 \bar{y}_k \tag{3}$$

In this case, the $x(t)$ function is only derivable once. However, the hypothesis of continuity of the $\bar{y}_k$ samples is wrong in the case of a white frequency noise (f^{-2} phase noise) or higher frequency noise. This method may only be applied to low frequency noises.

1.4. Reconstruction of the $\bar{y}_k$ samples by cubic spline functions.

Theoretically, this method could only be justified for very low frequency noises (f^{-3} frequency noise) ; nevertheless we decided to observe the behaviour of such a method for all the types of noises in order to confirm our theoretical considerations.

2. Analysis method

2.1. Use of the multivariance method

The multivariance method uses a system of several variances, calculated for several integration values τ, over the same signal [1, 2]. The results are the most probable (in the sense of the least squares) set of h_α noise coefficients and drift coefficients. Moreover, this method yields an estimation of the confidence interval of each coefficient.

In order to study the influence of the reconstruction way by the multivariance method, we generated several sequences of 8192 simulated $x(t)$ data. Each of these sequences was composed of one only pure noise (one sequence of f^{-3} frequency noise, ..., one sequence of f^{+2} frequency noise). Then, we removed a lot of data according to a real pulsar timing sequence : we kept only 167 irregularly spaced $x(t)$ data from the 8192 ones (see Fig. 2).

2.2. Responses of variances for the different reconstruction method

Figure 3 shows the responses of the modified Allan variance[7] for the different types of noises and for a linear frequency drift. On each graph, the response of this variance for one type of noises with equally time-spaced data (continuous line) is compared with the responses obtained with the different reconstruction methods. Actually, each curve is the average of the results for 100 different realizations of these noises.

For f^{-3} frequency noise and linear frequency drift, the reconstruction from the $\bar{y}_k$ yields curves closer to the reference curve (corresponding to equally spaced data) than the curves due to the reconstruction from the $x(t)$ data. In these cases, the $\bar{y}_k$ samples are strongly correlated with their neighbours and the smoothest reconstruction methods provide the best results. Moreover, for τ values greater than $50\tau_0$, which is about the ratio of 8192 over 167, the different curves converge to the reference one.

However, for the higher frequency noises, the curves corresponding to the reconstruction by linear interpolation of the $x(t)$ data, remains the closest to the reference curves. The only important difference is visible in the case of f^{+2} frequency noise : although the slope is the same as the one of the reference curve, the variance measurement are about 100 times greater than the reference variance measurements. We may also notice that the curves corresponding to the reconstruction by cubic spline functions of the $x(t)$ data are not very far from the curves corresponding to the reconstruction by linear interpolation of the $x(t)$ data.

On the other hand, the results given by the reconstruction of the $\bar{y}_k$ samples for f^0, f^{+1} and f^{+2} frequency noises always yield the same behaviour. Therefore, these 2 reconstruction methods should not be able to separate these 3 types of noises. Of course, interpolating high frequency noises by linear interpolation or, *a fortiori*, by cubic spline functions completely modifies the information about the initial data.

2.3. Generating a model of variance responses

In order to increase the sensitivity of the multivariance method, we used the results shown in Figure 3 as the theoretical responses of the different variances for the different types of noises and for the different reconstruction method. Thus, the determination of the noise and drift coefficients of a signal, will be obtained by minimizing the differences between the variance results for this signal and the new theoretical responses of variances.

Therefore, if we choose for instance the reconstruction by linear interpolation of the $x(t)$ for analysing a signal mapped as in Figure 2 (with 167 data obtained for the same date as in Figure 2), we will compare the variance results with the new model corresponding to this type of interpolation and not with the classical theoretical variance responses. Consequently, this method requires the calculation of the corresponding model for each irregularly spaced sequence.

3. Results and discussion

3.1. Results for pure noises

Figure 4 shows histograms of values obtained for 100 realizations of the same pure noises (only f^{-3} noise, ... , only f^{+2} noise) and for the different reconstruction methods. For the low frequency noises (f^{-3} and f^{-2} frequency noises), the different methods yield histograms similar to the reference one (in front), i. e. the histogram obtained with 8192 equally spaced data. The histogram corresponding to the reconstruction of the $x(t)$ data by cubic spline functions (3rd in order of depth) seems to be slightly better than the ones of the other methods.

For a f^{-1} frequency noise, the histogram corresponding to the reconstruction of the $\bar{y}_k$ by cubic spline functions (last in order of depth) is already larger as the other ones. These other histograms remains similar to the reference one.

Finally, for a f^{+2} frequency noise, the dispersion is very important for the different methods. Only the histogram of the reconstruction of the $x(t)$ by linear interpolation (2nd in order of depth) seems to be interesting.

3.2. Results for a signal composed of all types of noises

Figure 5 shows histograms obtained for 100 realizations of a signal composed of 6 types of noises:

$$S_y(f) = h_{-3}f^{-3} + h_{-2}f^{-2} + h_{-1}f^{-1} + h_0 f^0 + h_{+1}f^{+1} + h_{+2}f^{+2} \quad (4)$$

with

$$h_{-3} = 1.2 \times 10^{-7}; \;\; h_{-2} = 3.1 \times 10^{-7}; \;\; h_{-1} = 0.002; \;\; h_0 = 0.031; \;\; h_{+1} = 0.25; \;\; h_{+2} = 1$$

With these values, each type of noise prevails over the other within an interval of the studied range of frequencies.

Although the f^{-3} noise is detected by all different methods, the measurement of the h_{-2} coefficient is difficult, even in the case of 8192 equally spaced data. The best method seems to be the interpolation of $x(t)$ by cubic spline functions (3rd in order of depth), because the number of non–null measurement is about 60%, and the maximum of the histogram is about the entered value. However, for f^{-1} and, *a fortiori*, for f^{+2} frequency noises, the measurement is almost impossible (from 70 to 90% of null measurement).

Conclusion

The results obtained for pure noises shows that the 4 methods are able to measure a signal over which a low frequency (from f^{-3} to f^{-1} frequency noises) prevails. For higher frequency noises (f^0 to f^{+2} frequency noises), only the methods of reconstruction of the $x(t)$ seem to be reliable.

On the other hand, in the case of a signal composed of 6 different noises with noise coefficients of equivalent levels, only the f^{-3} frequency noise can be determined by the 4 methods and sometimes the f^{-2} frequency noise by the spline reconstruction of the $x(t)$. It may appear that these results are poor for a classical oscillator measurement.

However, in the case of the millisecond pulsars, we are only interested in the very low frequency noises (f^{-3} and f^{-2} frequency noises). The interest of the millisecond pulsars is their great long term stability. Especially, the question is: does the stability curve of the millisecond pulsars will continue to go down versus time, under the estimated threshold of the International Atomic Time stability, or will it change of slope and go up because of f^{-2} or f^{-3} frequency noises? Perhaps is it already possible to answer!

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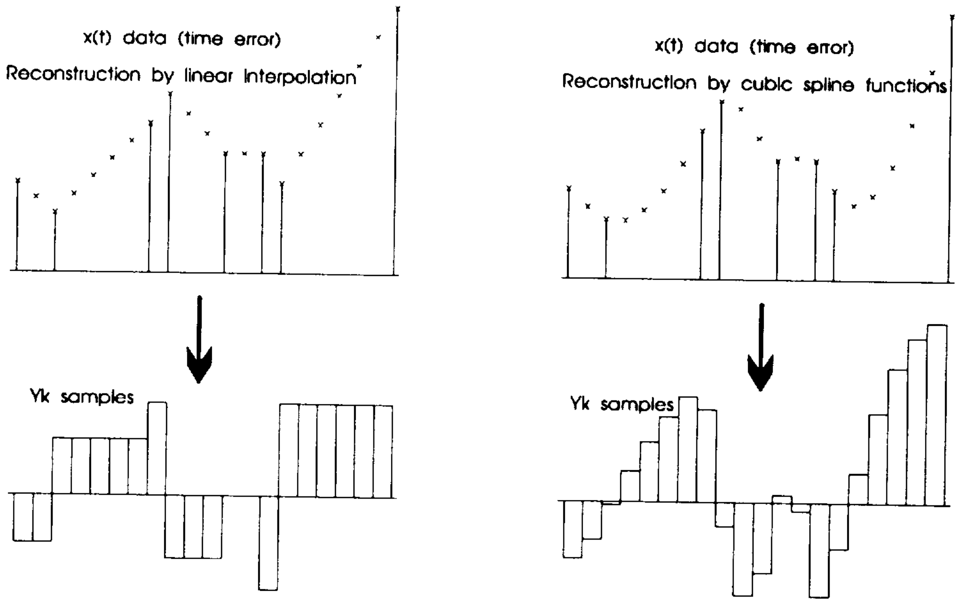

Figure 1 : Reconstruction by linear interpolation of the time error data (left) and by cubic spline functions of the time error data (right).

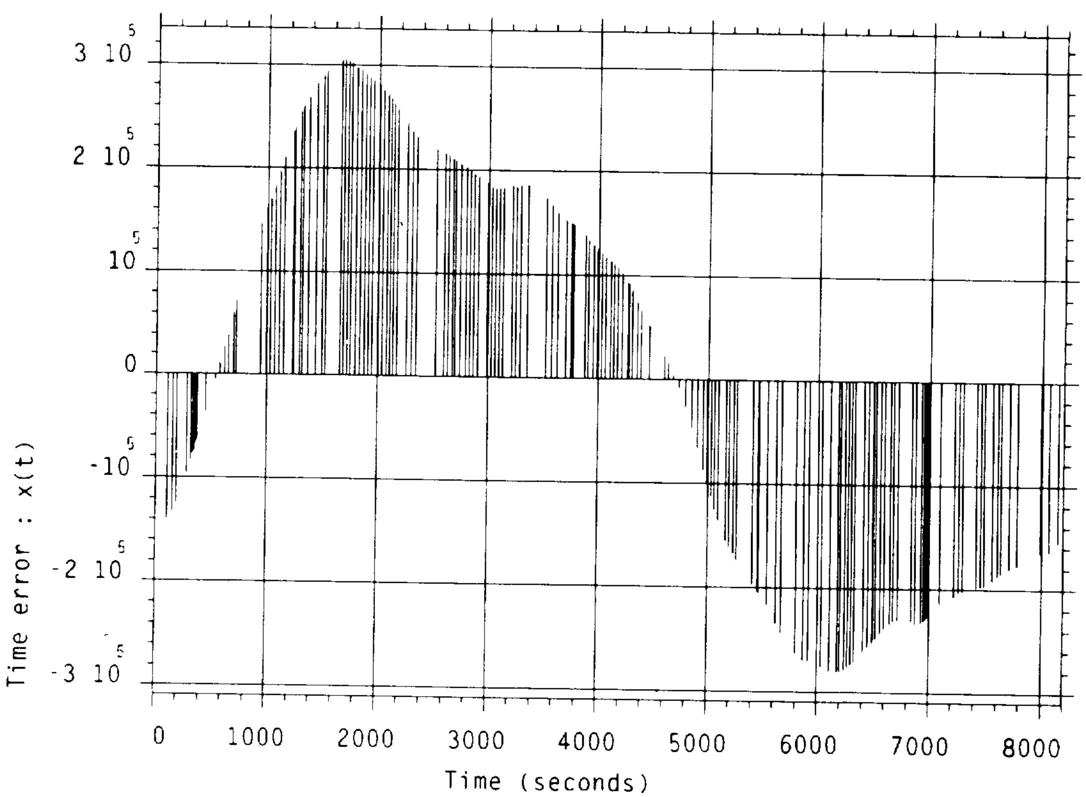

Figure 2 : Sequence of irregularly time-spaced data (167 data).

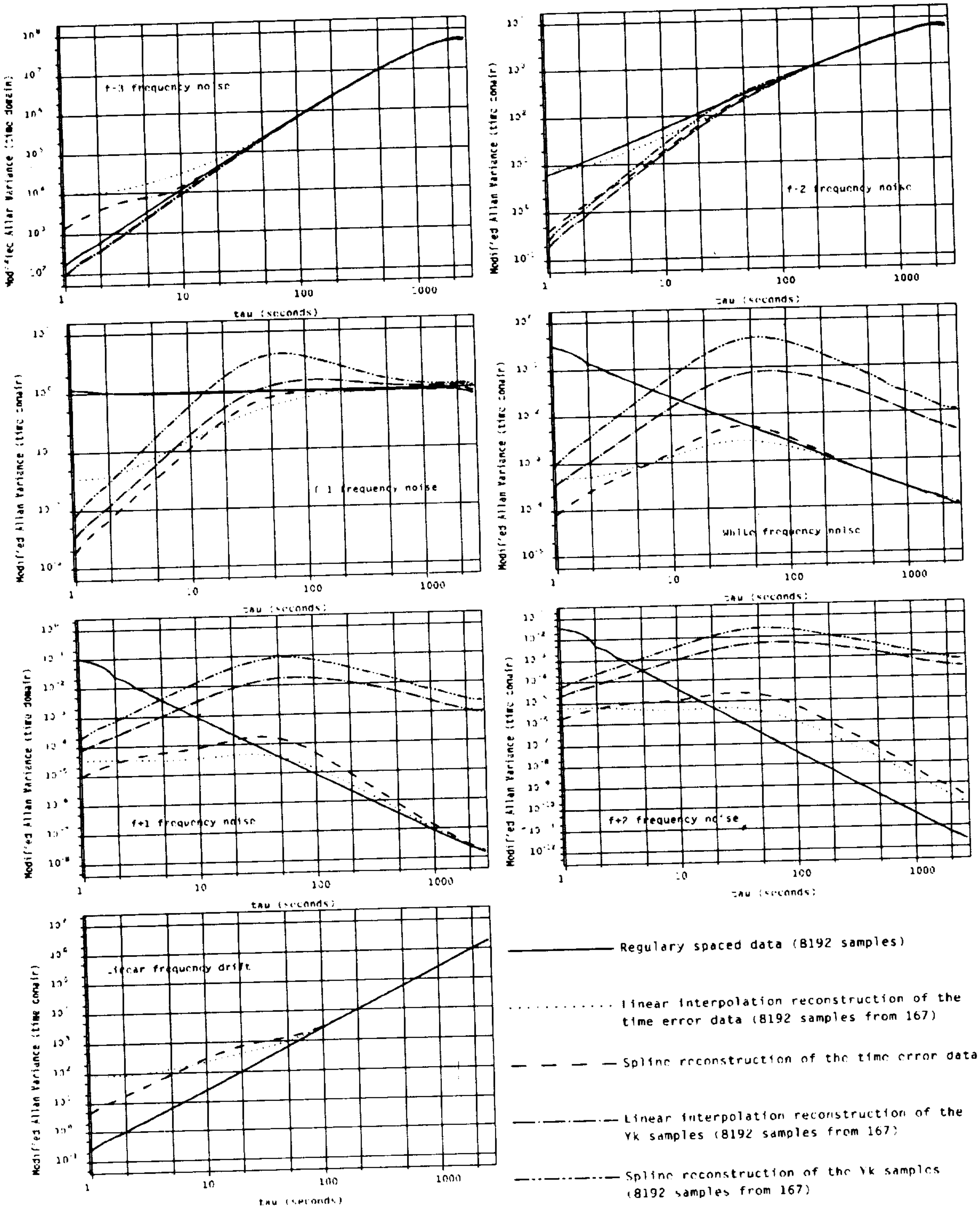

Figure 3 : Responses of the Modified Allan Variance for the different types of noises and for the different ways of réconstruction.

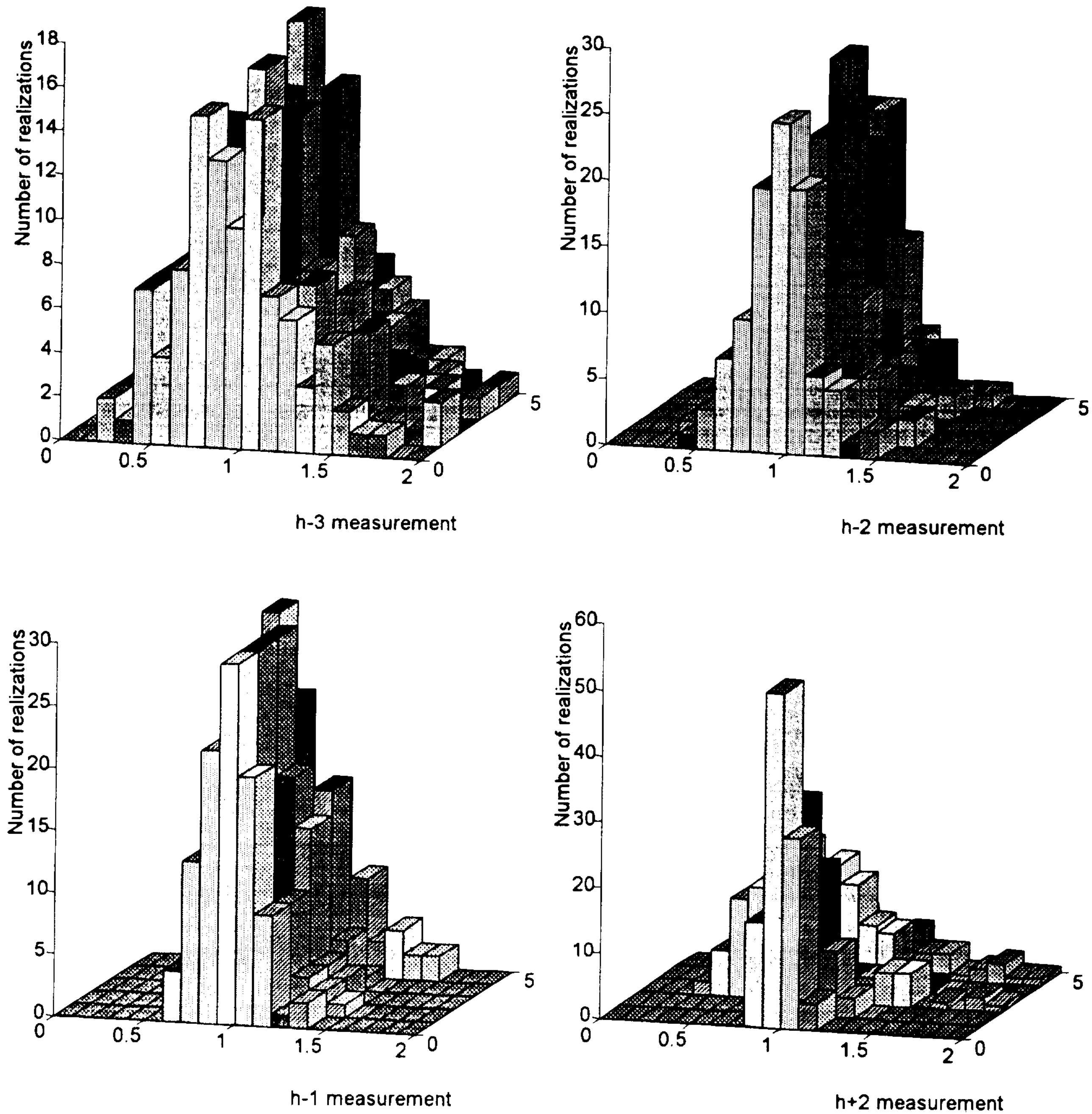

Figure 4 : Histograms of measurements of 100 realizations of pure noises. The first ones (in front) correspond to equally spaced data ; the second ones : reconstruction by linear interpolation of the x(t) ; the third ones : reconstruction of the x(t) by spline ; the fourth : reconstruction by linear interpolation of the $\overline{y_k}$; *the last (in the back) : reconstruction of the* $\overline{y_k}$ *by spline.*

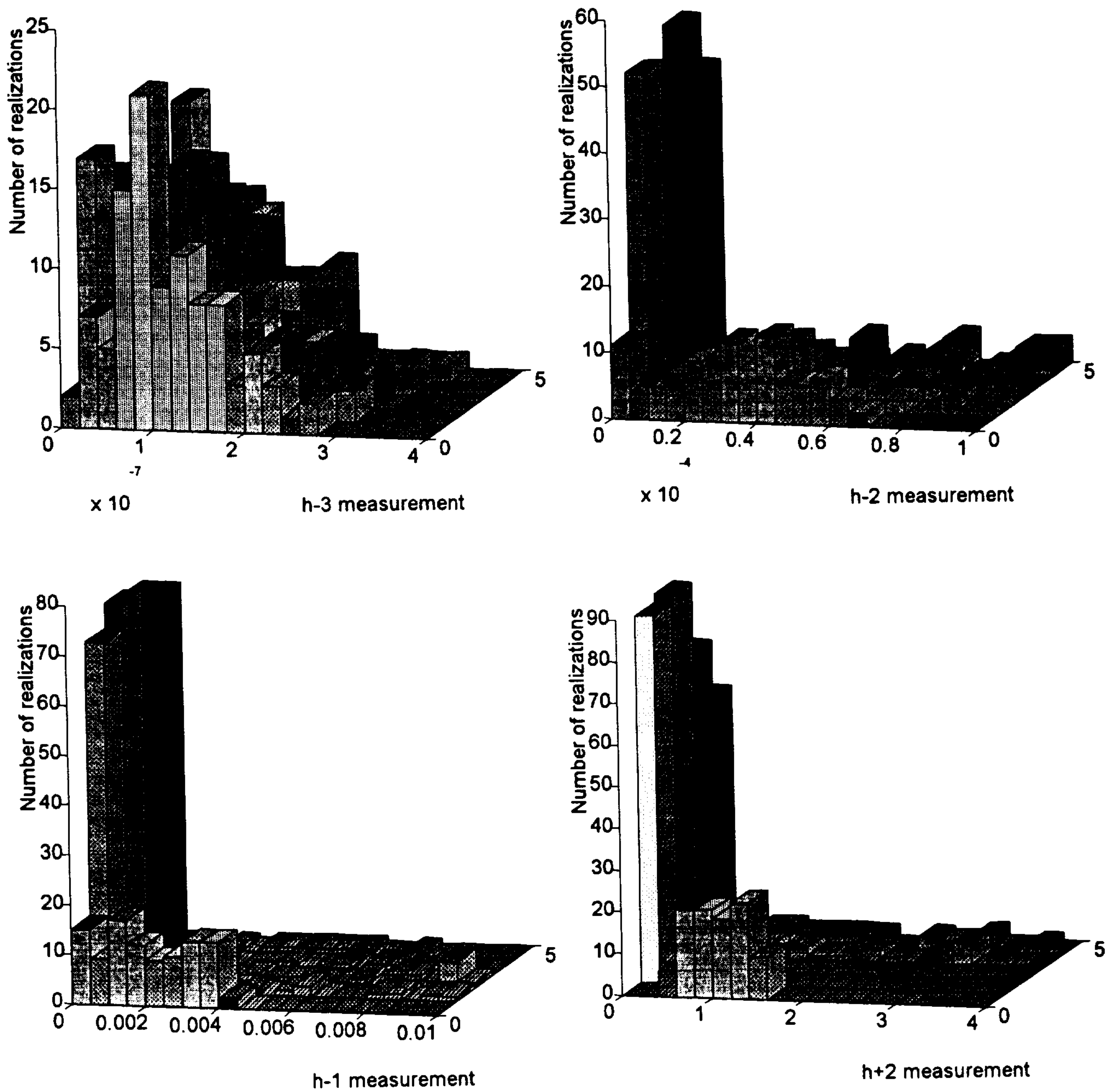

Figure 5 : Histograms of measurements of 100 realizations of a signal composed of 6 types of noises. The first ones (in front) correspond to equally spaced data ; the second ones : reconstruction by linear interpolation of the x(t) ; the third ones : reconstruction of the x(t) by spline ; the fourth : reconstruction by linear interpolation of the $\overline{y_k}$ *; the last (in the back) : reconstruction of the* $\overline{y_k}$ *by spline.*

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AN ALGORITHM FOR THE ITALIAN ATOMIC TIME SCALE

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Abstract

During the past twenty years, the time scale at the IEN has been realized by a commercial cesium clock, selected from an ensemble of five, whose rate has been continuously steered towards UTC to maintain a long term agreement within 3×10^{-13}.

A time scale algorithm, suitable for a small clock ensemble and capable of improving the medium and long term stability of the IEN time scale, has been recently designed taking care of reducing the effects of the seasonal variations and the sudden frequency anomalies of the single cesium clocks.

The new time scale, TA(IEN), is obtained as a weighted average of the clock ensemble computed once a day from the time comparisons between the local reference UTC(IEN) and the single clocks. It is foreseen to include in the computation also ten cesium clocks maintained in other Italian laboratories to further improve its reliability and its long term stability.

To implement this algorithm, a personal computer program in Quick Basic has been prepared and it has been tested at the IEN time and frequency laboratory.

The paper reports on the results obtained using this algorithm on the real clocks data relative to a period of about two years.

INTRODUCTION

The generation of an independent atomic time scale from an ensemble of clocks, used as a reference for the generation of a local UTC time scale, has been realized by several laboratories to obtain a more reliable and uniform time scale that, if needed, can be steered to UTC(BIPM) in order to synchronize within the limits recommended by the CCIR and by the CCDS. Moreover, a recent Recommendation – S5/1993 – of this last Committee, has suggested to the primary laboratories to coordinate with UTC(BIPM) within 100 ns.

The approach used in the generation of the UTC(IEN) time scale at the Istituto Elettrotecnico Nazionale (IEN), based on a single clock selected from the clock ensemble that allowed to maintain in the last years the Italian reference of time within ±1.2 s to UTC, will no longer be suitable to attain the new bounds of uncertainty.

The investigations performed in the past on the long term behaviour of the IEN time scale and on the six IEN cesium clocks, proved in fact that the effects of the frequency perturbations caused by the environmental conditions changes, the variations due to the electronics or to the human intervention, are seen as abrupt changes in the rate of the time scale that can easily exceed the uncertainty limits suggested by the international bodies. It was therefore decided to undertake the study of time scale algorithms to individuate a suitable procedure based, at the moment being, only on the IEN cesium clocks with plans to include in the near future also at least ten clocks maintained in other Italian laboratories.

In the sections that follows, some details will be given on the devised algorithm and on the computer program prepared for the automatic computation of the paper time scale.

The features of UTC(IEN) and of the first results of the paper time scale TA(IEN) will be discussed along with some considerations about the future activity at the IEN on this subject.

REALIZATION OF UTC(IEN)

Since 1970, the time scale of IEN, the primary metrological institute in Italy for the electrical quantities, has been realized by means of an ensemble of commercial cesium beam standards maintained in a temperature controlled room. According to its long term stability, a master clock has been selected from the ensemble, and its rate continuously adjusted by means of a phase microstepper to mantain a long term agreement within 3×10^{-13} with the international time scale UTC computed by the BIPM. UTC(IEN) has been maintained within ±1.2 s with this international reference and is the base of legal time in Italy. The IEN time scale is related to UTC by means of GPS syncronization method according to the "common view" measurements schedule coordinated by the BIPM.

The equipment used to realize the IEN time scale and to perform the clock intercomparisons is shown in Fig. 1; four cesiums are maintained in a room located at 10 m underground, with a strict temperature (±0.5 °C) and humidity (±10 %) control and other two cesiums are located in the Laboratory with a temperature control only within ±1 °C. The time comparisons are performed twice a day, at 00 and 12 UTC, with an uncertainty of 1 ns and stored in a data base.

The behaviour of UTC(IEN) versus UTC for the period January 1989 – September 1993, obtained from the time differences supplied by BIPM Circular T, is shown in Fig. 2 where the rate changes applied to the phase microstepper have also been marked. Two comments can be done about this graph: first, no change of the rate chosen in November 1991 to compensate for the master clock (IEN/Cs4) frequency departure has been necessary, up to now, to maintain UTC(IEN) in close agreement with UTC. This is a result of the new conditioning system of the clock room, performing also the humidity control, that was put in operation on February 1992 and has strongly reduced the seasonal effects previously observed on the cesium clocks. On the other hand, it can be noticed that at the end of January 1993 (MJD 49012), probably as a consequence of a failure in the humidity control system, there has been a sudden rate change of the master clock that recovered five days later and looks like a time step on the plot. Other abrupt rate changes of the master clock occured also in the past giving rise to serious reliability problems[1]. Fig. 3 shows the Allan deviation of the IEN time scale versus UTC for different observation times, computed over about 170 ten-day time differences.

GUIDELINE OF THE ENSEMBLE TIME ALGORITHM

After the first numerical experiments[1] and the following studies on time scales[2], an ensemble time algorithm has been recently proposed for the computation of the IEN paper clock.

Two are the main features of the clocks involved: they are all commercial cesium clocks – only one of the last generation – and till recently they showed a quite important seasonal frequency fluctuation due to the humidity variations in the clock room[3].

Two are also the aims of the ensemble time: improve the reliability and reduce the long term instability at one month of the Italian time scale UTC(IEN). Since UTC(IEN) has to be accessible in real time and it is foreseen to utilize also the measurements data of clocks kept in other Italian laboratories, the computation is a real time daily procedure on the internal clocks, that will be delayed of one week to permit the collection of the data of the other laboratories.

The computation algorithm starts from the weighted average of a clock reading and follows the same steps of the main ensemble algorithm nowadays in use[2]. The ensemble time TA(t) is defined as the weighted average of clock readings $h_i(t)$ as:

$$TA(t) = \frac{\sum p_i(t)[h_i - h\prime_i]}{\sum p_i(t)} \tag{1}$$

where $h\prime_i(t)$ is a time correction useful to avoid time and frequency jumps when clocks enter or exit the ensemble and when the weights are changed and $p_i(t)$ is the weight assigned to the clock.

Clock weights are defined as inversely proportional to the one–month instability of each clock. Due to the presence of seasonal noise, the one–month instability is evaluated by the "classical" variance of twelve samples of mean monthly frequencies. Each mean monthly frequency is estimated by a linear fit on the time deviations of each clock with reference to the ensemble time. The choice of the classical variance and of the twelve samples is due to the aim of reducing the possible seasonal noise. If this problem, as it is the case now for the internal clocks, is overcome by a better control of the clock room environment, the weight evaluation could be based on a recursive – maybe filtered – variance estimation.

Though from the theoretical point of view it is not necessary, the practice has shown the importance of an upper limit of weight, particularly in this case of a very small ensemble of clocks, to avoid the predominance of any one of them. Such an upper limit has been fixed to 50 %. Since the instability of each clock is estimated against the ensemble time scale to which the same clock contributed, a correction is introduced[4] to unbias this estimation.

A possible check of the evaluation of each clock instability could be performed by decoupling the noise contribution of each individual clock from the comparison measurements by means of a suitable N-cornered hat technique[5,6].

The other fundamental point of time scale algorithms are the time and frequency corrections to avoid the instabilities due to the entering and removal of clocks or to the variations of the weight values. To this aim it is necessary[2] to predict the frequency of each clock from day to day. By observing that the involved clocks show a minimal instability over an integration period of about ten days, it has been chosen to predict the frequency of each clock for the next day as equal to the mean daily value of its frequency evaluated over the previous ten days. The prediction step has also the duty of abnormal behaviour detection. In fact, if the predicted frequency results to be very different, more than 3σ ($\tau = 1\ d$) from the computed one, the clock is temporary left outside the ensemble time with weight equal to zero.

Much more care is necessary to avoid problems and to automatically face the possible anomalies occurring in the use of real clocks. Some of these necessary checks will be described in the next section. For example, a new entering of a clock, calls for an observation period permitting to evaluate its instability and hence its weight. In our case, a new clock entering the ensemble is observed for three months, receiving a weight equal to zero and from the fourth to the twelfth month, its annual instability is extrapolated from the variance of the mean monthly frequency samples at disposal and assuming random walk frequency noise as predominant. After one year of continuous operation, the weight determination automatically follows the procedure described above.

COMPUTER PROGRAM OUTLINE

To implement the time scale algorithm in the IEN automatic data acquisition system, a program in Quick Basic language has been prepared on a Personal Computer and it has been tested on the data of the IEN clock ensemble. Due to the complexity of the program, it has been divided in subroutines to simplify any modification it should be necessary to meet further developments of the algorithm. The program performs all the operations required to generate the paper time scale as the acquisition of the clock data, the daily computation of the mean time scale and the supply of the results in different forms. All the procedure is performed automatically and the human intervention is required only at the end of the process in case of anomalies. The program flow chart is shown in Fig. 4.

The first operation performed is to get the measured time differences from the data acquisition archive, to check for the number of clocks in operation and to report about any modification occured in the ensemble. Moreover the program checks for data anomalies or discontinuities on the available clocks. The standard chosen to detect the clock deviations from the expected rates is to verify if the difference between the actual time difference of a clock against UTC(IEN) and its predicted value, exceeds 3σ ($\tau = 1d$). The prediction is obtained by adding to the previous value its mean daily rate evaluated over the last ten days. The standard deviation, used as a threshold, is evaluated at least over a three month period up to a maximum of one year.

Due to the limited number of clocks presently available, to detect anomalies it has been necessary to use as a reference UTC(IEN) instead of the computed time scale TA(IEN), as usually done, because of the insufficient indipendence of this scale from the contributing clocks. Of course special care must be taken to recognize the master clock anomalies.

Afterwards, the weight of each clock is computed, as inversely proportional to the variance of its past twelve monthly frequencies, on the second day of each month and kept constant for the whole month.

At this point , the average time scale TA(IEN) is computed according to the selected algorithm, and the program checks the archive to verify if there is any advice of a man-made time or frequency step. If so, the program corrects one year backwards for the specified step all the previous data of the clock to eliminate such discontinuities. This is instrumental for a reliable prediction of the clock rates and to detect any abnormal rate change. If an anomaly is detected, the program sets the weight of the clock to zero and starts again the time scale computation.

In the next step, the date is checked, and if found coincident with the first day of the month, the mean monthly frequency of each clock against TA(IEN) is computed. These data are stored and used for the weighting of the clocks.

The procedure is now completed and the results are stored, displayed or printed and plotted together with a warning if any anomaly has occurred. At this step, it is still possible for an operator to introduce missing data and ask for a recomputation.

In details, the data supplied daily by the program are: the time differences between UTC(IEN) and TA(IEN), between each clock and TA(IEN), the relative weights of the clocks and their mean monthly frequency departures.

EXPERIMENTAL RESULTS

To evaluate the long term instability of the atomic time scale TA(IEN), computed with four cesium clocks for the period January 1992 – September 1993, the time differences for the standard dates versus UTC time scale have been computed and compared with those relative to UTC(IEN). The results are shown in Fig. 5 with a constant and a slope (-96 ns/d) removed in the case of TA(IEN). The Allan deviations of both IEN time scales versus UTC have been computed for the same period and for different sampling times, using 630 days of data and the results are represented in Fig. 6. The medium term instability, of the two time scales – from 1 to 8 days – has been evaluated over the last six months versus an HP cesium 5071A/opt. 001 (IEN/Cs8) and it has been found comparable showing that the ensemble algorithm optimized for the long term stability, does not waste, in any case, the medium term. Fig. 7 shows the Allan deviation of each clock contributing to TA(IEN) and the scale itself, computed over 630 days of data, and Fig. 8 reports their relative weights assigned by the algorithm.

If one compares the behaviour of the UTC(IEN) time scale from MJD 48622 to 48987 with the relative humidity swing in the clock room also reported in Fig. 5, and ranging from about 30 % to 70 %, can still find a relationship between the humidity changes and the time scale variations. This effect disappeared after April 1993 (MJD 49105) when the humidity control had been improved. TA(IEN) behaviour instead is not sensibly affected by the environmental effects, but its rate changes strongly depend on the relative weight of the contributing clocks due to their limited number (see Fig. 8). Also the peak-to-peak excursion of TA(IEN) is more restricted, 0.4 s, than that found on UTC(IEN) amounting to 1.3 s.

Concerning the long term frequency instability of the two time scales reported in Fig. 6, the Allan deviation for $\tau > 10d$ of TA(IEN) is always better. The same consideration can be done if one compares the Allan deviation of TA(IEN) with that of each clock contributing to this time scale (Fig. 7), with the exception of IEN/Cs8 that joined the clock ensemble only during the last four months.

As far as reliability is concerned, it can be seen that the abrupt rate change of the master clock occurred on MJD 49012 is well smoothed in TA(IEN). The anomalies detection procedure has individuated the frequency jump and set the weight of the master clock (IEN/Cs4) to zero. The ensemble time is anyway quite insensitive to the abrupt removal of one of the clocks.

FUTURE DEVELOPMENTS

From the experience gained in the experimental phase of the IEN ensemble time scale algorithm, it is foreseen to further improve the following features. As the control of the temperature and humidity of the IEN clock room has been improved, reducing any seasonal effect, the weighting procedure can be modified in order to shorten the observation time, now set at 12 months, allowing to insert also clocks available for short periods and increasing the number of clocks used in the mean scale computation.

To improve the reliability, additional effort will be done for what concerns the automatic detection of the clock anomalies, that now requires sometimes the human intervention; this feature is very important if the time scale computation has to be performed automatically.

A next step will consist in generating the UTC(IEN) time scale from TA(IEN), updating the amount of the microstepper correction according to the evaluation of the selected master clock rate against TA(IEN). In this way, a better long term stability and reliability of UTC(IEN) will be insured.

On the other hand, to improve the short term stability, the possibility of using a flywheel oscillator such as a good crystal or a maser is under study.

Further improvements in the ensemble time scale TA(IEN) can be obtained when also the data of other ten cesium clocks maintained in four Italian institutions are entered in the ensemble by means of the GPS synchronization link. This will require the implementation of a filter on the GPS results, to smooth the medium term noise added by this synchronization link.

The increase from 5 to 15 in the number of the clocks used to compute the Italian atomic time scale, will reduce its sensitivity to the introduction or removal of clocks from the ensemble and also to the variation of the relative weights attributed to the single clocks, leading to a gain as regards its reliability and long term stability.

CONCLUSIONS

To improve the long term stability and reliability of the UTC(IEN) time scale, an ensemble time algorithm has been devised, optimized for one–month stability and designed to smooth out the seasonal noise.

A PC program, written in Quick Basic, has been prepared to automatize the computation and it is operating in the IEN Time and Frequency Laboratory, supplying once a day, the time differences between each clock and the ensemble time scale. These data will be used to increase the reliability of the IEN reference time scale.

From the experimental results obtained, it turns out that a weighted average of clock readings meets our targets, provided that some checks on clock data are performed and all the information on human interventions are given.

Future plans include:

- the use of other atomic clocks maintained in other Italian laboratories referred to IEN by means of a GPS sychronization link;
- improvements in the algorithm as far as prediction, filtering and instability estimation techniques are concerned;
- the hardware realization of the ensemble time scale.

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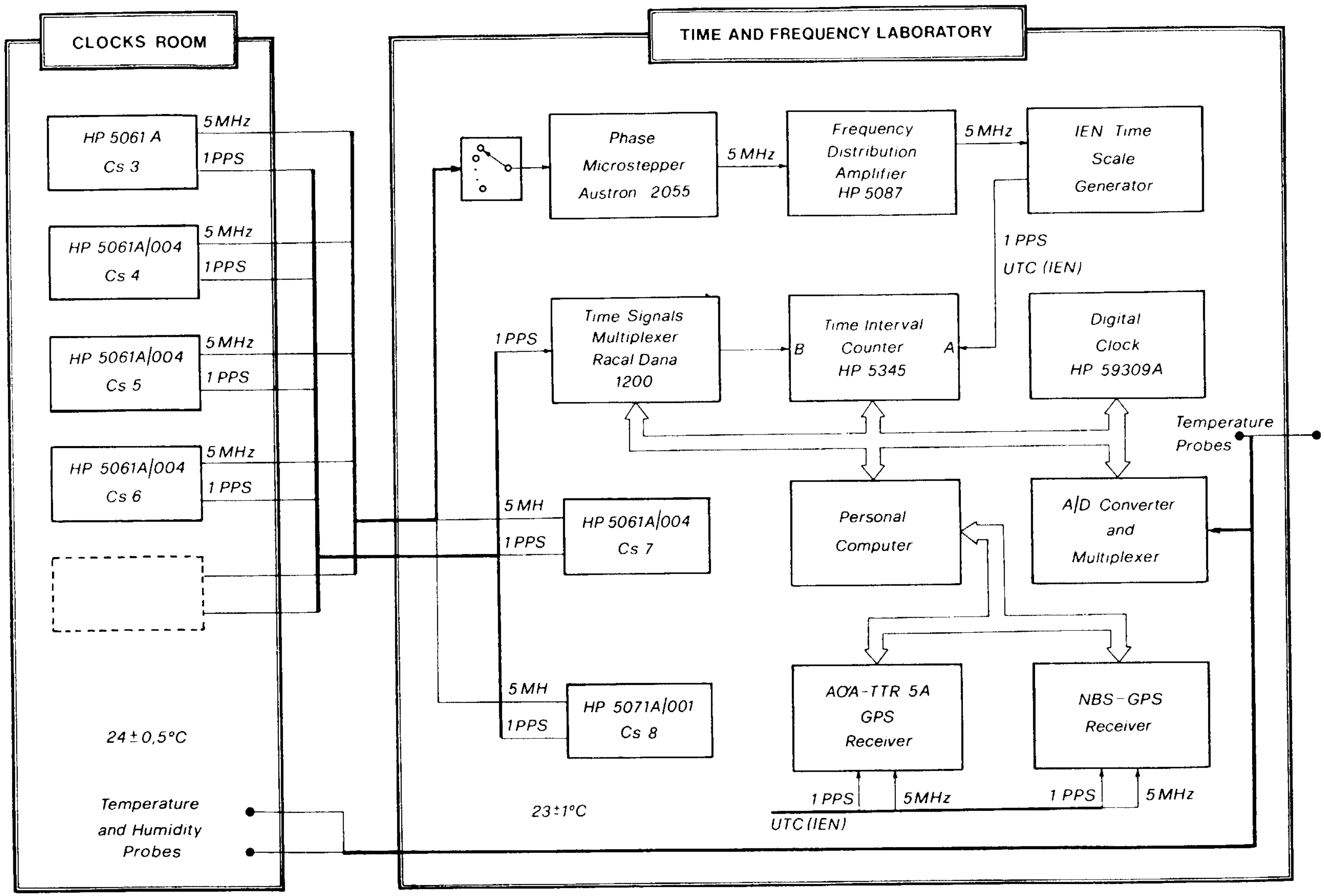

Fig. 1 - Block diagram of the equipment used to generate and compare UTC(IEN).

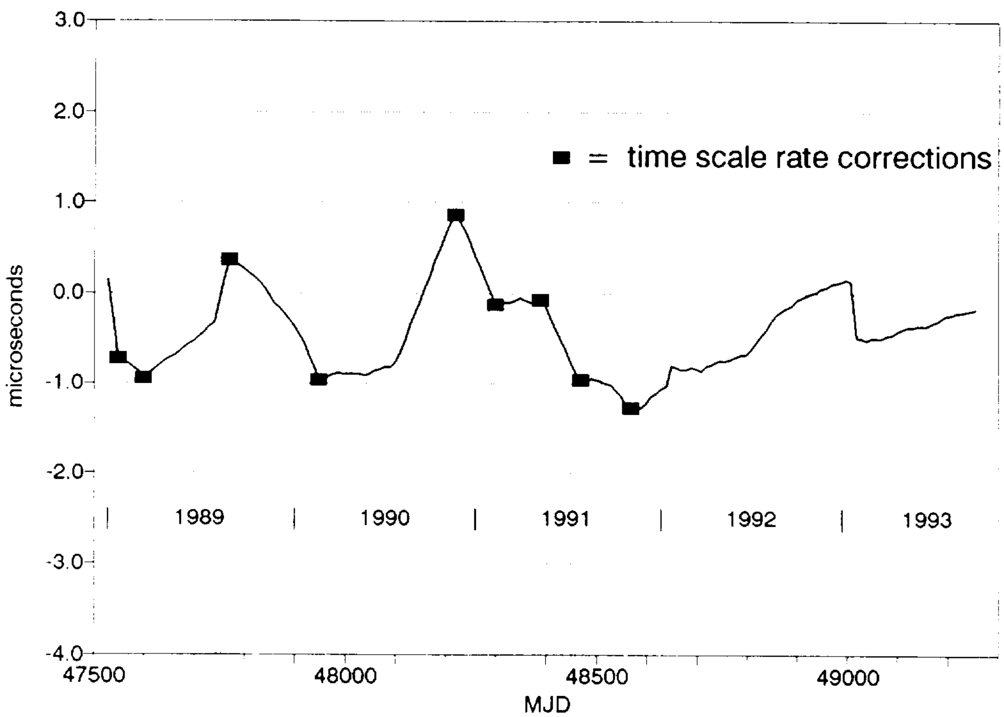

Fig. 2 - UTC(IEN) vs. UTC from January 1989 to September 1993.

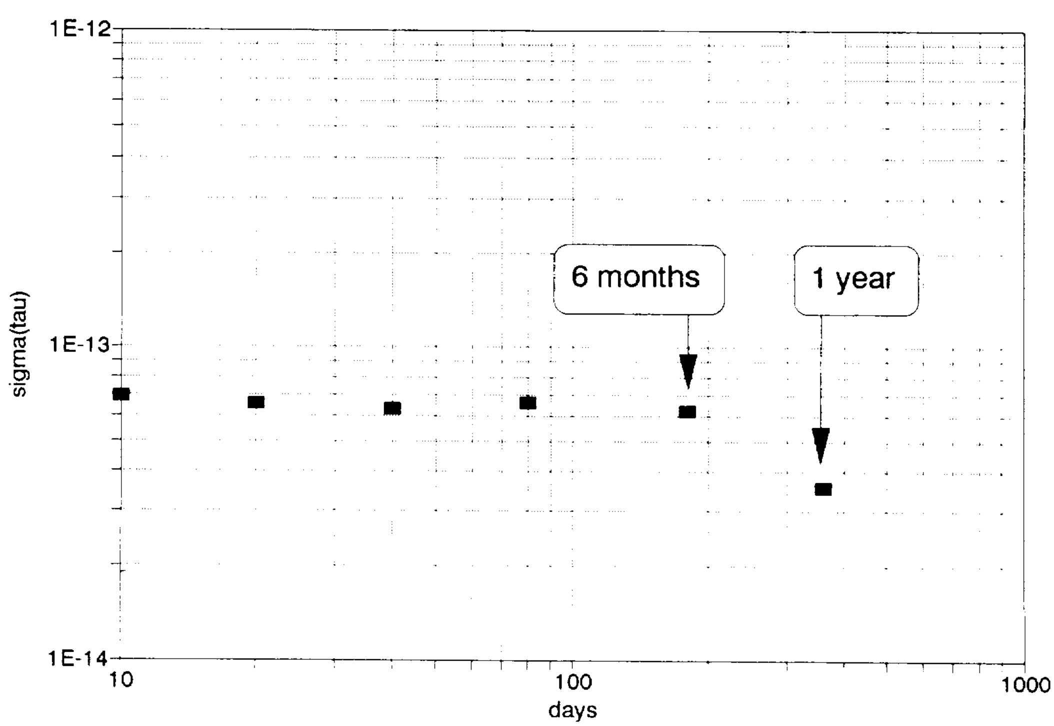

Fig. 3 - Allan deviation of UTC(IEN) vs. UTC (January 1989 - September 1993).

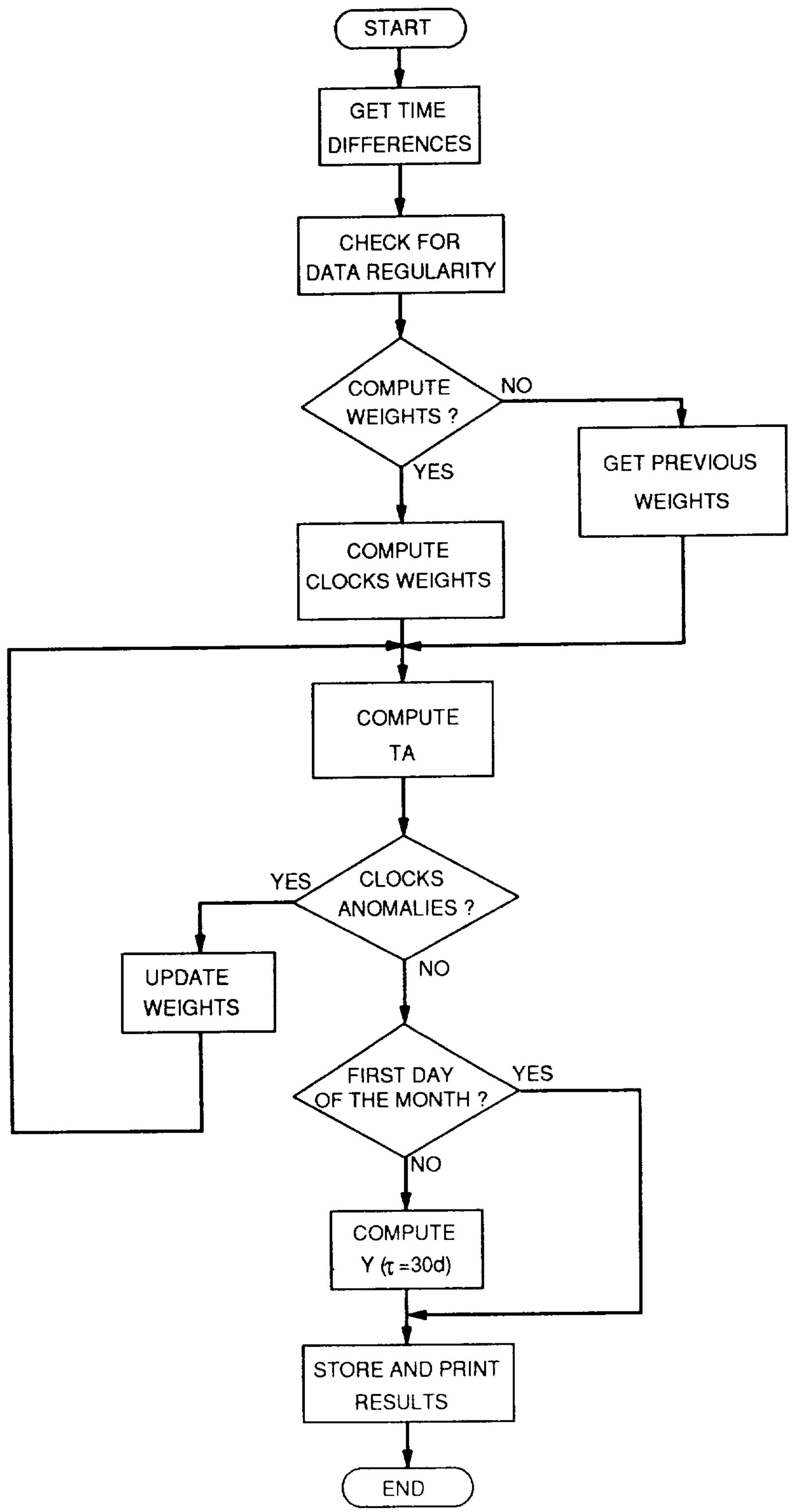

Fig. 4 - Program flowchart.

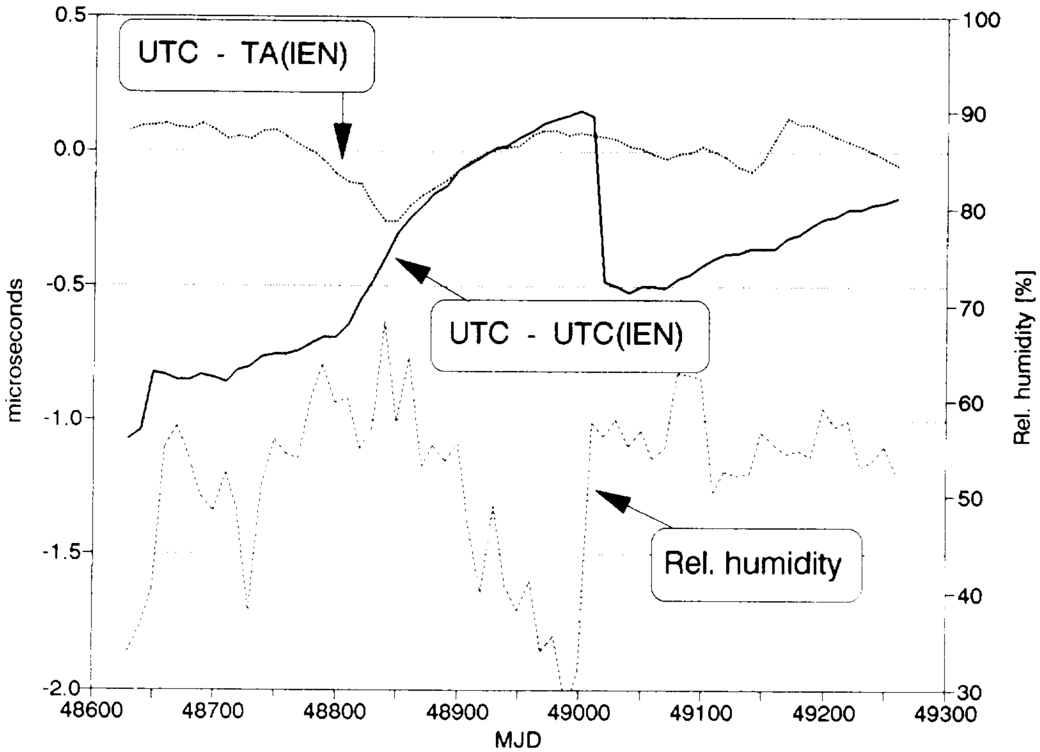

Fig. 5 - UTC(IEN), TA(IEN) and relative humidity behaviour.

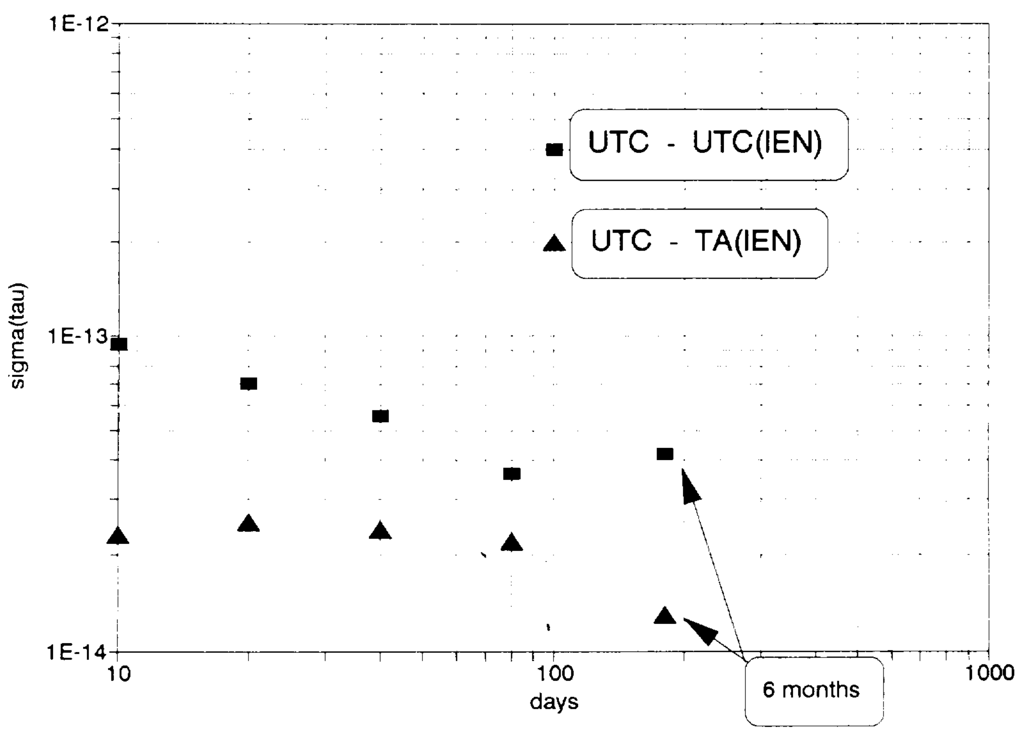

Fig. 6 - Allan deviation of UTC(IEN) and TA(IEN) vs. UTC (Jan. 1992 - Sep. 1993

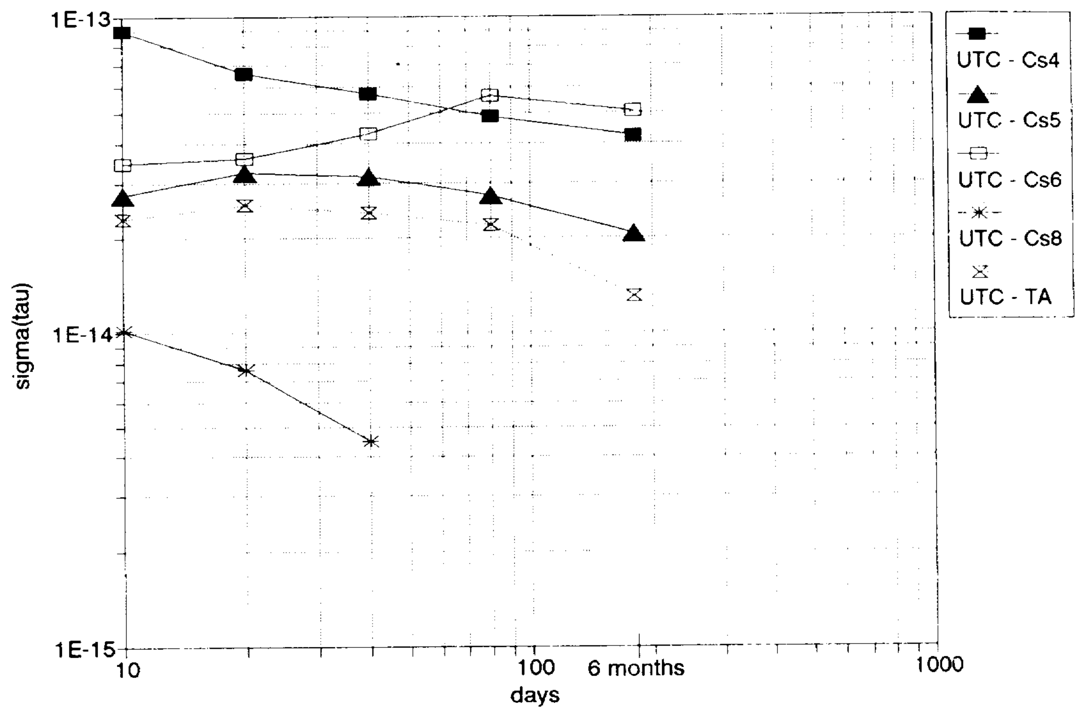

Fig. 7 - Allan deviation of the IEN clocks and TA(IEN) vs. UTC.

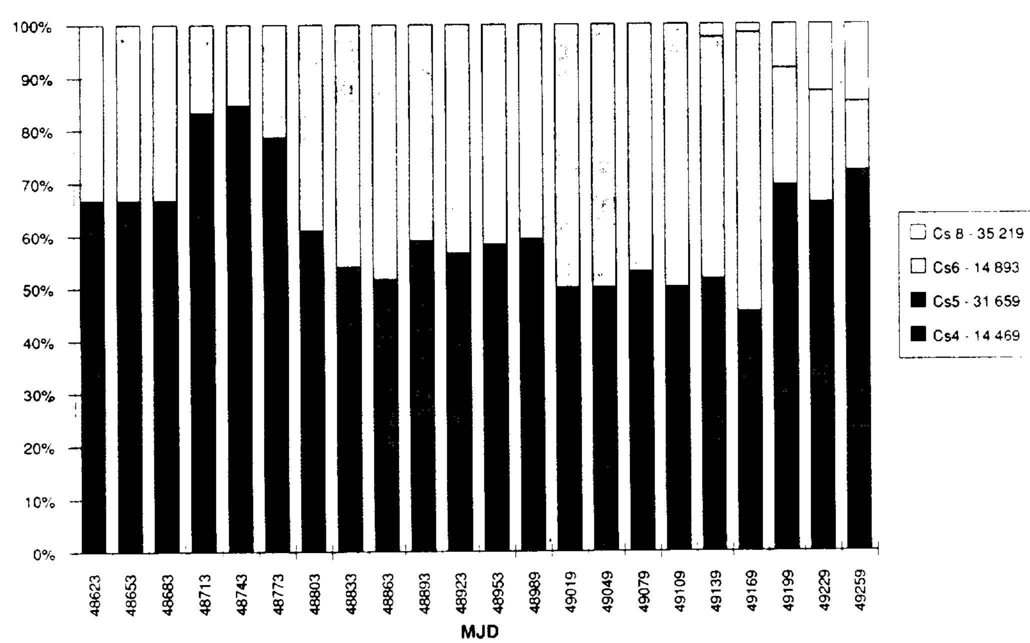

Fig. 8 - Relative weights of the clocks used in the TA(IEN) time scale.

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A COMPARATIVE STUDY OF CLOCK RATE AND DRIFT ESTIMATION *4031*

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ABSTRACT

Five different methods of drift determination and four different methods of rate determination were compared using months of hourly phase and frequency data from a sample of cesium clocks and active hydrogen masers. Linear least squares on frequency is selected as the optimal method of determining both drift and rate, more on the basis of parameter parsimony and confidence measures than on random and systematic errors.

INTRODUCTION

In the presence of random, time-independent errors, the mean of a series of measurements is an unbiassed estimator of the expectation value of a single variable, and least squares provides an optimal solution for unbiassed estimates of parameters which are a function of observed variables. In the case of time-dependent errors, these same estimators are valid if the errors (in this case called noise) are uncorrelated with frequency, i.e. their spectrum is white. The output of clocks (phase or its derivative, frequency) is typically afflicted by a mixture of different types of (generally power-law) noises which can bias the statistical estimation of such parameters as mean frequency (rate) or change in frequency (drift).

For example, in the presence of white FM noise, the rate of a clock could be accurately measured by either averaging successive first differences (differences between successive time-difference readings between a clock and another time reference) or by solving by least squares for the slope of the line relating phase and time. White FM noise corresponds to a noise process in phase called random walk. Similarly, random walk FM corresponds to a process in its derivative in what might be termed "white drift noise." In the presence of white drift noise, the drift of a clock could be accurately measured by either averaging second differences (differences between successive first differences) or by solving by least squares for the slope of the line relating frequency and time.

The type of power-law noise process (white PM or flicker PM or white FM or flicker FM or random walk FM) that predominates depends mainly on the sampling time and the type of clock. White FM noise predominates in cesium frequency standards from 10 seconds to days and in active hydrogen masers from 100 seconds to a few hours; random walk FM prevails in both types of clocks over periods of weeks or more [1].

If averages are taken or least-squares solutions made over sampling times outside the white-noise region for a particular type of measurement, the resulting estimates will be nonoptimally noisy and systematically unreliable. The choice of proper sampling time is complicated if different types of clocks are combined in an ensemble for the purpose of generating a mean timescale.

The current USNO timescale algorithm averages the rates of cesiums and masers determined from five-day, linear least-squares solutions on hourly phase measurements. The five-day rates are further averaged, unless drift is evident, in which case the drift is solved for by linear least squares on frequency over periods of 90 days or more and then is allowed for. The weighting scheme takes account of the different, time-varying weight of the masers relative to the cesiums [2].

Least-squares solutions on phase for frequency are optimal only for white PM noise, which applies to sampling times much shorter than an hour for both cesiums and masers. Averaging hourly first differences might yield superior rates. The current separate solutions for rate and drift also risk parameter incompatibilities and error underestimation. Perhaps rate and drift should be solved for simultaneously by least squares on frequency.

Solution for drift by averaging second differences should give valid results only when conducted in the random walk FM region. Indeed, Weiss et al. [3] analyzed simulated data and showed that an overall second difference spanning the entire data set yielded more efficient results than averaging successive second differences if white FM noise was present in addition to random walk FM. It would be of interest to repeat this test on real clock data and compare the drifts to those obtained by least squares.

DATA

The data consisted of hourly time-interval-counter measurements for 28 HP5071A cesiums, 5 SAO masers, and 4 Sigma Tau masers, all referred to the same maser (the very stable Sigma Tau maser "NAV5"; see Table 1). In comparison, HP5061 cesium data proved too noisy to use. Data segments of apparently constant drift and (aside from that) constant rate at least 90 days (and up to 565 days) in length were selected. Being primary frequency standards, stable cesium clocks should possess no intrinsic drifts. Accordingly, their average drift should be the negative of the drift of the reference maser; any cesium drifts > 3.0 times the rms of this average were rejected. Individual phase, frequency, or drift residuals (depending on method, as described below) > 3.0 rms were also rejected.

DRIFT DETERMINATION

Five possible methods of drift determination were selected for testing:

METHOD #1 Solve for drift and rate by linear least squares on frequency (specifically, first differences of phase)

METHOD #2 Solve for drift and rate by quadratic least squares on phase

METHOD #3 Solve for rate by least squares on 5-day bins of phase and then solve for drift by least squares on the rates

METHOD #4 Solve for drift by averaging frequency changes (specifically, second differences of phase)

METHOD #5 Solve for drift by computing the overall second difference (i.e. from the initial, mid, and final phases of the data segment)

Some methods may be more susceptible to nonwhite noise than others, producing systematic errors between them. Method #2 should yield inferior results to Method #1 because the former solves for one more least-squares parameter, decreasing the accuracy of all parameters obtained. Whether such deficiencies are statistically significant remains to be seen. Method #5 permits solution for the drift in the white drift noise region, and Method #3 nearly does as well, unlike Methods #1, #2, and #4.

The Cesiums

How should the methods be compared? Formal errors cannot be directly compared because they depend on how the drifts were derived. For example, Method #2 drifts have a much smaller rms error on average than the other methods because most of their error is absorbed into the least-squares constant term. Method #5 does not even have an rms.

Since the cesiums should not have intrinsic drifts, the methods were compared by computing the standard error (s.e.) of the average drift over all cesiums. This average drift should be the negative of the drift of the reference maser, assuming we have successively excluded cesiums with their own drifts. The best method should be the one giving the most consistent results, i.e. the smallest s.e. for this average drift. Since the rms of any drift determination decreases with the square of the time interval spanned, the clocks were weighted by the fourth power of the data length. The results were:

Method	Mean Drift	s.e.	Mean Drift Error	s.e.	
#1	+0.009	±0.013	±0.01530	±0.00022	parts in 10^{15}/day
#2	+0.009	0.013	0.000491	0.000007	
#3	+0.009	0.013	0.01814	0.00021	
#4	+0.8	1.2	43.59	0.14	
#5	+0.011	0.013			

From the mean drift and its s.e., we conclude:

- Method #4 is rejected out of hand. This is hardly surprising in view of the presence of noises other than random walk FM in the hourly data.
- The s.e.s of the other methods are identical, so these methods are equally good.
- The mean drifts of all methods agree within their s.e.s, so there are no systematic errors between methods.
- The drift of the reference maser is -0.009 ± 0.013 parts in 10 to the 15th/day.

As a check on the systematic errors, an average drift was computed across the methods (weighting them equally, except #4, which was weighted zero) for each clock and then the resulting residuals were averaged across the clocks (again weighting by the fourth power of the data length) for each method. The systematic errors thus obtained are strictly relative. The results were:

Method	Mean Sys. Error	s.e.	
#1	+0.0002	±0.0014	parts in 10^{15}/day
#2	+0.0002	0.0021	
#3	-0.0004	0.0011	
#4	+0.8	1.2	
#5	+0.0013	0.0020	

Again, no systematic error is significant.

The drifts obtained by Method #1 are given in Table 1. Unlike the drifts above, these have been referred to TAI by the addition of the drift (+0.007 ± 0.010 parts in 10 to the 15th/day) for the reference maser, as determined from 460 days (MJD 48769-49229) of data by G. M. R. Winkler (USNO; private communication). This maser has displayed the same drift for at least the 565 days spanned by our data, but solutions outside of this time span are degraded by variations in TAI.

Some 38% of the available cesiums displayed significant drifts of their own at one time or another, at which time they were excluded from our data. Most such cases were probably due to random walk FM, but it was decided to err on the side of caution, since the objective was to compare different methods using the same data, rather than to determine the absolute accuracy of any particular kind of drift.

The Masers

The drifts of the masers cannot be averaged as were those of the cesiums because they differ from maser to maser, but one can perform the same final check on the systematic errors as was done above on the cesiums. The results did not depend on the type of maser, though the Sigma Tau masers had smaller average drifts (see Table 1):

Method	Mean Sys. Error	s.e.	
#1	+0.0023	±0.0019	parts in 10^{15}/day
#2	-0.0017	0.0034	
#3	-0.0005	0.0017	
#4	-0.08	0.93	
#5	-0.0019	0.0012	

We conclude:

- Because the s.e. of the s.e.s themselves is about ±0.0005 parts in 10 to the 15th/day, the s.e.s of Methods #1, #3, and #5 are statistically identical, so these methods are equally good. Method #2 is slightly worse and Method #4 is rejected.

- The systematic errors agree within their s.e.s (allowing for the s.e.s of the s.e.s), so no difference between them is significant.

All the masers displayed significant changes in drift even in the data selected as apparently free of such changes. Maser NAV4 may have an annual variation (see Figure 1); more data are needed to be certain. The others showed changes in drift with coefficients ranging from -0.0012 ± 0.0001 to +0.0044 ± 0.0007 parts in 10 to the 15th/day^2, but these also change with time, often quite suddenly (see Figures 2 and 3). The figures plot one-day moving averages.

Choice of Method

We favor Method #1 because it involves solution for one less parameter than Method #2, and Method #2 is somewhat inferior for masers. Both, being simultaneous solutions, would probably yield slightly more compatible results for drift and rate than Method #3. Method #5 would not be robust against spontaneous or deterministic rate changes, all such being excluded from our data. It also lacks an rms as a measure of confidence, so practical use would require thorough filtering that subverts any savings of computational effort inherent in its simplicity.

RATE DETERMINATION

Four possible methods of rate determination were selected for testing:

METHOD #1 Solve for rate and drift by linear least squares on frequency (specifically, first differences of phase; same as Drift Method #1)

METHOD #2 Solve for rate and drift by quadratic least squares on phase (same as Drift Method #2)

METHOD #3 Solve for rate by linear least squares on phase, assuming a drift value

METHOD #4 Solve for rate by averaging first differences of phase, assuming a drift value

The drift values assumed were those found by Drift Method #1 above.

The Cesiums

The rates of the cesiums cannot be averaged as were their drifts because they of course differ from cesium to cesium, but one can compute sytematic errors and compare the s.e.s, as was done above for the drifts. We found:

Method	Mean Sys. Err.	s.e.	Mean Rate Error	s.e.	
#1	+0.12	±0.11	±0.0329	±0.0034	parts in 10^{15}
#2	-0.12	0.11	0.00092	0.00012	
#3	-0.11	0.11	0.0220	0.0016	
#4	+0.11	0.11	1.632	0.054	

We conclude:

- No method has a significant systematic error.
- All s.e.s of the systematic errors are identical, so the methods are equally good.

The Masers

Computing systematic errors as above, we found (unlike for the drifts) that the results differed significantly between the SAO and Sigma Tau masers. For the SAO masers:

Method	Mean Sys. Err.	s.e.	Mean Rate Error	s.e.	
#1	+0.07	±0.57	±0.0075	±0.0021	parts in 10^{15}
#2	-0.16	0.55	0.00069	0.00012	
#3	-0.16	0.55	0.0249	0.0045	
#4	+0.25	0.53	0.407	0.029	

For the Sigma Tau masers:

Method	Mean Sys. Err.	s.e.	Mean Rate Error	s.e.	
#1	+0.23	±0.12	±0.0154	±0.0025	parts in 10^{15}
#2	-0.26	0.11	0.00058	0.00012	
#3	-0.27	0.11	0.0108	0.0023	
#4	+0.30	0.11	0.543	0.056	

We conclude:

- No method has a significant systematic error for the SAO masers.

- All methods have significant systematic errors for the Sigma Tau errors. Methods #1 and #4 are statistically identical, as are Methods #2 and #3, but the two pairs differ significantly. This may only be evident because the s.e.s of the Sigma Tau masers are significantly smaller than those of the SAO masers. On the other hand, the sample of four masers may simply be too small to accurately gauge systematic errors. In view of the noises present, results from Methods #1 and #4 would seem to be preferable to those of Methods #2 and #3.

- All s.e.s for the systematic error of each type of maser are statistically identical, so no method can be preferred on the basis of random errors.

We favor Method #1 because it involves solution for one less parameter than Method #2, does not require a separate solution for drift like Methods #3 and #4, and is identical with Drift Method #1 that we preferred above.

Method #1 rates are given in Table 1, referred to TAI by the addition of the rate (+360.90 ± 1.3 parts in 10 to the 15th) of the reference maser, as determined by Winkler (private communication).

SUMMARY

Of the different methods of drift and rate determination studied, for hourly data:

- All are equally good when judged on the basis of their random errors, except averaging second differences, which is by far the worst method of drift determination.

- None has significant systematic errors, except perhaps among the rate determination methods for Sigma Tau masers.

- Solution by linear least squares on frequency is preferred on the basis of parsimony of parameters. Other studies concur that this the optimal method for estimating drift in the presence of white FM noise [1]. Also, compared to the overall second difference, it is a more robust method of determining drift. Accordingly, the former method will be tested for incorporation into the USNO mean timescale algorithm.

- All masers display significant changes in drift.

ACKNOWLEDGMENTS

The author acknowledges the help of summer assistant Blaine Bell.

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CORRIGENDA TO PREVIOUS PAPER

Because of typesetter errors, the following corrections should be made in [2]:

p. 298, eq. (5), for "z_{t_T}" read "z_{t-T}"

and for "x_{t_T}" read "x_{t-T}"

p. 300, l. 11, for "300 ns" read "300 ps"

FIGURE 1. SIGMA TAU MASER NAV4

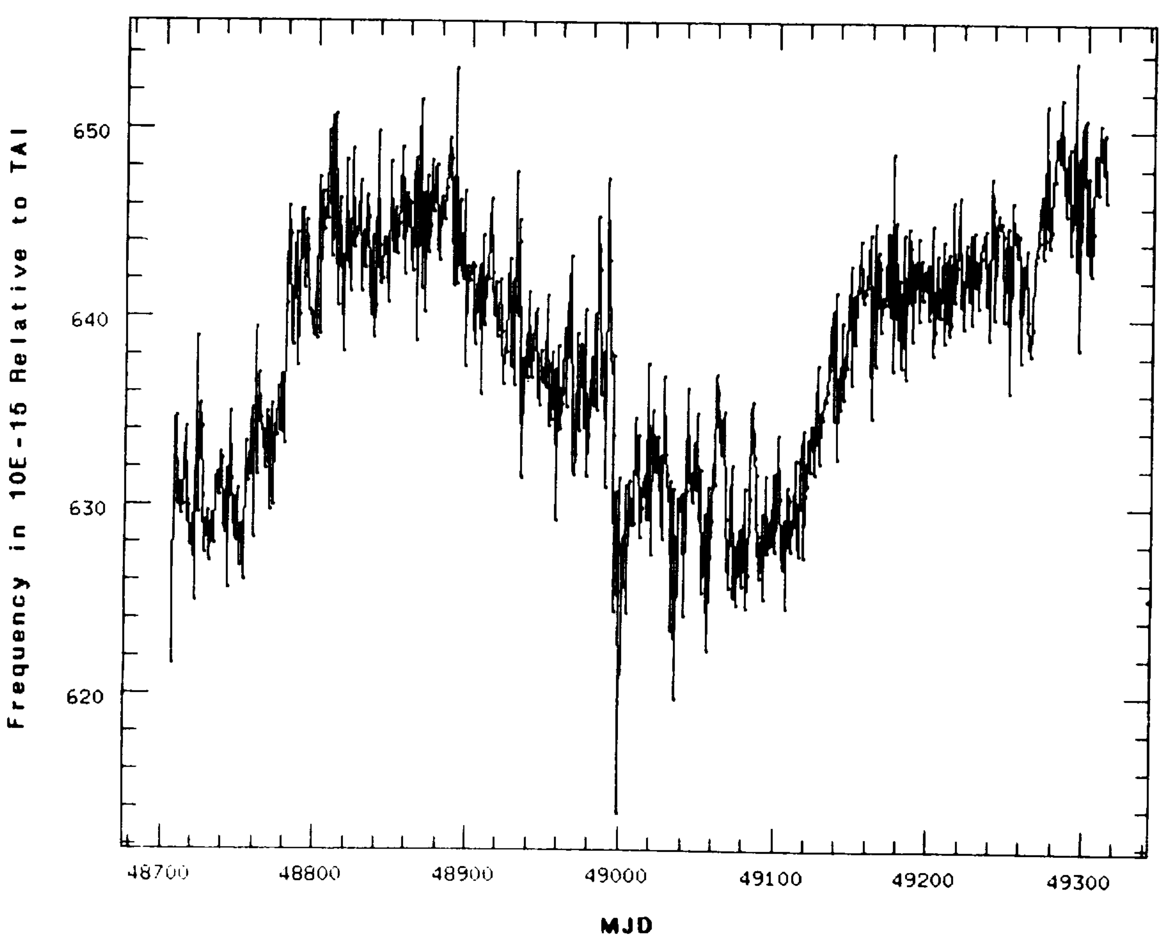

FIGURE 2. OTHER SIGMA TAU MASERS

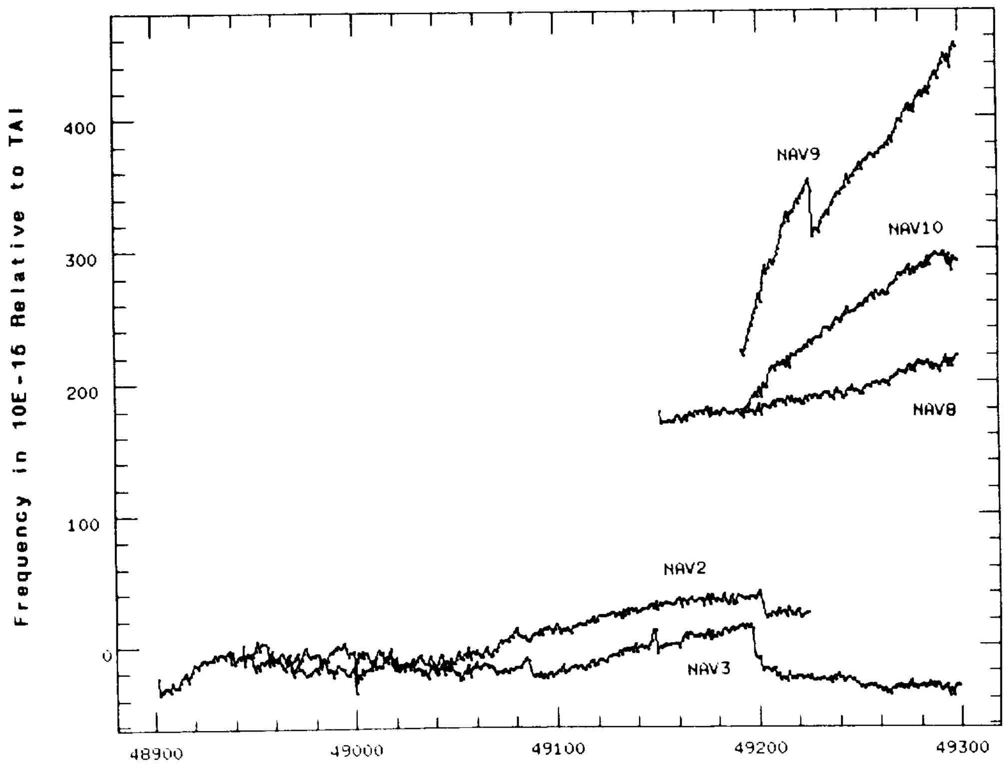

FIGURE 3. SAO MASERS

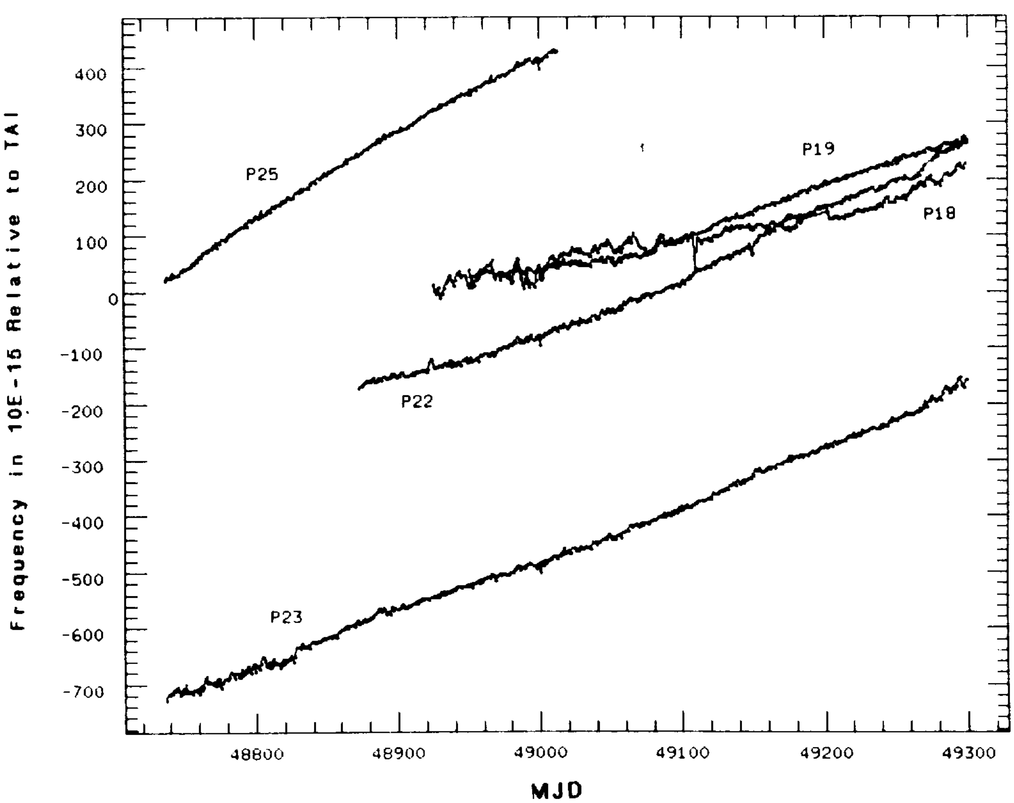

TABLE 1. Data Sources

Clock Type	Serial #	MJD Range	Drift Rel. to TAI (parts in 10^{15}/d)		Rate Rel. to TAI (parts in 10^{15})	
HP5071A Cs	0114	49094-49310	+0.068	± 0.024	-184.022	± 0.024
	0142	48922-49110	-0.002	0.029	+11.927	0.029
	0145	48912-49310	-0.098	0.011	+33.304	0.011
	0146	48932-49310	+0.101	0.010	-17.159	0.010
	0148	48912-49310	+0.015	0.009	+184.786	0.009
	0150	49105-49310	-0.003	0.026	-248.073	0.026
	0153	49038-49310	-0.030	0.016	-210.341	0.016
	0156	49100-49310	+0.045	0.027	-68.490	0.027
	0161	49027-49310	+0.046	0.018	-38.154	0.018
	0164	49028-49310	+0.026	0.016	-67.367	0.016
	0165	49041-49310	+0.027	0.017	-227.714	0.018
	0166	49047-49310	+0.049	0.019	+42.830	0.019
	0167	49028-49310	+0.058	0.016	-131.464	0.016
	0169	49042-49238	+0.045	0.031	+89.774	0.031
	0171	49027-49310	+0.073	0.017	-149.196	0.017
	0213	49126-49310	+0.014	0.032	+126.499	0.032
	0217	49139-49310	+0.069	0.035	+84.277	0.035
	0225	49134-49258	-0.080	0.055	-102.865	0.055
	0226	49196-49310	+0.076	0.059	+15.955	0.060
	0231	49134-49310	-0.084	0.037	+305.064	0.037
	0233	49145-49310	+0.094	0.035	+2.703	0.035
	0242	49140-49310	+0.135	0.038	-154.508	0.038
	0249	49160-49278	+0.043	0.065	+71.013	0.065
	0253	49140-49310	+0.012	0.033	+112.216	0.033
	0254	49140-49310	+0.060	0.034	+9.369	0.034
	0255	49189-49310	+0.055	0.059	+91.221	0.059
	0268	49160-49310	+0.009	0.039	-35.203	0.039
	0270	49179-49273	+0.096	0.084	-23.177	0.084
SAO masers	P18	48924-49181	+0.451	0.006	+71.163	0.006
		49202-49310	+1.044	0.016	+175.284	0.016
	P19	48949-49069	+0.289	0.015	+46.291	0.015
		49069-49310	+0.888	0.005	+177.147	0.005
	P22	48872-49270	+1.030	0.003	+6.372	0.003
	P23	48745-49310	+0.985	0.002	-444.601	0.002
	P25	48745-49013	+1.500	0.006	+251.615	0.006
Sigma Tau masers	NAV2	48943-49068	-0.029	0.014	-8.027	0.014
	NAV3	49087-49197	+0.368	0.016	-3.270	0.016
		49201-49310	-0.127	0.015	-28.837	0.016
	NAV4	48890-49106	-0.066	0.010	+634.392	0.010
		49160-49263	+0.035	0.027	+642.043	0.027
	NAV8	49150-49310	+0.341	0.009	+192.309	0.009

N94-30670

Providing Hydrogen Maser Timing Stability to Orbiting VLBI Radio Telescope Observations by Post-Measurement Compensation of Linked Frequency Standard Imperfections

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Abstract

Orbiting VLBI (OVLBI) astronomical observations are based upon measurements acquired simultaneously from ground-based and Earth-orbiting radio telescopes. By the mid 1990's, two orbiting VLBI observatories, Russia's Radioastron, *and Japan's* VSOP, *will augment the worldwide VLBI network, providing baselines to Earth radio telescopes as large as 80,000 km. The challenge for OVLBI is to effectuate space to ground radio telescope data cross–correlation (the observation) to a level of integrity currently achieved between ground radio telescopes. But, VLBI radio telescopes require ultra–stable frequency and timing references in order that long term observations may be made without serious cross–correlation loss due to frequency source drift and phase noise. For this reason, such instruments make use of hydrogen maser frequency standards. Unfortunately, space–qualified hydrogen maser oscillators are currently not available for use on OVLBI satellites. Thus, the necessary long–term stability needed by the orbiting radio telescope may only be obtained by microwave uplinking a ground–based hydrogen maser derived frequency to the satellite. Although the idea of uplinking the frequency standard intrinsically seems simple, there are many "contaminations" which degrade both the long and short term stability of the transmitted reference. Factors which corrupt frequency and timing accuracy include additive radio and electronic circuit thermal noise, slow or systematic phase migration due to changes of electronic circuit temporal operating conditions (especially temperature), ionosphere and troposphere induced scintillation's, residual Doppler–incited components, and microwave signal multipath propagation. What is important, though, is to realize that ultimate stability does not have to be achieved in real–time. Instead, information needed to produce a high degree of coherence in the subsequent cross–correlation operation may be derived from a two–way coherent radio link, recorded, and later introduced as compensations adjunct to the VLBI correlation process. Accordingly, this paper examines the technique for stable frequency/time transfer within the OVLBI system, together with a critique of the types of link degradation components which must be compensated, and the figures of merit known as coherence factors.*

ORBITING VLBI AND THE PHASE TRANSFER SYSTEM

VLBI astronomical observations are derived from received celestial radio signals by mutually crosscorrelating all of the data streams obtained from each radio telescope. That the signals are

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in the form of data streams is due to transformations whereby the RF bands are SSB translated to a lowpass range, sampled, and quantized (typically to one or two bits). For purposes of discussion in this paper, only a pair of signals will be considered, one derived from a ground radio telescope, and the other from the subject orbiting radio telescope.

A quality VLBI brightness observation depends on obtaining a very accurate crosscorrelation amplitude ("fringe pattern" maximum value). But, this measurement will be degraded from that ideally possible if the unconnected frequency reference systems (individual frequency standards) of the two radio telescopes are sufficiently unstable (i.e., they drift, and have a high level of phase noise) over the crosscorrelation period, T.

The process of transferring the needed stable reference frequency from the ground to an orbiting satellite is known by various clauses: "frequency transfer," "phase transfer," and "time transfer." These may be understood as counterpart descriptors, since frequency is the derivative of phase, and time units may be obtained as phase divided by the sinusoid's nominal angular frequency. In this paper, the phase of the frequency standard, or for the orbiting radio telescope the RF carrier phase, is the basic quantity of concern.

Figure 1 presents a synopsis model of the two–way phase transfer system, and illustrates the ground configuration, satellite, and two–way link, plus some principal sources of the detrimental phase components acquired through the phase transfer process. Beginning at the bottom left, a satellite tracking ground station, using a hydrogen maser frequency standard, generates and transmits an RF carrier. The carrier's frequency, as received by the orbiting satellite, inexorably undergoes a very significant Doppler shift due to the spacecraft's instantaneous radial velocity as it orbits the earth. Because the uplink frequency is used as the reference for the orbiting radio telescope, any significant Doppler shift creates a number of problems allied to the radio astronomy receiving process, and affects the ultimate coherence of the phase transfer reference. The limited scope of this paper precludes an exposè of these issues, but suffice it to say, it is prudent to employ an operation wherein the bulk of the Doppler is predictively removed from the uplink, so that the signal arriving at the satellite is substantially Doppler free. (A similar downlink Doppler removal is effected within the ground station's receiver.) The uplink carrier, which is coherently tracked by the satellite transponder receiver's phase–locked loop, ultimately forms the local frequency standard for the orbiting radio telescope.

In the process of being transferred from the ground to the satellite, the uplink carrier becomes phase modulated by effects within electronic circuits, plus propagation phenomena associated with the troposphere, ionosphere, and multipath. Thereby, the hydrogen maser stability of the ground frequency becomes unacceptably degraded by the time it reaches the satellite's radio telescope. Fortunately, two favorable conditions mitigate against unequivocal impairment. First, ultimate stability does not have to be achieved in real–time. Because VLBI signals are recorded on magnetic tape for later processing, an opportunity exists for introducing corrections during crosscorrelation. Secondly, the necessary correction information is readily obtained by transponding the uplink carrier (re–transmitting it at a slightly different frequency), and making a two–way (uplink plus downlink) phase measurement at the ground tracking station. Very important is the fact that the downlink introduces most of the uplink phase perturbations a second time, in a reciprocal, or nearly–reciprocal, manner. It is this characteristic which is critical to effectively making use of a scaled version of the measured two–way phase at the correlator, to minimize the uplink induced instabilities intrinsic within the VLBI observation data.

The downlink for the two–way phase transfer system is generated by coherently converting the received uplink frequency to a different frequency. The turn–around factor, assigned the symbol
itr, is the ratio of two integers. Typically, the downlink carrier is also modulated by the VLBI observation data. A ground receiving system detects and records the VLBI data, and extracts and records the two–way phase information. The receiving system also functions to construct the two–way Doppler profile, which is used for precise satellite orbit determination, essential to the ephemeral model needed at the correlator. All of this data, along with a corresponding observation from a ground radio telescope, is later applied to the VLBI crosscorrelation process.

PHASE TRANSFER MODEL

Figure 2 is a block diagram depicting the mathematical model of the two–way phase transfer; system. This figure effectively defines the phase component symbols (which, after brief study, should be reasonably obvious), their positions of entry into the model, and the phase transfer and compensation operations. Notice that all of the uplink and downlink phase contaminations have been divided into four principal portions: 1) the phase of the hydrogen maser source, 2) the phases introduced by the ground station, 3) the phases added by the propagation medium, and 4) the phases imparted by the satellite. Further, these principal components are made up of several terms peculiar to the realm within which they originate. The phase subscripts G, P, and S, denote respectively the Ground systems, the Propagation path, and the Satellite systems, while U designates the Uplink, and D the Downlink. Hydrogen Maser Source #1 is that stable frequency source located at the satellite ground tracking station and possesses the intrinsic phase noise ϕ_1, while Hydrogen Maser Source #2 is associated with a ground radio telescope, and has phase noise ϕ_2.

In what follows, the operations of Doppler removal are overlooked. ,For the purposes of modeling and analysis, the "system reference frequency" is defined as the nominal uplink microwave frequency, f_U, with K being the multiplication factor needed to obtain f_U from the Hydrogen maser standard frequency. At the satellite, f_U must be multiplied by an additional factor M (not necessarily an integer) in order to obtain the radio astronomy receiver's effective reference frequency, designated by the symbol f_A. Ultimately, its phase, denoted by $\phi_{reference}$, is the coherence degrading phase process which becomes imbedded within the VLBI sampled data transmitted to the ground. On the other hand, the two–way phase derived from up/down transfer link, and scaled by μM, is designated as $\phi_{two--way}$. Here, μ is the optimum scaling factor required to properly minimize, at the correlator, the uplink's effects.

The phase product from the VLBI crosscorrelation operation is assumed to depend solely on $\phi_{reference}$, $\phi_{two--way}$, and ϕ_2, all other actions being taken as ideal for the sake of the present investigation. Therefore, insofar as phase handling is concerned, the correlator may be represented by a series of differences, followed by finite integration, as shown within the dashed boundary on Figure 2. An additional feature of the VLBI correlator's comportment is the fact that it effectually diminishes the phase by a select first-order fit over the interval T. This is included in the model by introducing the linear expression $\hat{\Theta} + \hat{\alpha}t$, where the $\hat{}$over the coefficients denotes that they are estimated. Finally, the integrand involves the cosine of the reduced phase, this being the true form resulting from crosscorrelation of the actual signals involved. The output is called the generalized coherence function, and assigned the symbol $C(U;T)$. It now remains to specify μ, and evaluate $C(U;T)$.

CRITIQUE OF PHASE TRANSFER PERFORMANCE

Drawing on the definitions found on Figure 2, the effective phase input to the integrator, $C(U;T)$, may be written as:

$$\phi_{correlator} = \phi_{reference} - \phi_{two-way} - KM\phi_2 - (\hat{\theta}+\hat{\alpha}) = M \begin{pmatrix} K\phi_1 & -K\phi_2 \\ +(1-\mu r)\phi_{GU} & -\mu\phi_{GD} \\ +(1-\mu r)\phi_{PU} & -\mu\phi_{PD} \\ +(1-\mu r)\phi_{SU} & -\mu\phi_{SD} \end{pmatrix} - (\hat{\theta}+\hat{\alpha}t). \quad (1)$$

The brevity of this paper prevents a detailed review of all of the uplink and downlink phase components in respect to their individual characterizations and reciprocity. So, discussion must be limited to the point that the components are categorized by whether they are rapidly or slowly varying with respect to a specific value of T. Specifically, slow variation; (or slow phase) is attributed to any component which has its significant power manifest at frequencies below $1/T$, while fast variation; (or fast phase) means that the significant power of the component is embodied at frequencies greater than $1/T$. Components are additionally classified as to whether they are random variables, which can only be characterized statistically, or systematic temporal changes, conveniently represented by an algebraic function (e.g., a polynomial).

By way of simplification, the factor $K(\phi_1 - \phi_2)$ may be dropped from further consideration because it does not pertain directly to the subject of phase transfer, i.e., it is inherent in the crosscorrelation output between any two radio telescopes, whether one is space-based, or not. Secondly, it is assumed that the estimates $\hat{\theta}$ and $\hat{\alpha}$ adequately cancel their respective counterparts in $\phi_{reference} - \phi_{two--way}$, and that only quadratic phase terms, identified by the coefficients β_U and β_D], have significant effect. Lastly, like uplink and downlink phase pairs are identified, and the downlink phase process expressed in terms of the uplink phase by means of the normalized crosscorrelation ρ_i, plus δ_i, a prorating factor which assigns the type of reciprocity. Additionally, the term $\phi_{D_i-independent}$ is introduced to account for the uncorrelated remainder of the i^{th} downlink phase. Based upon these considerations, the generalized coherence function may be expressed by the form

$$C(U;T) = \frac{1}{T}\int_0^T \cos\left[M \begin{pmatrix} & [\sum_i \phi_{U_i} + \beta_U(T^2/6 - Tt + t^2)] \\ -\mu r & [\sum_i (1+\delta_i\sqrt{\rho_i})\phi_{U_i} + \beta_U(T^2/6 - Tt + t^2)] \\ -\mu & [\sum_i \sqrt{1-\rho_i}\phi_{D_i-independent} + \beta_D(T^2/6 - Tt + r^2)] \end{pmatrix} \right] dt. \quad (2)$$

The next step is to determine what value of the scaling factor, μ, optimizes $C(U;T)$. Since the integrand in (2) involves random variables, it is necessary to find conditions which maximize the expected value of the mean-square of $C(U;T)$, denoted by the symbol $\overline{(C^2(U;T)}$. Again, space prohibits inclusion of the details, but the solution for 100% reciprocal components (quadratic or random) is

$$\mu_{100\%\ reciprocal} = \frac{1}{2r}. \tag{3}$$

Of course, most components are not 100% reciprocal (some are not reciprocal at all). But it turns out that the predominant components are nearly 100% reciprocal, so little is practically lost by using the result expressed by (3) for most cases. The one outstanding exception is when the ionosphere exerts a very strong influence (which can happen if f_U is below 10 GHz, and solar-maximum conditions prevail). For this condition, a scaling factor slightly larger than $1/2r$ is required.

The coherence factor is defined as $\sqrt{\overline{C^2(U;T)}}$. Since many different independent phase pairs are involved, from this point forward it is convenient to deal with the coherence factors which involve the individual component pairs, ϕ_{U_i} and $\phi_{D_i-indendent}$. As a further shorthand, the i^{th} integrand terms of (2) are collectively represented by ϕ_i. Accordingly, it can be shown that the system coherence factor may be determined from component-pair coherence factors via the relationship

$$\sqrt{\overline{C^2(U;T)}} = \overline{C_Q(U;T)} \times \prod_i \sqrt{\overline{C^2_{\phi_i}(\mu;T)}}, \tag{4}$$

where the term with the subscript Q betokens quadratic phase, and the subscript i connotes the i^{th} random component pair.

Formal calculation of the individual random component coherence factors involves a double integral, given by

$$\overline{C^2_{\phi_i}(U;T)} = \frac{2}{T^2}\int_0^T (T-\tau)\exp\left[-\int_0^\infty S_{\phi_i}(\mu;f)\sin^2(\pi\tau f)df\right]d\tau, \tag{5}$$

where ϕ_i is assumed to be Gaussian, and $S_{\phi_i}(\mu;f)$ is its one-sided power density spectrum. It is especially notable that the phase noise spectrum is the cardinal measure of phase stability as reflected by the gauge of coherence factor. It is also important to realize that coherence is a decreasing function of the integration interval T. As an example, with the phase noise spectrum represented generically by

$$S_{\phi_i}(f) = \begin{cases} N_{0_i} f^{-v_i} & \text{for } 0 \le f \le f_m \\ 0 & \text{for } f < f_m \end{cases}, \tag{6}$$

Figure 3 shows coherence factor behavior for two indicated conditions of phase noise as a function of $f_m T$, f_m being the effective high frequency cutoff of $S_{\phi_i}(\mu; f)$. For very large $F_M; t$, and provided that Φ_i has a finite variance $\sigma^2_{\phi_i}$, the minimum coherence value of (5) may simply be obtained from the limiting result

$$\overline{C^2_{\phi_i}(\mu; T)} \approx \exp[-\sigma^2_{\phi_i}/2], \qquad f_m T \gg 1. \tag{7}$$

Finally, the residual quadratic phase coefficient, β, is obtained from the pertinent integrand terms of (2), and its coherence factor calculated through the use of Fresnel integrals by the expression

$$\overline{C_Q(\mu; T)} = \frac{1}{z}\sqrt{C^2(z) + S^2(z)}, \qquad z = \sqrt{\beta T^2/2\pi}. \tag{8}$$

SOME PHASE TRANSFER SYSTEM DESIGN CONSIDERATIONS

There are no less than ten independent and quantifiable sources of phase noise which impinge the phase transfer process. Some of these sources are termed "operative," because they stem from apparatus and actions which can be controlled by design. Operative sources include microwave and electronic circuit noise, slow or systematic phase migration due to changes of electronic circuit temporal operating conditions (especially temperature), residual Doppler–induced components, and microwave signal propagation multipath. Other sources are termed "natural," because the system designer essentially has no control over them. These are principally the ionosphere and troposphere.

Substantial degradation by many operative sources can be avoided through good design practices. A part of evaluating system coherence is determination of coherence factors for individual functional circuit assemblies (such as amplifiers, mixers, filters, frequency multipliers, etc.). For random phase noise, independence between assemblies is presumed. What is of concern at the electronic unit level are the phase components which are added to an input sinusoid over and above the circuit's intrinsic thermal noise (a natural source). The nuance of the unit's phase noise intrusions is that of "degradation." In this sense, an individual circuit should be treated as if it were inherently free of thermal noise, because in a hierarchy of cascaded units, all of the intrinsic noise contributions should be handled as an equivalent thermal noise at the input to the chain. This noise, usually expressed as a noise figure for the entire system, is ultimately reckoned in terms of SNR. What should be accounted for at the unit level are 1) any in–band spurs (perhaps due to RFI coupling), 2) power supply noise, 3) common mode noise contributions, 4) VSWR effects, 5) AM/PM, 6) any nonlinear characteristics which give rise to an increased in–band thermal noise level relative to linear throughput, 7) the effects of reference frequency phase noise if the circuit has a reference frequency input, 8) deliberate modulation, and 9) operating point induced phase drifts.

Other loss catalysts which can substantially reduce coherence are Doppler, and unaccountable slow phase variations, especially quadratic and higher–order phase changes, which are not reciprocal on the two-way microwave radio link. Minimization of this class of loss is promoted by the use of predictive Doppler removal from the phase transfer uplink (at the transmitter) and downlink (at the receiver), and techniques for minimizing "drift" phase.

Through judicious design, the compensated coherence loss due to all operative sources (both ground and satellite) can typically be kept below 1%. On the other hand, the largest coherence losses are typically caused by severe troposphere and ionosphere phase scintillations, and quadratic phase due to changing troposphere propagation path length as the ground station antenna changes elevation angle while tracking the satellite's orbit. But even these natural effects can be minimized by using the highest uplink frequency possible, because the ionosphere's effects are proportional to the inverse of the uplink frequency. For this reason, X-band or higher is preferred.

PHASE TRANSFER SYSTEM PERFORMANCE

A goal of the phase transfer system is to maintain very high coherence (0.9900, or 99%) for centimeter wavelength (e.g., 1.35 cm or 22 GHz) radio telescope signal reception over measurement periods, T, of 300 (and up to 1000) seconds. In order to attain this goal, a great deal design effort has been made toward minimization of all sources of operative phase noise in ground and satellite microwave and electronic systems.

Table 1 presents a summary of the expected *Radioastron* and *VVSOP* phase transfer performance. In all cases the coherence due to operative sources is better than 99%. It is the natural sources which drive the complete system coherence below 99%. Notice that *Radioastron* performs worse than *VSOP* in this regard, because *Radioastron*'s uplink is at X-band, while *VSOP*'s is at Ku-band.

PHASE NOISE AND COHERENCE MEASUREMENTS

Proper measurements of the underlying processes or components which contribute to phase transfer degradation is a vital element of OVLBI system development. Characterizing phase behavior requires that simultaneous measurements of the input and output, of a unit or subsystem under test, be taken in order to obtain differential performance information. A further fundamental requirement is that the measuring instrument itself either a) contribute negligible phase noise/errors, or b) be fully calibrated so that phase noise/errors may be taken into account in forming the final measurement results.

The commercial test equipment market is essentially devoid of the type of equipment needed to make several simultaneous and synchronous phase measurements. The best solution to the phase measurement problem is to make use of the basic two-way phase measurement technique developed for ground station two-way phase extraction and processing. By this method, a device being tested is excited by a high-quality (very stable) frequency, and phase measurements are simultaneously taken at the device's input and output. In order to obtain phase process data from the input and output sinusoidal waveforms, each is demodulated by a quadrature phase detector referenced to a stable frequency standard, producing sine–of–phase and cosine–of–phase signals. These two signals are individually lowpass filtered, and then sampled by an analog–to–digital converter capable of taking time–coincident samples from several quadrature phase demodulators.

Sample pairs are input to computer or special digital processor for reduction into useful results. Phase data reduction and analysis consists of a series of complex operations which 1) condition the data samples to correct for imperfections introduced by the test hardware, 2) computes unambiguous phase from corrected data, and 3) derives the systematic and random phase measures. Coherence may be computed directly from the unambiguous phase data. Additionally, the measured random phase component may be analyzed to extract its standard deviation, power density spectrum, etc. When multiple outputs (such as with a transponder) are being analyzed, crosscorrelation may be used as a data reduction tool.

ACKNOWLEDGMENT

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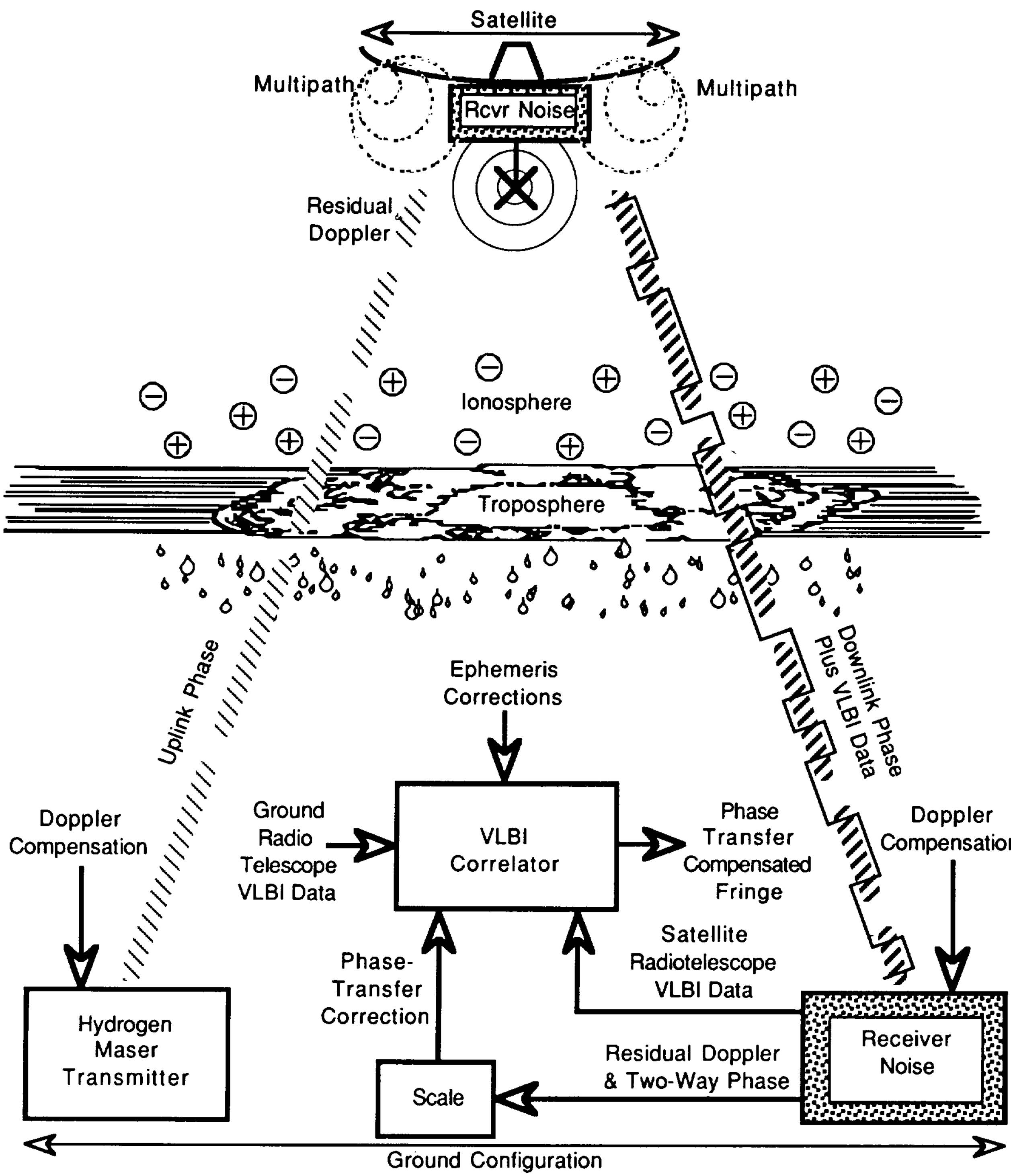

Figure 1 – Synopsis Model of Two-Way Phase Transfer System

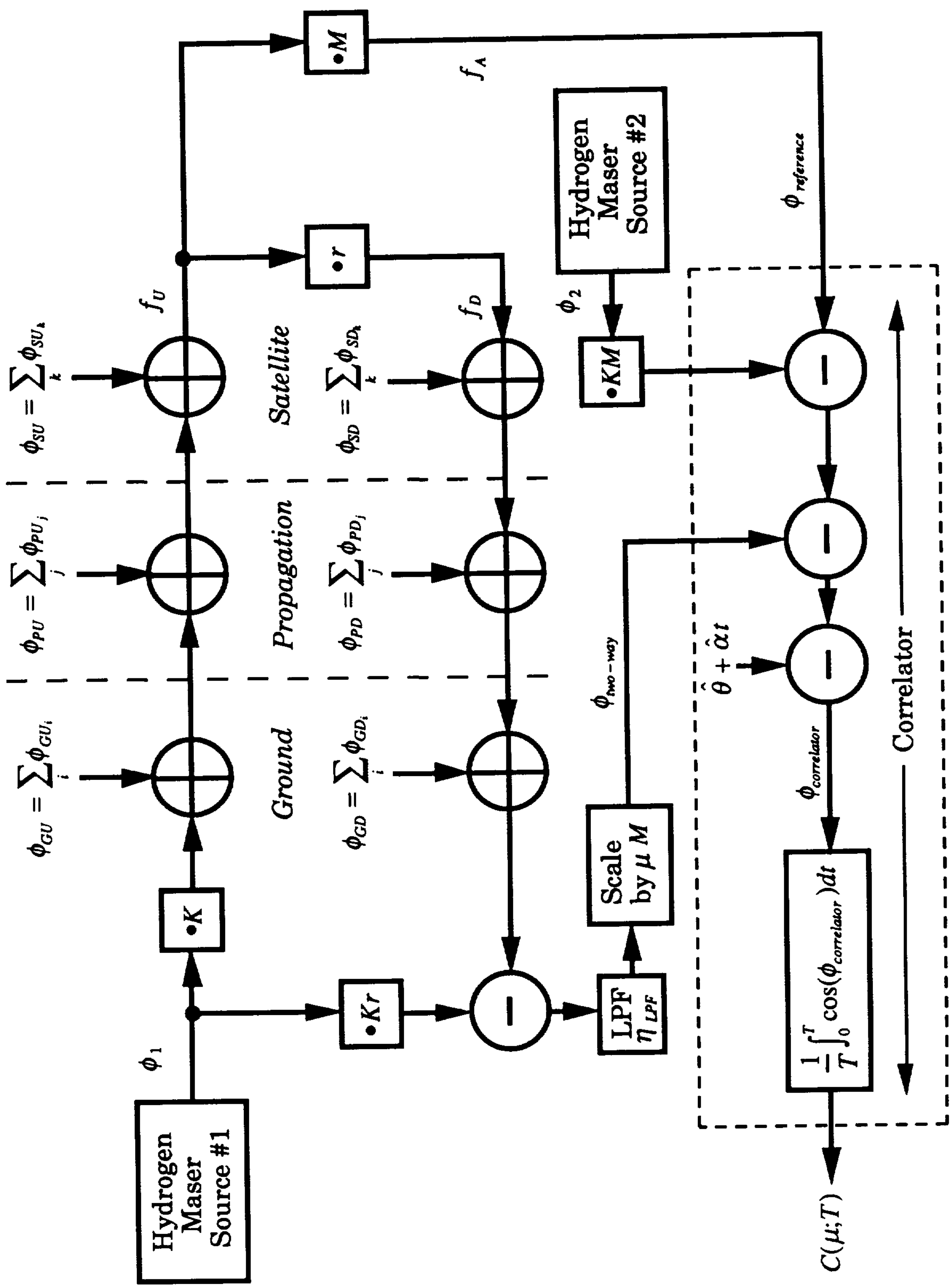

Figure 2 – Mathematical Model of Two-Way Phase Transfer System

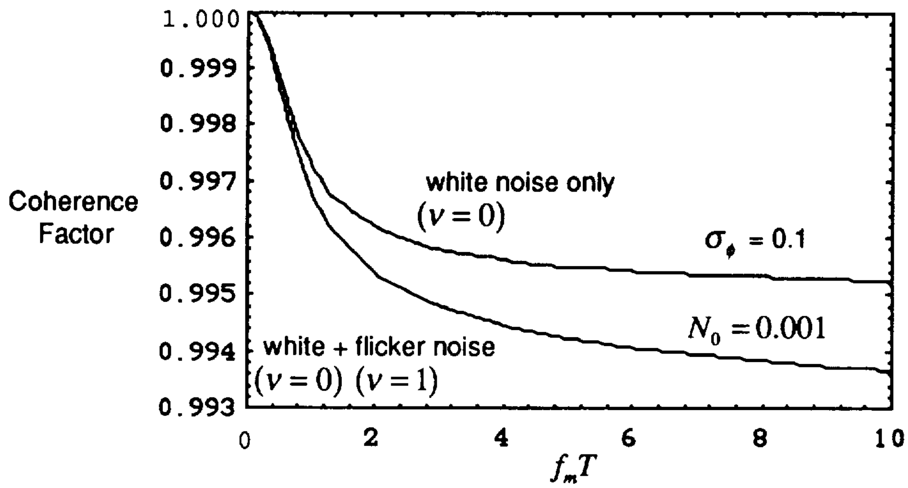

Figure 3 – Coherence Factor Behavior

	Radioastron		*VSOP*	
	Uplink	Downlink	Uplink	Downlink
Phase Transfer Link Frequencies (GHz)	7.21	8.47	15.3	14.2
Corrected Coherence Factors	Worst-Case	Typical	Worst-Case	Typical
Operative Sources	0.9913	0.9940	0.9941	0.9970
Natural sources	0.9482	0.9954	0.9938	0.9982
Complete System	0.9399	0.9895	0.9880	0.9952

Table 1 – *Radioastron* and *VSOP* Phase Transfer Performance

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PRECISION FREQUENCY SYNTHESIZING SOURCES WITH EXCELLENT TIME / FREQUENCY PERFORMANCES

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ABSTRACTS

Precision frequency synthesizing sources are needed in the time / frequency measuring system, atomic frequency standards, telemetry, communication and radar systems. This kind of frequency synthesizing sources possesses high frequency accuracy and excellent long term and short term frequency stability.

Several precision frequency synthesizing sources developed by Beijing Institute of Radio Metrology and Measurement (BIRMM) are described in this paper, which have been successfully applied to the time / frequency measuring system, atomic frequency standards system and radar system. In addition, the working principle, implementation approach and the main technical specifications obtained of the frequency synthesizing sources are also given in this paper.

INTRODUCTION

With the development of the electronic technique, the requirements for the frequency accuracy and stability of the signal sources grow higher and higher.In many electronic systems, it is required that the signal sources should work in the wider frequency band and possess excellent frequency stability and accuracy. All of these requirements bring out the development of the frequency synthesizing technique. With the advent of the large-scale integrated circuits (LSIC) and the applications of high-speed programmable divider, fractional divider and direct digital synthesizer (DDS), great progress has been made in some aspects of the modern frequency synthesizer such as output

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frequency band, phase, noise, frequency stability and accuracy, frequency resolution, spurious suppression, etc.

Now, the modern frequency synthesizing technique has been widely applied to various electronic systems such as communication, navigation, measurement, frequency standards systems, etc. In this paper, several kinds of frequency synthesizing sources developed by BIRMM according to practical demands, as well as their characteristics, working principle and technical specifications are introduced.

MICROWAVE PHASE–LOCKED FREQUENCY SYNTHESIZING SOURCES

The microwave phase–locked frequency synthesizing sources developed by our institute have excellent frequency stability and accuracy as well as high frequency agile rate.

This frequency source adopts the digital phase–locked technique, the reference frequency source consists of the 100MHz crystal oscillator with high stability and isolated amplifier. The microwave frequency standards system consists of three low–noise microwave higher multipliers and selection switches. The single loop with the mixer is adopted in the phase–locked loop and the pulse–swallow programmable divider with low noise is added in the feedback circuit. In the loop, the low noise circuits are used in both the digital detector and loop filter. The control terminal of the voltage controlled oscillator (VCO) is equipped with the voltage presetting circuit so as to assure the quick and reliable locking of the loop.

The principle block diagram of the microwave phase–locked frequency synthesizer is shown in Fig.1.

In the design of the frequency synthesizer, the major consideration is to decrease the phase noises. In the phase–locked loop, the noises coming from every link will cause additional phase jitter at the output terminal, thus, degrading the quality of the output spectrum in the result. The mathematical model of the loop phase noises is shown in Fig.2.

In the figure, $S_{\varphi TN}(\omega)$— additional phase noise of the variable programmable divider; $S_{\varphi Tn}(\omega)$—additional phase noise of the fixed divider; $S_{\varphi m}(\omega)$—additional phase noises of the frequency multiplier, mixer and switch circuits; $S_{\varphi c}(\omega)$—output phase noise of the crystal oscillating source; $S_{V1}(\omega)$, $S_{V2}(\omega)$—noise voltages of the corresponding points of the loop; $S_{\varphi}(\omega)$—additional phase noise of the voltage controlled oscillator (VCO); $e^{-p\tau d}$ —time-delay factor (leaving it out of consideration when analysing the noise).

The total output phase noise is:

$$S_{\varphi 0}(\omega) = [S_{\varphi C}(\omega)(\frac{N}{n} + M)^2 + S_{\varphi rn}(\omega)(\frac{N}{n})^2$$

$$= + \frac{S_{V1}(\omega)}{K_{\varphi}^2} N^2 + S_{\varphi m}(\omega) + S_{\varphi TN}(\omega)] \cdot$$

$$|H_r \xi\omega)|^2 + [S_{V2}(\omega)\frac{K_{VCO}^2}{\omega^2} + S_{\varphi VCO}(\omega)] \cdot |H_{er}(j\omega)|^2$$

In the formula: $H_r(j\omega)$—closed-loop transfer function of the loop; $Her(j\omega)$—error transfer function of the loop; K_{φ}—sensitivity of the phase detector; N—dividing ratio of programmable divider; M—times of the frequency multiplication; n—dividing ratio of fixed divider; K_{VCO}—voltage controlled sensitivity of the voltage controlled oscillator. In the formula (1), the phase noises at the loop output terminal are divided into two parts due to low-pass and high-pass filtering performances.

One part of the phase noises mainly comes from the reference source, fixed divider, phase detector, loop filter amplifier, frequency multiplier, variable programmable divider as well as their frequency dividing ratios N and n; frequency multiplication ratio M, these phase noises are related to closed-loop transfer function of the loop and possessed of low-pass performance. Therefore, within the range of the loop bandwidth, the phase noises at the output terminal completely depend on the noise superposition of the above-mentioned elements in the loop and the phase noises beyond the range of the loop bandwidth will be attenuated.

The other part of the phase noises mainly comes from the voltage controlled oscillator VCO, which is related to the error transfer function of the loop and possessed of high-pass performance. Therefore, the phase noises of the output signal beyond the range of the loop bandwidth is mainly decided by the open loop feature of the voltage controlled oscillator.

In order to ensure the minimum output phase noise and spurious spectrum, the following measures shall be taken in the design of the phase–locked loop.

a. To use HF crystal oscillator with high quality and stability as the reference source so as to decrease affection of the noises and the times of the frequency multiplication as well.

b. In the feedback branch of the loop, the frequency dividing ratio N of the programmable divider increases the phase noises by N times of the reference source, fixe d divider outside the loop (n), phase detector (PD) and low–pass filter (KF). So lower feedback frequency dividing ratio N shall be adopted as far as possible. In addition, variation of N results in the variations of the loop gain K and natural frequency ω_n, which certainly affects the stability of the loop. For this reason, the design using 3 direct selective microwave frequency multipliers has been accepted.

c. To raise the phase discriminating frequency f_r, which can not only be useful for increasing the agile rate, but also be more effective for filtering the leakage of the phase discriminating frequency by means of the loop filter. Generally, $f_r / 2\xi f_n > 10$.

d. To raise the phase discriminating sensitivity K_d and DC amplifier gain K_F so as to enhance the noise suppression capability of the loop.

e. To make the design of various parameters such as gain K, bandwidth ω and damping coefficient ξ optimum, therefore, optimizing the loop characteristics within the whole working frequency range.

The short term frequency stability of the frequency synthesizer at S waveband reaches $\sigma_T = 6 \times 10^{-11}$ / ms; phase noise $L(f) < -100$dBC / Hz, $f_m = 1$kHz, $L(f) < -110$dBc / Hz, $f_m = 10$kHz. The frequency agile rate is lower than 40μs when the phase stabilization reaches 0.1 °.

Such kind of phase–locked frequency synthesizer is used for the measuring equipment and radar system.

The phase noise curve of the microwave phase-locked frequency synthesizer with output frequency of 3.5GHz is shown in Fig.3.

HF AND UHF SYNTHESIZING SOURCES

Now, the direct and phase-locked frequency synthesizing sources have been developed by our institute. The direct UHF synthesizer adopts the $U_1$and U_2frequency synthesizing units with BCD code step type, the step interval is 10kHz. Through twice up-conversions, the frequency is transferred to the UHF band. The stability at milli-second level is 7×10^{-10}/ms in case the frequency is 320MHz and the phase noise $L(f) < -106$dBc/Hz, $f_m = 1$kHz, is $L(f) < -131$dBc/Hz, $f_m = 10$kHz. The frequency agile rate is less than 10μs.

The UHF phase-locked frequency synthesizing sources adopts the single-loop phase-locked system and take the 5MHz crystal oscillator with high stability as their reference source. In the loop, the specially designed digital phase detection and fractional divider with high sensitivity and low noise are adopted, the minimum step of the frequency dividing ratio N of the fractional divider is 1/10. Thus, the non-phase correcting fractional frequency dividing circuit is used. The double mode predivider adopts $\div 4 / \div 5$ mode and directly works at UHF band. Moreover, the voltage controlled oscillator (VCO) in the phase-locked loop adopts the inductance sectionalization mode, thus ensuring a wide output frequency bandwidth and good phase noises. In the loop, the trapper is adopted to suppress the stray in the output signal. In case the output frequency is 410.5MHz, the phase noise $L(f) = -90$dBc/Hz, $f_m = 10$Hz, $L(f) = -102$dBc/Hz, $f_m = -100$dBc/Hz, $L(f) = -120$dBc/Hz, $f_m = 1$kHz, strays: -90dBc, $f_m > 3$kHz. The frequency agile rate of the frequency synthesizer is less than 1ms.

In order to meet the demands for the development of the small-scale passive hydrogen (H) atomic frequency standards, we have also designed one kind of frequency synthesizers in its electronic system, which adopts the phase accumulating technique, its frequency resolution is better than 1mHz so as to satisfy the demands of the small-scale hydrogen clock electronic system on variable small frequency step.

CONCLUSION

This paper describes the achievements made by BIRMM in the field of frequency synthe sizing technique in recent years. With the development of the frequency synthesizing technique and in order to meet the practical demands on the frequency stability measurement and atomic frequency standards, there is still much work to be done in the area of frequency sources, such as expending frequency range, rèducing phase noises; increasing frequency stability; developing high precision crystal oscillator with excellent long term and short term frequency stability, etc.

During the development work mentioned above, Mr. Ruida Mao and many colleagues gave us a lot of help, we wish to express our heartfelt thanks.

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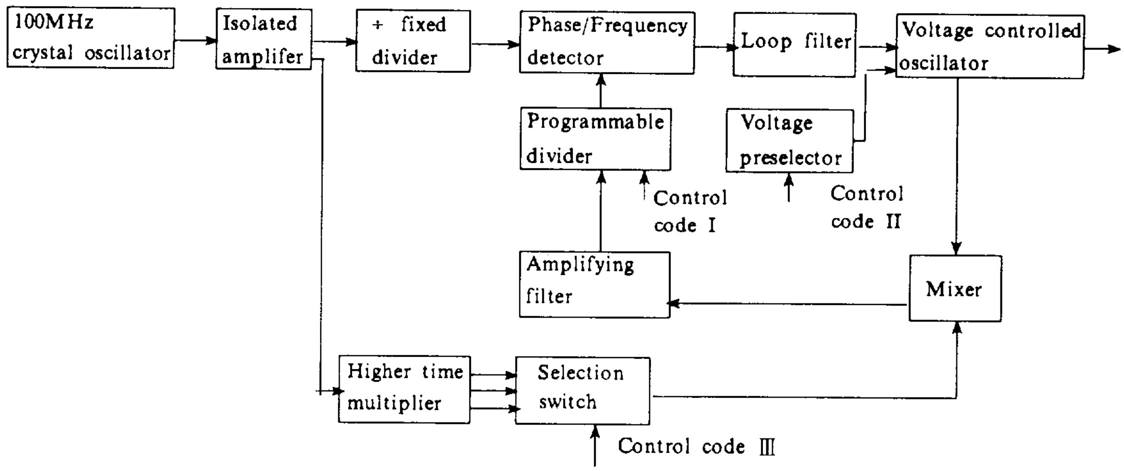

Fig.1 Principle block diagram of the microwave phase – locked frequency synthesizer

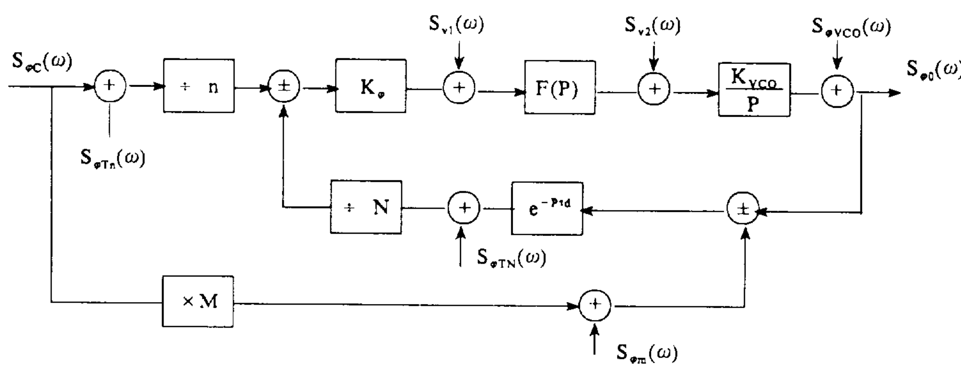

Fig.2 Mathematical model of the phase – locked loop noise

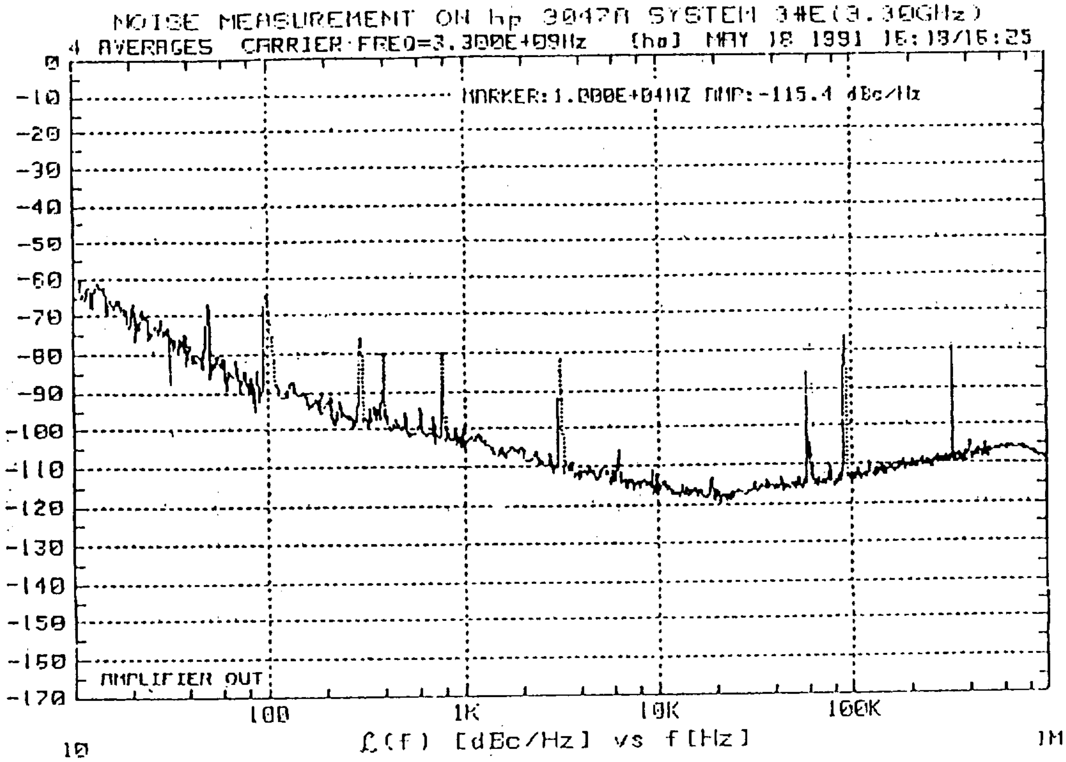

Fig.3 Output phase noise curve of the microwave phase-locked frequency synthesizer

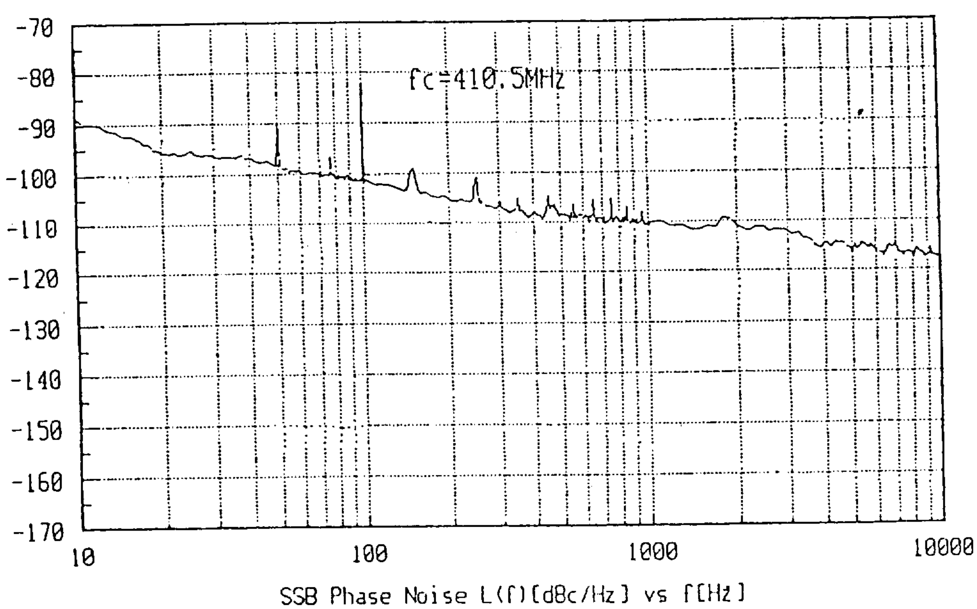

Fig.4 Output phase noise curve of the UHF phase-locked frequency synthesizer

TIME MAINTENANCE SYSTEM FOR THE BMDO MSX SPACECRAFT

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Abstract

The Johns Hopkins University Applied Physics Laboratory (APL) is responsible for designing and implementing a clock maintenance system for the Ballistic Missile Defense Organizations (BMDO) Midcourse Space Experiment (MSX) spacecraft. The MSX spacecraft has an on–board clock that will be used to control execution of time–dependent commands and to timetag all science and housekeeping data received from the spacecraft. MSX mission objectives have dictated that this spacecraft time, UTC(MSX), maintain a required accuracy with respect to UTC(USNO) of ± 10 ms with a ± 1 ms desired accuracy. APL's atomic time standards and the downlinked spacecraft time were used to develop a Time Maintenance system that will estimate the current MSX clock time offset during an APL pass and make estimates of the clock's drift and aging using the offset estimates from many passes. Using this information, the clocks accuracy will be maintained by uplinking periodic clock correction commands. The resulting Time Maintenance system is a combination of Offset Measurement, Command/Telemetry, and Mission Planning hardware and computing assets. All assets provide necessary inputs for deciding when corrections to the MSX spacecraft clock must be made to maintain its required accuracy without inhibiting other mission objectives. This paper describes the MSX Time Maintenance system as a whole and details the clock Offset Measurement subsystem, a unique combination of precision time maintenance and measurement hardware controlled by a Macintosh computer. Simulations show that the system estimate the MSX clock offset to less than ± 33 μs.

TIME MAINTENANCE OVERVIEW

The Midcourse Space Experiment (MSX) Time Maintenance system is composed of four subsystems: the spacecraft clock, the Offset Measurement (OM) subsystem, the Command/Telemetry subsystem, and the Operations Planning Center (OPC). Figure 1 shows a top–level view of the system and its major components. Spacecraft time, UTC(MSX), is telemetered in the spacecraft housekeeping data stream, passes through the APL Satellite Tracking Facility (STF) and Mission Control Center (MCC) downlink hardware, and is compared to a locally maintained time, UTC(MCC), in the OM subsystem. In order to accurately estimate the clock offset, the OM subsystem also receives propagation delays and the scheduled clock corrections from the MCC computer network. The computed clock offset, drift, and aging are then passed to the network from which they get distributed to the MSX community, including the OPC. The OPC has software that will schedule and generate the necessary clock correction commands. These are sent back to the MCC computer network for uplinking to the spacecraft through the MCC uplink or the Onizuka Air Force Base Test Support Complex (TSC). The Time Maintenance system is also required to disseminate the UTC(MSX) offset (error) and characteristics to the MSX community, to set and characterize the MSX clock during spacecraft integration and test, and to set the clock just before launch.

Spacecraft Clock

The MSX spacecraft clock, UTC(MSX), is actually a software-maintained, 35 bit integer with 1 ms resolution representing the number of milliseconds into the current year. This counter increments by 1000 ms every time it receives the spacecraft 1 pulse/s (1 PPS) time epoch. This time epoch is obtained by direct division of one of the two APL-built ultrastable 5 MHz quartz crystal oscillators, so its drift and aging characteristics are determined solely by the oscillator's frequency offset and drift. For these oscillators, the deviation from the nominal frequency, or frequency error, at any time, $f_{err}(t)$, can be modeled by a simple linear equation,

$$f_{err}(t) = f_{err}(0) + \Delta f_{err}[t - t_0] \tag{1}$$

where $f_{err}(t)$ is the frequency drift. Integrating this frequency error over time with respect to the nominal oscillator frequency, f_n, yields a simple quadratic equation for modelling the UTC(MSX) clock offset versus time, $Y(t)$,

$$Y(t) = Y(t_0) + [f_{err}/f_n][t - t_0] + [\Delta f_{err}/f_n][t - t_0]^2/2 \tag{2}$$

The oscillator specifications call for a normalized frequency error of less than 5×10^{-8} and a drift rate of less than 1×10^{-10}/day. To compensate for these oscillator frequency instabilities, the spacecraft command system has implemented a 1 ms resolution clock offset command that is added to the software-maintained UTC(MSX).

The UTC(MSX) time is downlinked in real time in each major frame of the 16 kbps housekeeping telemetry stream. The major frame epoch of this stream is coherent with the spacecraft 1 PPS epoch. From this epoch and time, the UTC(MSX) offset can be determined with a high degree of accuracy.

Command/Telemetry

The Command/Telemetry downlink receives the telemetry signal, separates out the 16 kbps housekeeping, and sends it to the Offset Measurement subsystem. The telemetry portion of the Command/Telemetry subsystem consists of the necessary RF and digital downlink hardware to receive, downconvert, and demodulate the S-band spacecraft signal to separate out the digital housekeeping stream. The uplink portion contains the hardware and software to format, modulate, and upconvert the clock correction command. The MCC computer network provides the OM with the needed spacecraft telemetry propagation delays and the previous clock corrections for each APL pass.

Operations Planning

The scheduling software in the OPC contains a time update utility that uses the current estimated clock offset and characteristics to determine when a clock update should be sent. The oscillator specifications stated above translate to an maximum clock drift of 5 ms/day, requiring a maximum of five corrections per day to remain within the desired accuracy.

Because of the manner in which the OPC schedules its many events, the scheduling software must schedule events up to 2 days in advance. The time update utility will predict the clock offset ahead for 2 days and, whenever this predicted offset is greater than ± 0.5 ms, an attempt will be made to schedule a clock correction. If data will not be corrupted by the correction, a correction of 1 ms will be made. Thus ideally the offset versus time would be a sawtooth fluctuating between +0.5 ms and −0.5 ms. However, the realities of scheduling may, very likely, force a slightly larger error on occasion. To accommodate this offset prediction capability, the Time Maintenance system has a goal of 2 day prediction errors of less than ± 100 μs.

Offset Measurement Subsystem

The heart of the Time Maintenance System is the OM subsystem, and the remainder of this paper will be devoted to detailing its operation. This subsystem is composed of specialized offset measurement hardware, a Macintosh time management unit (TMU), and custom time and frequency generation (T&F) equipment. For the purposes of this paper the OM subsystem will be broken into four parts: UTC(MCC) time generation; Delta measurement; offset estimation; and drift and aging estimation. Figure 2 shows an overview of the OM subsystem.

All measurements of the spacecraft clock offset will be made with respect to a reference UTC(MCC) 1 PPS epoch. Obviously, this epoch is not exactly the UTC(USNO) 1 PPS time epoch; thus the accuracy of any estimate of the spacecraft offset will depend greatly on the accuracy of this reference clock and the reference frequency. Therefore, a critical requirement of the OM subsystem is to provide precise time and frequency to the offset measurement hardware.

UTC(MCC) Time Generation

Figure 3 details the methodology for time transfer to the OM. The APL Time and Frequency Standards Laboratory (T&FSL) maintains atomic time and frequency standards. UTC(APL) is consistently maintained to within 2 μs of UTC(USNO)[1]. The STF receives time and frequency standards over fiber optics from the T&FSL in the form of IRIG B, 1 PPS, and 5 MHz. The STF regenerates the IRIG B and 1 PPS, both to account for the signal delay to the STF (the T&FSL is about 0.5 mile away) and to allow stand-alone capability should the T&FSL signal drop out. The STF phase-locks a 1 MHz disciplined crystal frequency standard to the incoming T&FSL 5 MHz, allowing for the long-term stability of the 5 MHz while cleaning up the transmitted frequency reference for better short-term stability. This 1 MHz is used as the

STF time code generator (TCG) time base. Informal round–trip testing with the T&FSL and comparison with a local GPS receiver has shown the STF time output to be consistently within $\pm$ 10 μs of UTC(USNO). The STF T&F outputs are the OM T&F inputs.

The OM does a similar time regeneration to allow for stand–alone operation and to produce a stable time output. The 5 MHz from the STF is input to a 10 MHz rubidium (Rb) PLL followed by a 10 to 5 MHz scaler and a 5 MHz buffer/isolator. This allows for the OM 5 MHz reference to be phase–locked to the APL 5 MHz reference when it is present and to be derived from the stable Rb oscillator when it is not. Because the Rb has specifications about 2 orders of magnitude better than the spacecraft oscillator, for a short period of time the Time Maintenance operation could continue with the Rb as its time base.

A buffered 5 MHz output is the time base for the TCG, whose output is UTC(MCC). This custom TCG will initially synchronize to the IRIG B and 1 PPS time standards with less than 1 microsecond error. Then the synchronization software will be turned off and the TCG will free run off its 5 MHz reference. This is to prevent the TCG from trying to track any noise in the IRIG B and 1 PPS inputs. Because UTC(MCC) is generated from a direct division of the 5 MHz reference, the long–term stability of UTC(MCC) will be the same as the 5 MHz reference. While no longer synchronizing to its reference inputs, the TCG monitors the difference between its 1 PPS output and the reference inputs (again to sub–microsecond accuracy) to ensure that UTC(MCC) does not drift from UTC(STF). This difference is queried by the TMU and triggers an alarm if greater than 5 μs. The OM also monitors the distributed UTC(MCC) IRIG B, 1 PPS, and 5 MHz outputs via status lines sent to the TMU parallel board from the distribution units.

Delta Measurement

The critical offset measurement signal is the transmitted spacecraft 16 kbps major frame epoch, which occurs nominally once per second. It is this signal that contains the precision information about the spacecraft time epoch and oscillator performance. Once per second during an APL pass the OM makes a measurement of the time interval, Delta, between the local UTC(MSX) 1 PPS reference and the recovered spacecraft epoch. Figure 4 details the Delta measurement hardware. The spacecraft epoch is recovered by the frame synchronizer/demux (FS/D) using the first bit transition of the major frame sync word as the epoch edge. Calibration tests have shown that the offset between this recovered epoch and the actual major frame epoch is consistent and measurable and can thus be accounted for. Every second, the Time Interval Measurement Unit (TIM) is set up by the TMU to measure the time interval between the recovered epoch and the 1 PPS reference edge. For accuracy, the TIM uses the 5 MHz reference as its timebase.

The FS/D will send six of the housekeeping telemetry words to the TMU parallel I/O board. These words contain the UTC(MSX) time, the mission elapsed time (MET), and the spacecraft oscillator being used. Once the MCC has acquisition of signal (AOS) for the 16 kbps telemetry (which the TMU determines from the FS/D status signal), the TMU will first empty the FS/D buffer and get major frame synchronization using an end of frame (EOF) signal. Then the sequence of events for each second is as follows:

1. The TMU sets up the TIM to make a Delta measurement.
2. The TMU waits until the TIM reports that a measurement is complete.
3. The TMU reads the UTC(MSX) time from the TCG (only concerned with second accuracy because, by definition, the 1 PPS occurs on a 1 s boundary).
4. The TMU reads the Delta measurement.
5. The TMU reads the FS/D buffer to get the UTC(MSX) of the next epoch.

This sequence is repeated until loss of signal (LOS). Hardware is controlled and data are retrieved over a local GPIB bus controlled by the TMU.

When the received spacecraft epoch approaches coincidence with the 1 PPS rising edge, the TMU will automatically command the TIM to measure from the 1 PPS falling edge. This prevents noise from generating an ambiguity in the time difference measurements around even second intervals. This switching will take place after a pass is complete. Calibration of the 1 PPS duty cycle allows the approximate 0.5 s bias to be accounted for.

Offset Estimation

The UTC(MSX) Offset estimation takes place in the TMU. At any given time, t_0, this offset has been defined to be

$$T(t_0) = \mathrm{UTC(USNO)}_0 - \mathrm{UTC(MSX)}_0 \tag{3}$$

However, this offset is not simply the Delta measured by the TIM. Both biases and noise must be accounted for to the greatest degree possible. Figure 5 illustrates the offset measurement biases. These biases are measured before launch (for spacecraft biases) and periodically during the mission (for ground station biases). The propagation delays, td4, are computed for each second in the MCC Computer Network based on the estimated MSX orbit and sent to the TMU prior to every APL pass. With this bias data, the TMU has the information necessary to compute the offset for any given second during the pass using the equation,

$$Y(t_0) = \mathrm{UTC(MCC)}_1 + \mathrm{Delta} - [\mathrm{UTC(MSX)}_0 + \sum \mathrm{td}(1-8)] + \sum td(9,10) \tag{4}$$

Each of these offset samples is contaminated with the noise of the downlink, so the samples from each pass will be condensed to a single offset estimate to reduce the random error. The time of closest approach (CA) was chosen as the best time to estimate the offset because this is where the range error effects would be least. The offset samples are also windowed about CA to further minimize the range error effects. Since the oscillator drift is very linear over the period of a pass (5 to 15 minutes), a first–order least squares regression is used to estimate the single pass offset estimate. A higher order estimate may attempt to fit the range error curve or noise. The general first–order linear equation is,

$$Y_1 = \beta_0 + \beta_1 X_1 + \epsilon_1 \tag{5}$$

where X_i are the time of the offset samples: Y_i are the actual offset samples; β_n are the actual offsets and drift; and b_n are the estimates of β.The fitted equation, Equation 6, is used to estimate the offset:

$$\hat{Y} = \bar{Y} + b_1(X - \bar{X}) \tag{6}$$

where

$$b_1 = \frac{\sum(X_i - \bar{X}(Y_1 - \bar{Y}))}{\sum(X_i - \bar{X})^2} \tag{7}$$

For a given estimate, $\hat{Y}_h$, the standard deviation is

$$\sigma_h = \sigma_i \left[\frac{1}{n} + \frac{(X_h - \bar{X})}{\sum(X_i - \bar{X})^2}\right]^{\frac{1}{2}} \tag{8}$$

when $X_h = \bar{X}$, σ_h is minimized and the offset estimate is $\hat{Y}_h = \bar{Y}$.

This shows that if the offset samples are windowed about CA, the standard deviation of the estimate will be minimized at CA and the offset estimate is just the average of the offset samples. As an independent verification of the estimated offset, the TSC has agreed to make their own spacecraft offset estimations. These will be used to detect errors in the Time Maintenance system.

Drift and Aging Estimation

From Equation 2 we know that these offset estimates over time can be approximated by a simple quadratic. So, after an offset estimate has been made for at least three passes, the UTC(MSX) drift and aging will be solved for by using the offset estimates from each pass in a second–order least squares regression. Only the offsets from the previous week or so will be used so that the estimates are not too heavily weighted with old data and are able to respond to new oscillator trends. Equation 2, written in a slightly different format and notation (to avoid difficulties of inverting the $X'X$ matrix), is

$$Y_i = \beta_0 + \beta_1 x_i + \beta_1 x_i^2 + \epsilon \tag{9}$$

or in matrix form, $\mathbf{Y} = \mathbf{x}\beta + \epsilon$, where X_i are the time of the offset estimate from each pass; Y_i are the actùal offset estimates from each pass; β_n are the actual offset, the drift, and the aging; b_n are the least squares estimates of b using x; B_n are the least saquares estimates of b using X; and $x_i = X_i - \bar{X}$. The least squares estimators, b, of β are

$$\mathbf{b} = (\mathbf{x}'\mathbf{x})^{-1}\mathbf{x}'\mathbf{Y} \tag{10}$$

The least squares estimators, B, of β are

$$\begin{aligned} B_0 &= b_0 - b_1\bar{X} + b_{11}\bar{X}^2 \\ B_1 &= b_1 - 2b_{11}\bar{X} \\ B_{11} &= b_{11} \end{aligned}$$

These equations allow one to solve for clock drift, B_1, and aging, $2B_{11}$. A complete history of the UTC(MSX) characteristics will be maintained for the mission duration for each of the spacecraft oscillators.

An analysis of the offset measurement error sources show components of both a "fixed" (such as the UTC(MCC) error) and a "variable" (such as the telemetry propagation time errors and thermal noise) nature with respect to a time period of a pass or longer. The fixed errors are effectively an unknown bias and, as such, will directly affect the ability to estimate and predict the clock offset. The variable errors can be effectively reduced by the regression analysis. Simulations were run using worst–case fixed errors of $\pm$ 12 μs, variable errors of $\pm$ 3 μs rms, and $\pm$ 2 μs range errors. These showed that with the data from only six passes, the estimation error of the current pass offset is less than 14 μs and the 2 days prediction error is less than 30 μs.

The TMU uses LabVIEW software to perform the hardware control, data acquisition, data processing, data display, and user interface functions. LabVIEW is a graphical programming language with a graphical user interface and lends itself readily to the requirements of real–time offset sample display and pass estimate graphing.

Correction Verification

When the scheduling software schedules a spacecraft clock correction, it reports the time and magnitude of this scheduled offset to the TMU. Since the uncertainty of a pass offset estimate is much less than the magnitude of the corrections, the TMU is able to verify that each of the scheduled corrections actually took place. For each pass, the TMU will predict what the expected clock offset should be based on the last pass offset, the clock drift and aging rates, and the scheduled clock corrections. If the two agree within a specific tolerance, the offset is "verified" and added to the history of previous offsets for use in the second order regression. Before the regression is done, however, the clock corrections must be subtracted out as the regression needs uncorrected offset estimates to model the oscillator characteristics.

Control/Status and Data Transfer

The Offset Measurement subsystem is an automated subsystem driven by commands from the MCC computer network via the MCC configuration control computer over its separate GPIB bus. Satellite alerts driven software will tell the TMU to go into a data collection mode just before the pass starts, to terminate data collection when the pass is complete, and to process the pass samples after the pass. The OM also reports subsystem status, mode, and errors over this bus.

Once the OM data processing is completed, the clock characteristics must be transferred to the MCC computer network for distribution to the MSX community. To accomplish this, the TMU runs software that makes it a DECNET end–node on the MCC Ethernet network. This makes it possible for the MCC computer network to write the needed propagation delay and scheduled correction data on the TMU hard disk before each pass and to read the clock characteristics results from the TMU hard disk after each pass. A handshake file on the TMU hard disk lets the network know the current progress of the TMU collection and processing.

Test and Calibration

The spacecraft simulation capability is an important aspect of the OM subsystem for testing and calibration. This simulation capability consists of a telemetry simulator driven by a frequency synthesizer. The simulator puts out a 16 kbps housekeeping stream containing the normal UTC(MSX) clock words that can be synchronized to UTC(MCC) plus a known bias. The synthesizer is driven by the same MCC 5 MHz reference that drives UTC(MCC). Thus, if the synthesizer is set to the nominal oscillator frequency, the simulator offset should not vary over time with respect to UTC(MCC). Once this synchronization bias has been measured, the simulated data stream can be fed into the normal telemetry path and the downlink delays can be calibrated. This is done before every cluster of passes over APL to verify both that the delay has not changed (indicating a possible problem) and that the OM subsystem is operational. The simulator is also used to calibrate the duty cycle of the 1 PPS by changing the Delta measurement trigger edge and calculating the difference in measured offset.

For additional testing capabilities, the TMU can change the synthesizer frequency. A programmed frequency offset will simulate a clock drift, and varying this offset linearly over time will simulate clock aging. The synthesizer is of the direct digital synthesis variety, so it is possible to make these frequency changes without causing phase discontinuities in the output. It also has 1 μHz resolution, making it possible to simulate range error effects for more accurate pass simulations.

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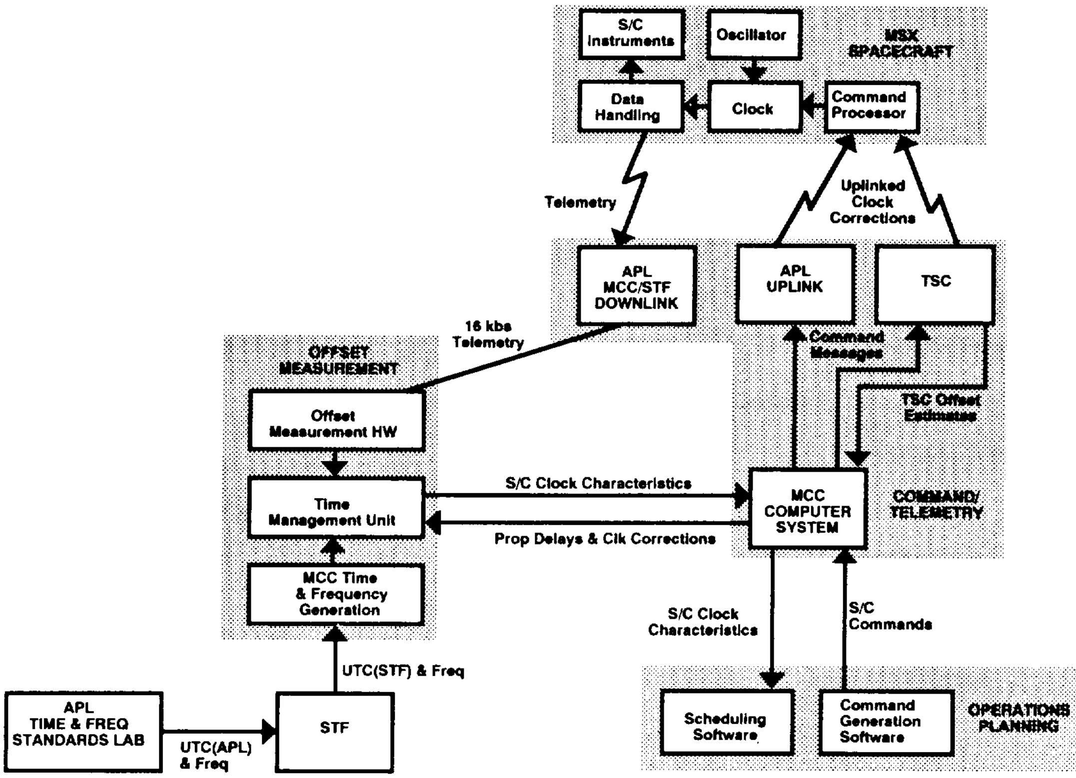


Figure 1 Time Maintenance Overview

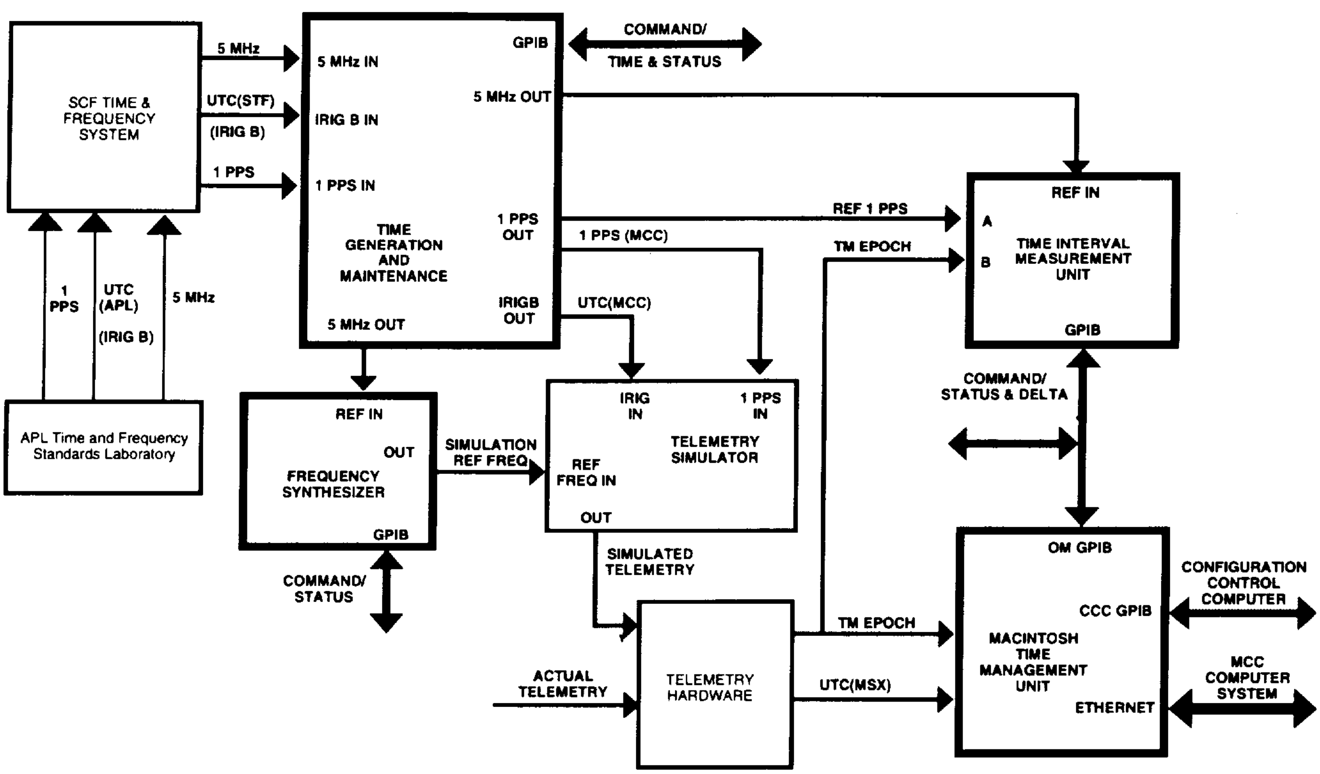


Figure 2 Offset Measurement Subsystem

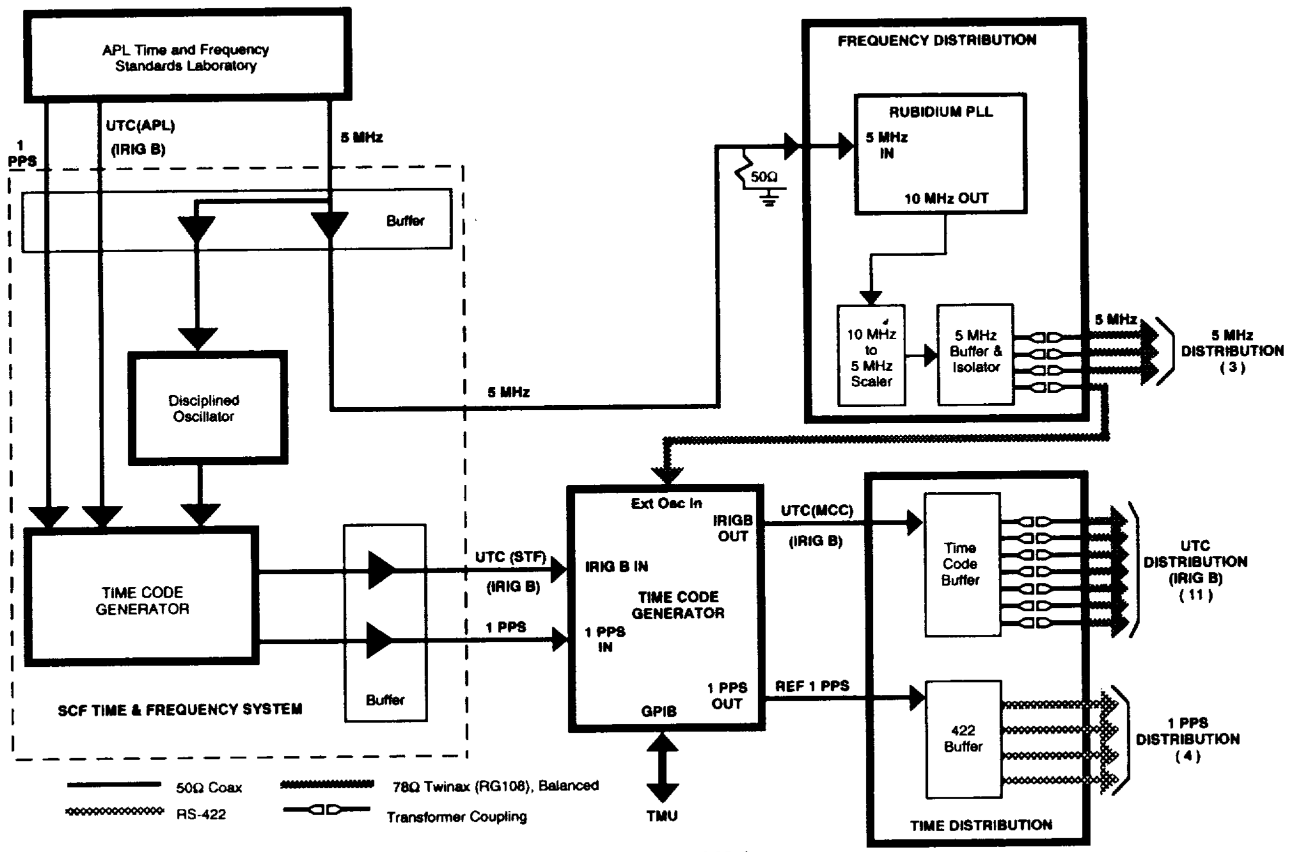


Figure 3 MCC Time Generation and Maintenance

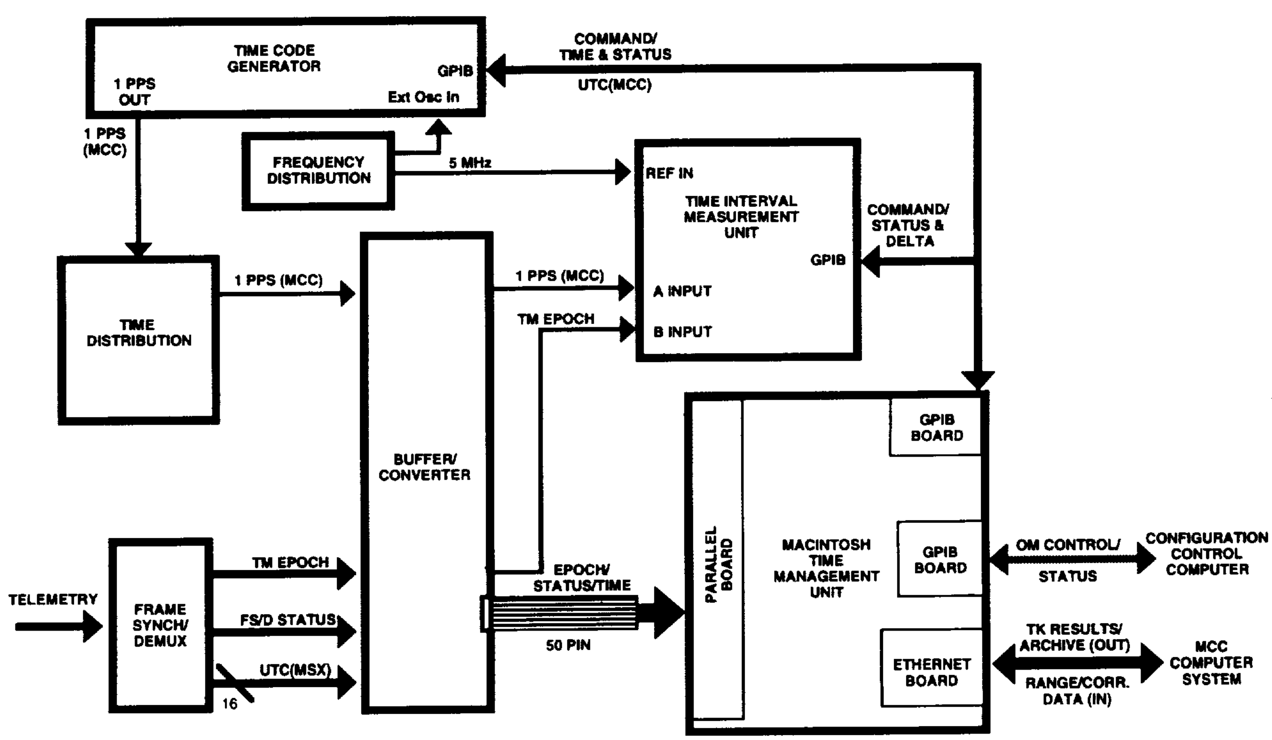
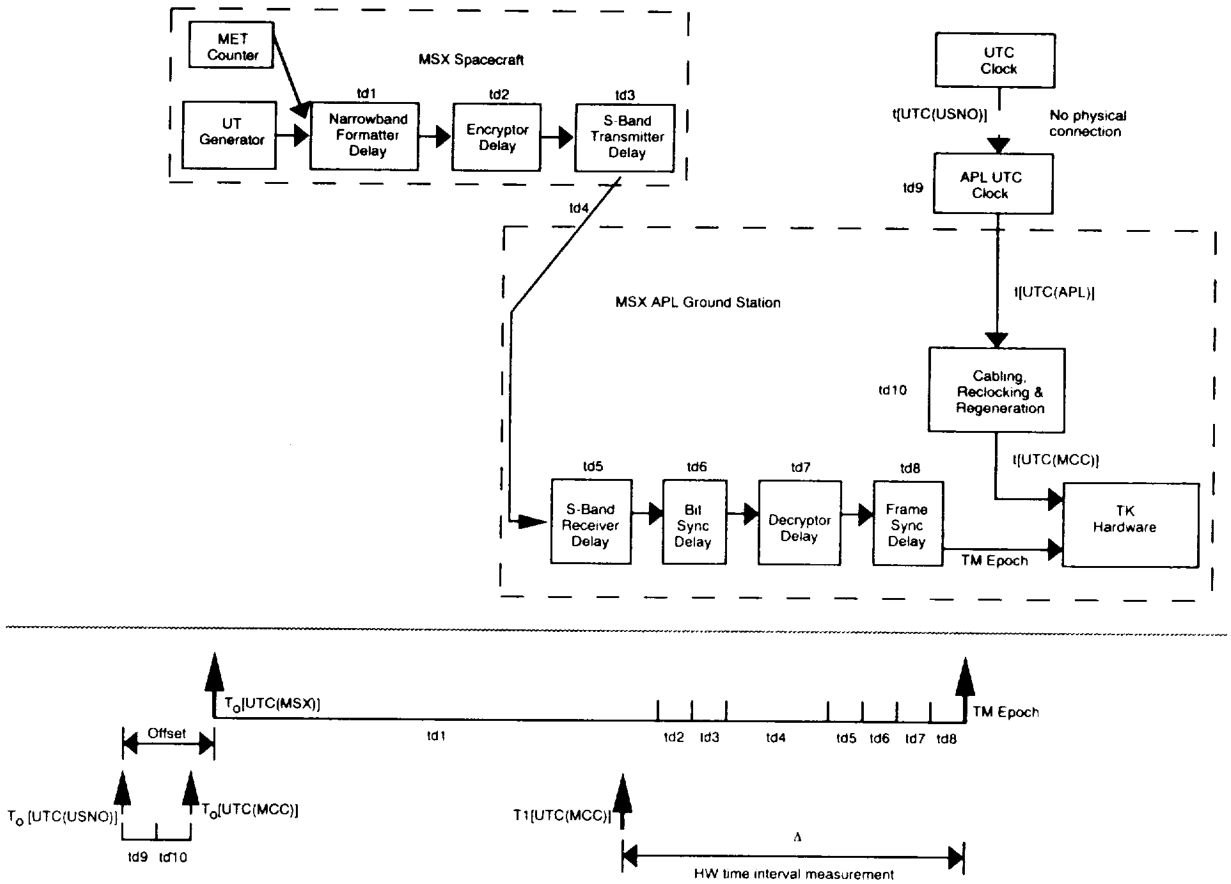


Figure 4 Delta Measurement Hardware



Simplified Offset Equation: Offset = T1(MCC UTC) + Δ - [T0(MSX UT) + Σtd(1-8)] + td(9,10)

Figure 5 Offset Measurement Biases

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MEASUREMENT OF THE FREQUENCY STABILITY OF RESPONDERS IN AIRCRAFT

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ABSTRACT

Measurement on an aircraft orbit, such as a satellite launching orbit, is made by the responder in the aircraft along with several remote track stations on the ground. During the launching, the system is required to have precise time synchronization and frequency accuracy. At the same time, accurate measurement of aircraft velocity requires high frequency stability of the system. However, atomic frequency standards in the ground stations supply time and frequency reference standard with excellent long term and short term frequency stability for the above-mentioned goals. The stability of responder is also an important factor affecting the performance of the system and there are more requirements for the corresponding time / frequency measurements. In the system, the responders do not use continuous wave (CW) but narrow pulse modulated wave, consequently, the characterization theory of their stability is more complicated and the measurement technique is more difficult for pulsed wave than that for CW.

In this paper, a systematic characterization theory of the frequency stability for pulsed wave is demonstrated and the measuring methods are discussed. The paper describes the measurement systems, which have been set up in Beijing Institute of Radio Metrology & Measurement (BIRMM) and can be used to test the frequency stability of pulse coherent responders in time domain and frequency domain with high sensitivity and accuracy. Using these measurement systems, we have made successful measurements for the responders, with which the satellite launching orbits have been precisely obtained and tracked.

INTRODUCTION

In the 1960s D.W. Allan, J. A. Barnes, etal proposed to adopt finite sampling variance to characterize the short-term frequency stability of continuous wave signal, and they also deduced the mathematical relation between the finite sampling variance and the phase noise power spectral density, thus, establishing a theoretical system of taking Allan variance (finite sampling variance of continuous double sampling) as the time domain characterization of the short-term frequency stability and phase noise as the frequency domain characterization (1).

In the 1970s the measurement technique of Allan variance and phase noise was further studied, and many companies turned out their relevant measuring equipment. On this basis, many countries established their respective metric standards for short-term frequency stability one after another. Since then, this complete set of characterization theory and measurement technique has been widely approved and used (2), (3), (4).

So far, the above-mentioned characterization theory and measurement technique have found a wide application for various continuous wave and quasi-continuous wave signals. However, the unstability of the pulse-modulated wave, eg. an RF pulse of the radar transmitter, is a major factor affecting the system performance after all. The RF pulse being usually a pulse-modulated wave with a small duty ratio, the charaterization theory of continuous wave signals is not applicable now and the technical difficulty of the measurement has also increased. Therefore, it is a practical problem for us how to characterize the short-term frequency stability of radio-frequency pulse theoretically and how to measure it.

Some systems have been employed to measure the frequency stability of the pulse-modulated wave in time domain and frequency domain, as reported many times (5), (6), (7), (8). M. I. Sholnik, J. M. Milan, etal also presented the relation between the pulse-to-pulse frequency fluctuation of radio-frequency pulse and the radar improvement factor (9), (5). The commercial measuring equipment for frequency stability such as HP3048 phase noise measurement system being employed, however, can only be used in the measurement of continuous waves or quasi-continuous waves with the duty ratio greater than 10%. In fact, most of measurement systems for short-term frequency stability of the RF pulse are developed by the users themselves.

As a time / frequency metrological and measurement service, BIRMM has been studying the characterization theory and measurement technique for short-term frequency stability of RF pulse for more than ten years(10); and it has succeeded in developing many kinds of measurement systems for this function, which have been used in the measurement of various radar transmitters and pulse power amplifiers. Some scientists from BIRMM published their papers in this aspect in the PTTI meeting (11), (12).

The frequency stability measurement of pulse coherent responders is another successful example. The pulse coherent responder in aircraft is an important component of the trajectory measurement system, whose frequency stability determines the measuring accuracy of aircraft orbits. As it operates in a narrow RF pulse condition with the pulsewidth of about $1\mu s$, no instrument is available to measure its frequency stability. To settle this problem, BIRMM has established time-domain and frequency-domain systems: (1) to characterize the short-term frequency stability in time domain by Allan variance of single carrier spectrum and measure it by the fine spectrum extracting method; (2) to characterize the short-term frequency stability in frequency domain by near-carrier phase noise and measure it by the microwave phase bridge. These two systems have the advantages of high sensitivity and low noise. The pulse coherent responders tested by them have been used in the orbit measurement for satellite launching successfully.

REQUIREMENTS FOR THE FREQUENCY STABILITY OF RESPONDERS

Measurement on an aircraft orbit, such as a satellite launching orbit, is made by the responder in the aircraft along with several trajectory measurement stations on the ground. During the launching, the system is required to have precise time synchronization and frequency accuracy. Meanwhile, accurate measurement of aircraft velocity requires high frequency stability of the system. To meet the above-mentioned requirements, atomic frequency standards are employed in the ground measurement station to supply time and frequency references. The stability of the responder is also an important factor affecting the performance of the system. The pulse coherent responder is mounted in aircraft and operates in a pulse-modulated state. After receiving a pulse-modulated microwave signal from the ground station, the responder modulates various motion parameters of aircraft onto this signal, which is then sent back to the ground station through Doppler shift for data processing, thus, realizing the measurement of aircraft orbit.

The carrier frequency of the responder input signal is correlated to that of its output signal. Therefore, if the frequency of the responder proper is not stable or there occurs additive frequency / amplitude-modulated noise, the whole trajectory measurement system will not be able to extract Doppler shift properly or measure it accurately, thus, failing in the accurate measurement of aircraft orbit and flight velocity.

There is a typical pulse coherent responder which operates in a microwave frequency range with pulse width less than 1μs. In order to ensure the time synchronization and frequency accuracy during the launching, it is designed to have excellent long-term frequency stability; besides, it also has good short-term frequency stability to meet the requirements of velocity measurement for the system. The short-term frequency stability is embodied in frequency domain and time domain. The system requires that the frequency stability of the responder $\sigma y^2(\tau)(\dot{\tau} \approx 0.1s)$ should be superior to 1×10^{-10}, while the background noise of the phase noise measurement system should be at least 20dB lower than the corresponding phase noise of the tested responder.

CHARACTERIZATION OF THE SHORT-TERM FREQUENCY STABILITY OF PULSE-MODULATED WAVE

1 Time domain characterization

In mathematics, variance characterization is adopted in time domain and power spectral density characterization in frequency domain to describe a random process. In fact, however, we usually use finite sampling variance to estimate the above variance, which is described as below:

$$<\sigma^2(N,T,\tau)> = <\frac{1}{N-1}\sum_{n=1}^{N}(\overline{Y}_n - \frac{1}{N}\sum_{n=1}^{N}\overline{Y}_n)^2> \quad (1)$$

where

T: sampling repetition period,

τ: sampling time interval,

$\overline{Y}_n$: n periods, sampling average value of relative frequency fluctuation within τ.

Now, we will discuss special cases of the following two finite sampling variances.

(1)Continuous double sampling: The finite sampling variance $<\sigma^2(N,T,\tau)>$ obtained in case of $T=\tau$, $N=2$ is well-known Allan variance $\sigma_y^2(\tau)$. It is generally acknowledged as the time domain characterization method of frequency stability thanks to its advantages of easy measurement and near-carrier convergence. It can be proved that

$$\sigma_y^2(\tau)=\frac{1}{2}<(\overline{Y}_1-\overline{Y}_2)^2> \qquad (2-a)$$

(2)Noncoherent sampling ($T/\tau>>1$). Now, $<\sigma^2(N,T,\tau)>$ is an unbiased estimation of true variance and is also irrelevant to N. By selecting $N=2$, we take the finite sampling variance $<\sigma^2(2, T, \tau)>$ ($T>>\tau$) obtained as the time domain characterization of short-term frequency stability of pulse-modulated wave, named as Allan variance $\sigma^2(T, \tau)$. It can be seen that the pulse-to-pulse variance is an unbiased estimation of true variance as long as the sampling group numbers are many enough in doing this. It is characterized by easy measurement and near-carrier convergence, the same as Allan variance; therefore, formula (2) is still applicable here:

$$\sigma^2(T,\tau)=\frac{1}{2}<(\overline{Y}_1-\overline{Y}_2)^2> \qquad (2-b)$$

It is more important that the pulse-to-pulse variance is identical to the actual condition of pulse-to-pulse fluctuating characteristics required by radar transmitted pulse, so it is more suitable to characterize radar transmitted signal.

2 Frequency domain characterization

It has a long history to be engaged in characterization of frequency domain of a random process by power spectral density (13); and it is also generally acknowledged that power spectral density of phase noise can be taken as the frequency domain of short-term frequency stability. However, there are some sharp differences between the phase noise of RF pulse and that of continuous wave, which are described as follows.

(1) For an RF pulse, only the frequency-modulated spectrum which offsets from the carrier frequency by $1/2T$ and where Doppler frequency is applied is taken into consideration. Moreover, according to the sampling theorem, only the above-mentioned spectrum can be got for pulse-to-pulse sampling data. For this reason, we call the RF pulse as near-carrier phase noise and use it to characterize the frequency domain of the

short-term frequency stability of pulse-modulated wave.

(2) After a continuous wave signal is processed through pulse modulation, a superposition effect is produced in its power spectrum. Now the power spectrum offsetting from the carrier frequency by 1 / 2T can be considered as the superposition of a series of sideband spectra, which can be written as:

$$S_P(f)=\frac{1}{2}\sum_{n=-\infty}^{\infty} S_C(f+\frac{n}{T}) \tag{3}$$

where

$S_C(f)$: power spectrum of continuous wave,

$S_P(f)$: power spectrum of modulated and superposed pulse.

3 Relations between time domain and frequency domain

It can be proved that there occur some relations between true variance and power spectral density of generalized stationary random process, which are stated as follows:

$$\sigma^2(\tau)=(\frac{1}{f_0})^2\int_0^\infty S_\varphi(f)(\frac{Sin\pi\tau f}{\pi\tau})^2 df \tag{4-a}$$

or

$$\sigma^2(\tau)=\int_0^\infty S_y(f)(\frac{Sin\pi\tau f}{\pi\tau f})^2 df \tag{4-b}$$

The equivalent signal of finite sampling variance can be thought to pass a linear system; thereby, we can get the relation between finite sampling variance and power spectrum as follows:

$$<\sigma^2(N,T,\tau)> = \int_0^\infty S_y|G_0(f)|^2|G_N(f)|^2 df \tag{5}$$

Where

$$G_0(f)=(\frac{Sin\pi\tau f}{\pi\tau f})^2, \quad G_N=\frac{N}{N-1}[1-(\frac{SinN\pi\tau f}{NSin\pi Tf})^2]$$

As mentioned above, the finite sampling variance means Allan variance in case of N = 2, T = τ. The expression is:

$$\sigma_y^2(\tau)=2\int_0^\infty S_y(f)\frac{Sin^4(\pi\tau f)}{(\pi\tau f)^2} df \tag{6}$$

Now, we make some analyses on the pulse-modulated wave. For a random process of a discrete signal, the Wiener-Khinchin theorem is also applicable here, whose expressions are:

$$S_m(\omega) = \sum_{m=-\infty}^{\infty} R(m) e^{-jmT\omega} \qquad (7-a)$$

$$R(m) = \frac{T}{2\pi} \int_{-\frac{\pi}{T}}^{\frac{\pi}{T}} S_m(\omega) e^{jmT\omega} d\omega \qquad (7-b)$$

It can be seen that samplings are irrelated to each other when $T >> \tau$, that means, $<Y_N> = 0$. Then the true variance is:

$$\sigma^2 <\overline{Y}> = <[Y_N - <Y_N>]^2> = <Y_N^2> = R(0) \qquad (8)$$

Substituting this formula into the Wiener–Khinchin theorem, we can obtain:

$$\sigma^2(\overline{Y}) = R(0) = \frac{T}{2\pi} \int_{-\frac{\pi}{T}}^{\frac{\pi}{T}} S_m(\omega) d\omega \qquad (9)$$

Based on what it mentioned above, we can draw a conclusion that the linear system through which the pulse–to–pulse finite sampling variance passes also possesses the transfer function described in formula (5), which is expressed as below:

$$\sigma^2(N,T,\tau) = (\tfrac{T}{2\pi}) \int_{-\frac{\pi}{T}}^{\frac{\pi}{T}} S_m(\omega) G_N d\omega \qquad (10)$$

Let $N = 2$, then we can get the relation between pulse–to–pulse variance and pulse–to–pulse power spectrum as follows:

$$\sigma^2(T,\tau) = 4T \int_0^{\frac{1}{2T}} S_P(f) Sin^2(\pi T f) df \qquad (11-a)$$

or

$$\sigma^2(T,\tau) = 4T \int_0^{\frac{1}{2T}} (\frac{f}{f_0})^2 S_\varphi(f) Sin^2(\pi T f) df \qquad (11-b)$$

To characterize the frequency stability of RF pulse by pulse–to–pulse variance, formula (11) can be employed to change the relation between the variance and the power spectral density. The frequency stability of the power coherent responder discussed in this paper is characterized by Allan variance of carrier frequency single CW spectrum produced through fine spectrum extraction. Therefore, the conversion relation provided in formula (6) is also applicable here.

MEASUREMENT TECHNIQUE AND ESTABLISHMENT OF THE MEASUREMENT SYSTEMS

In principle, the measurement technique for CW short–term frequency stability is still applicable in the measurement of the frequency stability of pulse–modulated wave.

However, as the duty ratio of the RF pulse is very small, the available effective energy is very low. The measurement system usually requires a much higher sensitivity than that of continuous wave and its collecting speed is much faster than that of the latter; moreover, synchronous collection is required to avoid missing any data. According to the requirements for the frequency stability of responder and the above-mentioned characterization theory, we have set up time domain and frequency domain measurement systems.

1 Time domain measurement system

In order to meet the requirements for Doppler velocity measurement accuracy, it is necessary to measure the short-term frequency stability of the master spectrum obtained after RF pulse is filtered and smoothed. Now the signal spectrum appears signal master spectrum and is in the nature of continuous wave, that means, to extract the master spectrum from the RF pulse. The above-mentioned method is the so-called fine spectrum extracting method. The time domain measurement system used to measure the frequency stability of pulse coherent responder is just designed on the basis of this method. For its block diagram, see Fig.1. As shown in the Figure, through the high-stability crystal oscillator the frequencies of the two frequency synthesizers become interrelated. Having passed through the responder to be tested, the signal of one channel is changed into a low-intermediate frequency signal after being processed once or twice by the frequency conversion unit. Then it is used to extract master spectrum through the narrow-band crystal filter and measure Allan variance $\sigma_y(\tau)$ of the master spectrum.

2 Frequency domain measurement system

Adopting microwave phase bridge is the optimum method to measure additive phase noise of the dual-terminal component. It is also available to the measurement of additive phase noise and pulse-to-pulse phase fluctuation of the pulse coherent responder. For the block diagram of the frequency domain measurement system see Fig.2. Its expression of phase-demodulating principle is:

$$V(f) = K_{\varphi}[2\pi\tau_0 f\Phi_R(f) + \Phi_A(f)] \tag{12}$$

where

V(f): video output of the phase discriminator,

$\Phi_R(f)$: phase fluctuation of the source,

$\Phi_A(f)$: additive phase fluctuation of the responder,

K_Φ: sensitivity of the phase discriminator,

τ_0: dual-channel delay difference.

It can be seen from formula (12) that when the dual-channel electrical length remains the same, the system background noise produced owing to the unstability of the signal source is very small and is only determined by the thermal noise of the phase discriminator. Therefore, the sensitivity of the system can be designed to be very high for the sake of satisfactory measurement of the responder.

SYSTEM CALIBRATION

There are two calibration methods involved for the frequency domain measurement system of the short-term frequency stability of radio-frequency pulse. One is to determine the transfer function of the system, the other is to produce a known pulse-to-pulse frequency (phase)-modulated signal (e.g. discrete spectrum), by which the measurement random spectrum can be calibrated.

1 Determination of transfer function: The typical method is to determine the phase demodulating sensitivity. Generally, a balanced phase discriminator works in an unsaturated region; and its phase demodulation output voltage is related to dual-channel phase difference sinusoidally as shown below:

$$V = V_0 Sin\Phi \qquad (13)$$

when $\Phi << 1$,

$$V = V_0\Phi \qquad K_\varphi = \frac{V}{\Phi} = V_0(V / rad) \qquad (14)$$

Therefore, we can measure out peak voltage $V_0$of the output video-frequency pulse by adjusting the variable phase shifter, then the phase demodulating sensitivity $K_\varphi$near the quadrature point can be obtained.

2 There are many methods employed to produce a known frequency (phase)-modulated signal. One of them is to connect an electrically tunable phase shifter with the circuit, thus, producing a known phase-modulated signal. The electrically tunable phase shifter can be composed of varactor diodes (14). Another method is to produce a known

pulse–to–pulse variance with a frequency–halving circuit. For its block diagram see Fig.3. When positive and negative peak values of the video frequency pulse are corresponding with those of the frequency–modulated signal through adjusting delay line, the pulse–to–pulse variance of the output signal is the peak frequency offset.

3 It can be seen through calibration that the background of the time–domain measurement system is $\sigma_y(100\text{ms}) \approx 1 \times 10^{-12}$, better than that ($1 \times 10^{-10}$) of the responder to be tested by two orders of magnitude; while the background noise $S_\Phi(20\text{Hz})$ of the frequency domain measurement system is −80 dBc / Hz or so, about 30dB lower than the additive phase noise of the responder.

ACKNOWLEDGEMENTS

I wish to express my thanks to Mrs. Guiliang Wu and my students, Mr. Zhongying Liu and Mr. Yi Ma who have given me great help in the demonstration of characterization theory raised in this paper and in the establishment of the measurement system.

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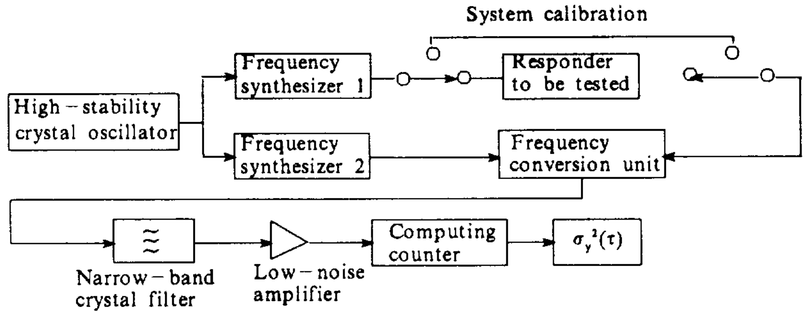

Fig.1 Block diagram of the time domain measurement system for pulse coherent responder

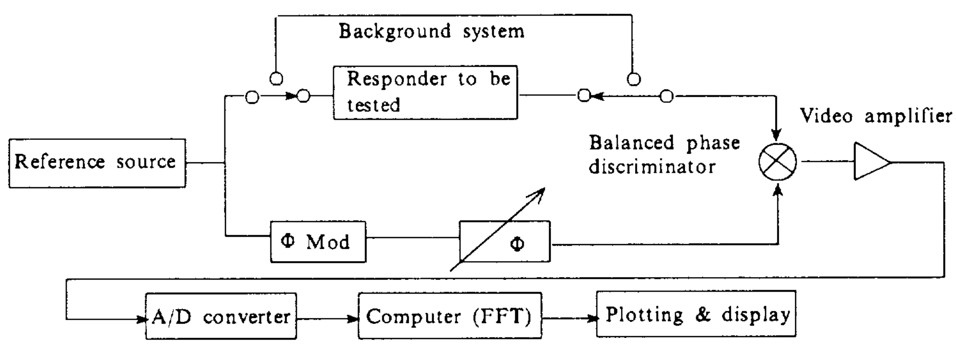

Fig.2 Block diagram of the frequency domain measurement system for ICW responder

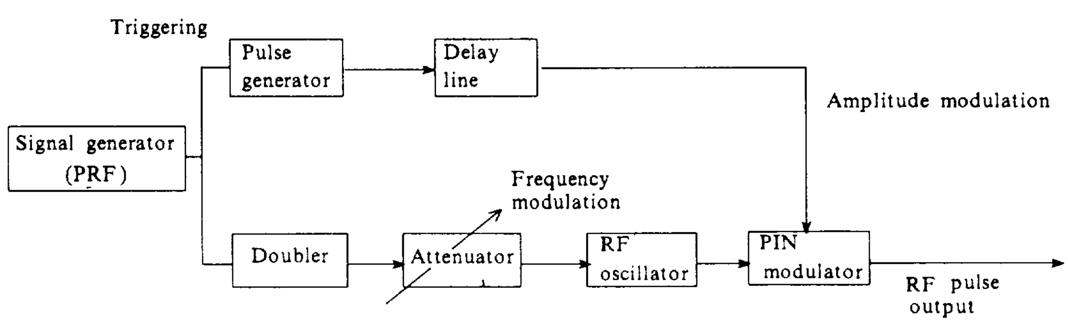

Fig.3 Calibration circuit of pulse-to-pulse variance

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GROUND CONTROL SYSTEM FOR THE MIDCOURSE SPACE EXPERIMENT UTC CLOCK

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Abstract

One goal of the Midcourse Space Experiment (MSX) spacecraft Operations Planning Center is to maintain the onboard satellite UTC clock [UTC(MSX)] to within 1 millisecond of UTC(APL) (the program requirement is 10 msec). The UTC(MSX) clock employs as its timebase an APL built 5 MHz quartz oscillator, which is expected to have frequency instabilities (aging rate + drift rate + frequency offset) that will cause the clock to drift approximately two to ten milliseconds per day. The UTC(MSX) clock can be advanced or retarded by the APL MSX satellite ground control center by integer multiples of 1 millisecond.

The MSX Operations Planning Center is developing software which records the drift of UTC(MSX) relative to UTC(APL) and which schedules the time of day and magnitude of UTC(MSX) clock updates up to 48 hours in advance. Because of the manner in which MSX spacecraft activities are scheduled, MSX clock updates are planned 24 to 48 hours in advance, and stored in the satellite's computer controller for later execution.

Data will be collected on the drift of UTC(MSX) relative to UTC(APL) over a three to five day period. Approximately 6 times per day the time offset between UTC(MSX) and UTC(APL) will be measured by APL with a resolution of less than 100 microseconds. From this data a second order analytical model of the clock's drift will be derived. This model will be used to extrapolate the offset of the MSX clock in time from the present to 48 hours in the future. MSX clock updates will be placed on the spacecraft's daily schedule whenever the predicted clock offset exceeds 0.5 milliseconds.

The paper includes a discussion of how the empirical model of the MSX clock is derived from satellite telemetry data, as well as the algorithm used to schedule MSX clock updates based on the model.

INTRODUCTION

The Midcourse Space Experiment (MSX) spacecraft will have an onboard clock denoted UTC(MSX) which will be used to timetag all data recorded by the satellite. The timebase for UTC(MSX) is an APL built precision 5 MHz quartz crystal oscillator, which is expected to exhibit frequency instabilities (aging rate + drift rate + frequency offset) that will cause the clock to drift approximately two to ten milliseconds per day with respect to UTC(APL). UTC(APL) is the ground based reference clock chosen for use on the MSX program, and is defined as UTC time as maintained by APL's time and frequency laboratory. APL maintains the traceability of UTC(APL) to UTC time as defined by the United States Naval Observatory [UTC(USNO)].

In this context, clock drift is defined as the rate at which the offset between the UTC(MSX) clock and the UTC(APL) clock is changing, and clock offset is defined as the time interval (in milliseconds) between a UTC(MSX) clock 'tic' and a UTC(APL) clock 'tic'. A clock update refers to advancing or retarding the UTC(MSX) clock in order to reduce the size of its offset from UTC(APL). A Clock Update Maintenance Event is the set of spacecraft commands that perform a clock update to the MSX UTC clock.

In order to maintain the integrity of spacecraft data, the MSX Operations Planning Team (OPT) is required to maintain UTC(MSX) to within 10 milliseconds of UTC(APL). UTC(APL) is maintained by APL's atomic frequency standards, and typically exhibits a clock drift on the order of 10 nanoseconds per day. The Operations Planning Team has as its goal to exceed the 10 millisecond requirement, and maintain UTC(MSX) to within 1 millisecond of UTC(APL).

In order to keep the UTC(MSX) clock within 1 millisecond of UTC(APL), the Operations Planning Team schedules MSX Clock Update Maintenance Events, which consist of a single spacecraft command to advance or retard the onboard clock by an integer multiple of 1 millisecond. Because of the procedure used to schedule MSX spacecraft activities, the commands to execute Clock Update Maintenance Events will be uplinked to the satellite 24 to 48 hours in advance, and stored in the satellite's computer controller for later execution.

Software known as the Time Update Utility, or TUU, is used to plan all MSX clock updates. Because it has to schedule clock updates up to 48 hours in advance, the TUU has to extrapolate the MSX clock offset into the future based on past clock performance. To extrapolate the spacecraft clock's offset, the Time Update Utility derives an analytical model of the offset between UTC(MSX) and UTC(APL) as a second order polynomial of the general form:

$$\mathrm{OFFSET(t)} = \mathrm{Xt}^2 + \mathrm{Yt} + \mathrm{Z} + \mathrm{Updates(t)} \tag{1}$$

where t = time in milliseconds since the start of the time interval being modelled, Z = the initial offset of the clock at t = 0, X and Y are constants, and Updates(t) is a time dependent function accounting for all clock updates scheduled during the time interval being modelled.

By design, the Time Update Utility will be run once for each day of the MSX mission. Assume for the purposes of this discussion that Clock Update Maintenance Events for Day N of the MSX mission are being scheduled. Planning for Day N will occur early on Day N-1, giving rise to the requirement that clock maintenance events be scheduled from 24 to 48 hours in advance.

To schedule clock updates for Day N, the Time Update Utility models five days of clock performance. Days N-4 to N-2 are modelled using measurements of the offset between UTC(MSX) and UTC(APL) recorded by the MSX Mission Control Center. Days N-1 and N will be modelled using an extrapolation derived by the TUU from the measured data.

OPERATION OF THE GROUND CONTROL SYSTEM FOR THE MIDCOURSE SPACE EXPERIMENT UTC CLOCK

The UTC(MSX) clock essentially consists of a counter which continuously counts the number 5 MHz cycles output by the oscillator in units of milliseconds. The UTC(MSX) clock drift is entirely due to the frequency instability in the MSX oscillator time base accumulating over time; the digital counting circuit does not contribute to the clock drift. The MSX spacecraft clock will be maintained to its desired accuracy by executing a series of Clock Update Maintenance Events which correct for the measured offset between UTC(MSX) and UTC(APL).

A Clock Update Maintenance Event consists of sending a command to the spacecraft that advances or retards the digital clock counter by an integer number of milliseconds. This means that clock updates have no effect on the 5 MHz oscillator and therefore no effect on clock drift. MSX clock drift and clock updates are considered to be two independent phenomena that, when added together, define the UTC(MSX) clock's total offset from UTC(APL). This allows the TUU to separate the extrapolation of the total clock offset into a clock drift model and a separate clock update model. The MSX oscillator driven drift is modelled using an analytical expression derived from measured clock offset data. Clock Update Maintenance Events will be modelled mathematically as a series of step functions, with a step in the UTC(MSX) clock offset occurring at the time the clock update was executed.

The MSX spacecraft orbit is such that it will pass over APL five to six times per day. During each pass of the spacecraft over APL, the Mission Control Center will measure the offset of UTC(MSX) from UTC(APL) with a resolution of less than 100 microseconds. At the beginning of mission Day N-1, a data file containing measurements of the offset between UTC(MSX) and UTC(APL) versus time from the start of Day N-4 to the end of Day N-2 will be made available to the Time Update Utility by the MSX Mission Control Center; this datafile will also contain a list of all Clock Update Maintenance Events that occurred during the same time period.

When the measured MSX clock offset is plotted, the data will appear similar to the curve labelled "Typical Measured UTC(MSX) Clock Offset" in Figure 1. The discontinuities in the plot are due to clock updates executed during Days N-4 to N-2. The slopes of the continuous portions of the Typical Measured UTC(MSX) Clock Offset curve are due solely to the drift of the UTC(MSX) clock relative to UTC(APL). In order to model the UTC(MSX) clock drift, the Time Update Utility uses the list of Clock Update Maintenance Events that occurred on Days N-4 to N-2 to subtract out the discontinuities from the Typical Measured UTC(MSX) Clock Offset curve, resulting in a continuous curve similar to that labelled "Clock Offset - Clock Updates" in Figure 1.

The TUU performs a second order polynomial fit to the continuous 'Clock Offset - Clock Updates' curve resulting in an analytical expression describing the MSX clock drift of the form:

$$At^2 + Bt + C(N-4) \tag{2}$$

where t = time in seconds since the start of Day N-4, C(N-4) = initial measured clock offset at the start of Day N-4, and A and B are constants. The value of C(N-4) will be obtained from the measured data received from the Mission Control Center. The model will use the values of A and B derived in this step to extrapolate the clock drift through the end of Day N. During Day N the clock offset model will be of the form:

$$\mathrm{OFFSET(t)} = \mathrm{At}^2 + \mathrm{Bt} + \mathrm{C(N-1)} + \mathrm{Updates(t)} \tag{3}$$

where OFFSET(t) = the predicted UTC(MSX) clock offset at time t, A, B and t are as defined in equation 2, Updates(t) = the sum of all clock updates scheduled to occur on Day N prior to time t, and C(N-1) is a constant to be determined.

C(N-1) is a constant which accounts for both the initial offset of the MSX clock at time t=0, and for all of the Clock Update Maintenance Events occurring prior to the start of Day N. The initial clock offset, C(N-4), is read from the datafile received from the Mission Control Center, as are the magnitudes of all the clock updates executed by the spacecraft during Days N-4 through N-2. At the time the Time Update Utility software will be run for mission Day N, Clock Update Maintenance Events will have already been placed in the spacecraft's Day N-1 daily schedule. (recall that the TUU software is executed for mission Day N at the beginning of Day N-1) The Time Update Utility reads the magnitudes of all clock updates scheduled for mission Day N-1 from the MSX daily spacecraft schedule. C(N-1) is then set equal to C(N-4) + the sum of all the clock updates scheduled to occur between the start of Day N-4 and the end of Day N-1.

When summing the magnitudes of the clock updates to calculate C(N-1), an update which retards the clock will be added in as a negative offset, and one which advances the clock is added as a positive offset. This definition of C(N-1) is equivalent to lumping all the Clock Update Maintenance Events occurring prior to the start of Day N into one event occurring at the end of Day N-1 (or the beginning of Day N). Since the Utility is only interested in accurately modelling the clock performance during Day N, this procedure is reasonable.

With A, B and C(N-1) determined, the Utility extrapolates MSX clock performance and schedules Clock Update Maintenance Events for Day N using the following equation:

$$\mathrm{OFFSETn(t)} = \mathrm{At}^2 + \mathrm{Bt} + \mathrm{Cn(t)} \tag{4}$$

where OFFSETn(t) = expected clock offset during Day N, t = time since the start of Day N-4 (in milliseconds), and Cn(t) = C(N-1) + the sum of all clock updates scheduled for Day N prior to time t.

The extrapolation of UTC(MSX) performance through Day N will be a iterative process. Using equation 4, the Time Update Utility propagates the clock's offset from the start of Day N through the first point in time during Day N that the clock offset is predicted to be greater than 0.5 milliseconds. This time is called Ti, and the TUU places a Clock Update Maintenance Event at a time as close to Ti as possible on the MSX Day N daily schedule.

Because the spacecraft's schedule will have been previously filled with numerous data collection and data playback events, it is unlikely that the clock update can be scheduled exactly at Ti.

The TUU therefore scans the current Day N MSX daily schedule and identifies a time Tu, which is the time closest to Ti that an event can be scheduled. A Clock Update Maintenance Event completes in seconds, so it can be scheduled in very small gaps of open time. Once Tu is specified, the TUU substitutes Tu into equation 4, and solves for the expected clock offset at that time.

The magnitude of the clock update to be scheduled on the spacecraft has to be an integer number of milliseconds, and is determined as follows:

if the expected offset at time Tu is positive

$$\text{UPDATE(Tu)} = \text{-ROUND(OFFSETn(Tu))} \quad \text{(milliseconds)}$$

if the expected offset at time Tu is negative

$$\text{UPDATE(Tu)} = \text{ROUND(-OFFSETn(Tu))} \quad \text{(milliseconds)}$$

where the ROUND function simply rounds a decimal number to the nearest integer, UPDATE(Tu) is the number of milliseconds by which the MSX clock will be advanced or retarded, and OFFSETn(Tu) is the expected clock offset at time Tu.

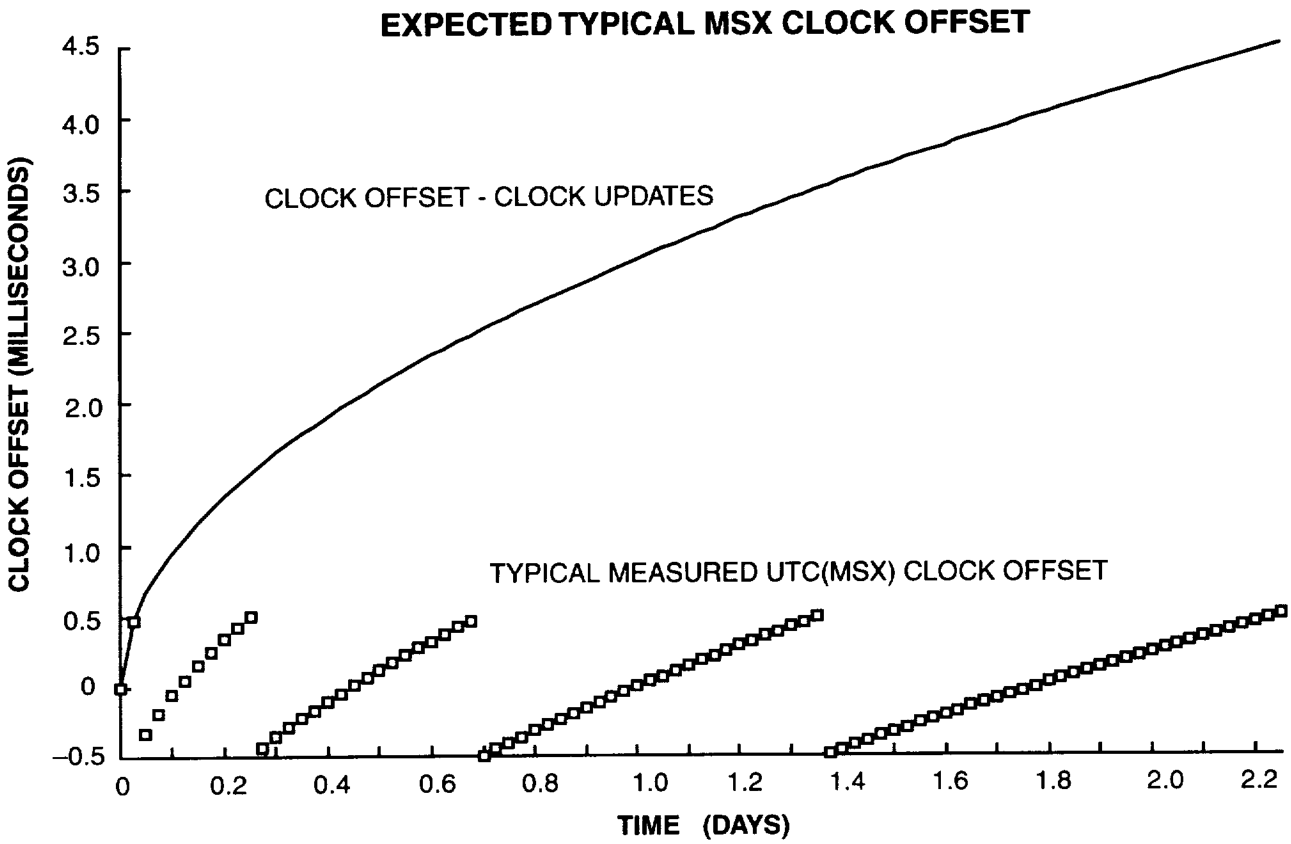

Figure 1

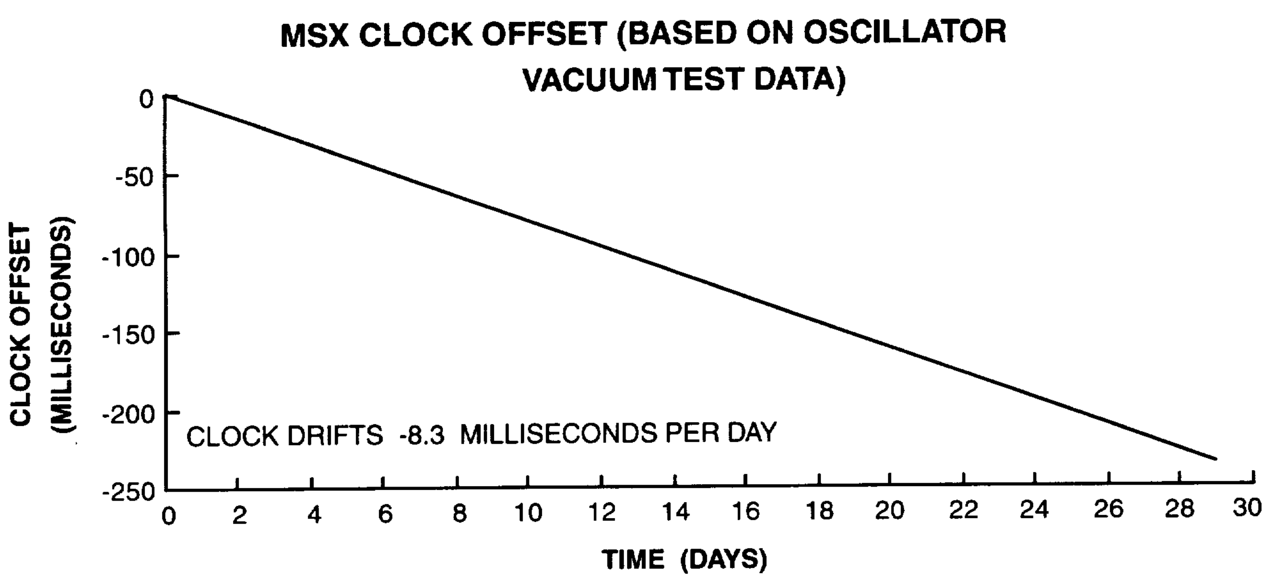

Figure 2

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TIME SYNCHRONIZED VIDEO SYSTEMS

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Abstract

The idea of synchronizing multiple video recordings to some type of 'range' time has been tried to varying degrees of success in the past. Combining this requirement with existing time code standards (SMPTE) and the new innovations in desktop multi–media however, have afforded an opportunity to increase the flexibility and usefulness of such efforts without adding costs over the traditional data recording and reduction systems. The concept described can use IRIG, GPS or a battery backed internal clock as the master time source. By converting that time source to Vertical Interval Time Code or Longitudinal Time Code, both in accordance with the SMPTE standards, the user will obtain a tape that contains machine/computer readable time code suitable for use with editing equipment that is available off–the–shelf. Accuracy on playback is then determined by the playback system chosen by the user. Accuracies of ± 2 frames are common among inexpensive systems and complete frame accuracy is more a matter of the users' budget than the capability of the recording system.

INTRODUCTION

The use of video in monitoring various types of testing has become common place. Flight testing and ground battle simulations are just two examples of situations that require multiple views of the events under evaluation. The added flexibility of being able to review each of these views in sync with each other has not been practical for most facilities in the past due to the incompatibility of existing timing systems and available video playback equipment capable of this type of high accuracy playback. With the merging of computer and video technologies in the form of multi–media, many products have been introduced that are lower in cost and more easily adapted to precise command and control. Once precise control over these lower cost playback machines was available the matter of synchronizing them to a "range" time became a simple process of finding the most usable common time format. Once that format was determined, reader cards could be used to read the time from the tape and make that time available to control software. The software can then give the user the option of searching all playbacks to any point on the tape and provide synchronized playback from that point. Using current systems up to seven video tapes may be synchronized. Future systems are expected to offer control of up to 30 playbacks with additional types of playback decks being available choices.

SYSTEM DESCRIPTION

Note: The system described used assumptions not necessarily applicable to the reader. Wherever applicable, time sources, video sources, or video recorders may be substituted without effect on the overall system assuming accuracy is not compromised. That is to say that GPS may be used instead of IRIG, for example.

A typical application uses multiple video sources, such as a HUD camera, an over the shoulder camera and a DDI or heads down display (could include FLIR). These signals may all be recorded on a Hi–8mm triple deck recorder available from TEAC. Most test vehicles receive IRIG–B for synchronization of various test data. Video tape has often had this 1 kHz IRIG–B recorded on an available audio track. This method does not lend itself to recording on single audio channel recorders or playback on stereo recorders that mix the audio tracks (most do). A method was required that would allow recording time in a machine readable fashion that would not interfere with the audio or video. Video time insertion did not meet this requirement. The use of Vertical Interval Time Code (VITC) was selected for this use since it was widely accepted as a standard method of recording time on a tape for editing purposes.

The IRIG to VITC converter was developed with the addition of a feature to allow the user to identify the vehicle and video source. The SMPTE VITC standard allows for three user defined bits to be imbedded in the data inserted on lines 16 & 18 of the video signal. These unique user bits allow the user 999 different tape codes to help identify a specific tape with a specific vehicle, perspective, and event. This combines with the Julian date and time to make each tape immediately traceable in the event mislabeling.

Once the recording of the test is complete, playback becomes the primary concern. The video tapes are played on a video playback deck that can be controlled via computer. The Sony V–deck was chosen for this application, but many interfaces exist for other types of playback decks. The video is routed through the PC card to detect the time information on the video. Although this is commonly referred to as 'stripping off' the time code, the time code information remains in the vertical interval so that any duplicates made will contain the exact same time information and remain frame accurate.

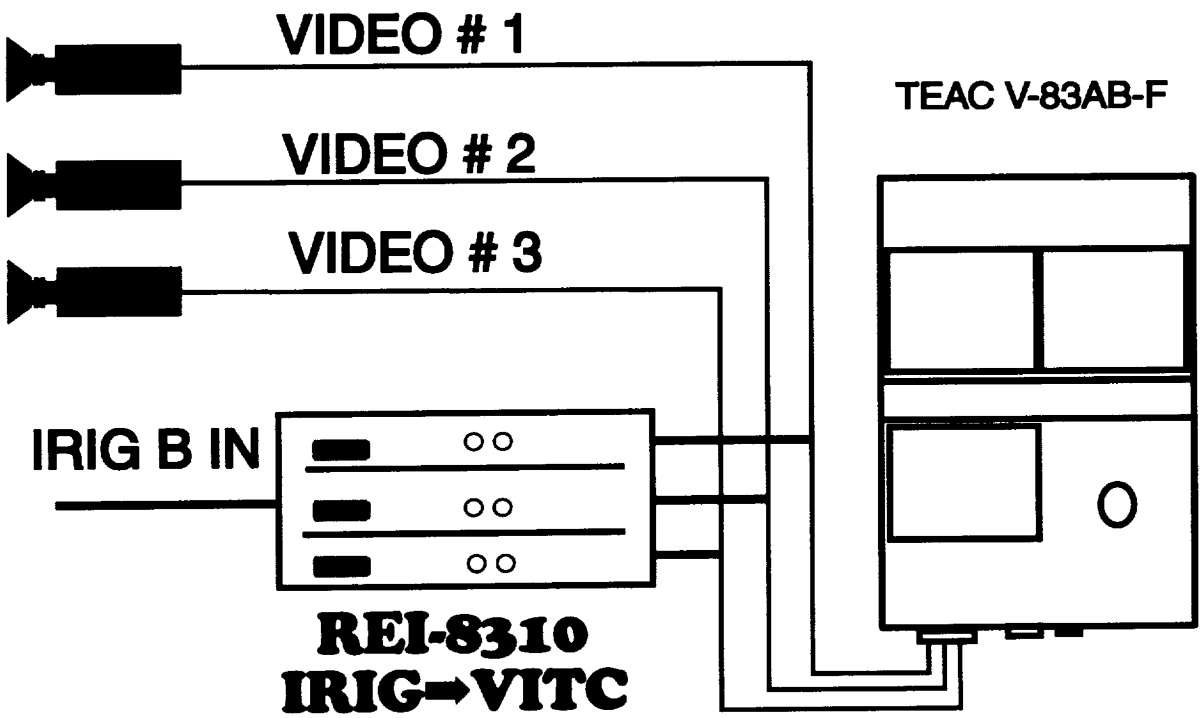
The time information is read into the PC memory by the card for use by the software. Although the software used was created for PC Based Editing, a "Sync Roll" feature has been added to the program. The tapes may be searched to any point in time on the tape, placed in pause and then commanded to play using the Multi–source command. The playback decks are commanded to play on a given clock cycle, which allows the use of a serial command interface. Most decks have identical times from pause to play, but provisions exist in the software to compensate for inconsistencies in response times between decks.

The result is a system that will play tapes at normal, slow, and fast speeds in sync (± 2 frames). Other system enhancements include a VITC to IRIG converter for returning the original IRIG information, and an IRIG display with user ID selection for displaying time and ID.

As indicated in the beginning of this section, one may substitute components for a variety of purposes. If, for example, superior editing capability is required, a high end editing playback deck with Time Base Corrector may be used. These decks are equipped with external sync and precise servo systems. The result would be a completely frame accurate system, that would add $15–20K to the price of a system. Also GPS can very easily be used as a time source without adding significant cost. The real key to the system is acquiring real time as the video is acquired and storing it in a manner that does not interfere with the video and that is machine/computer readable.

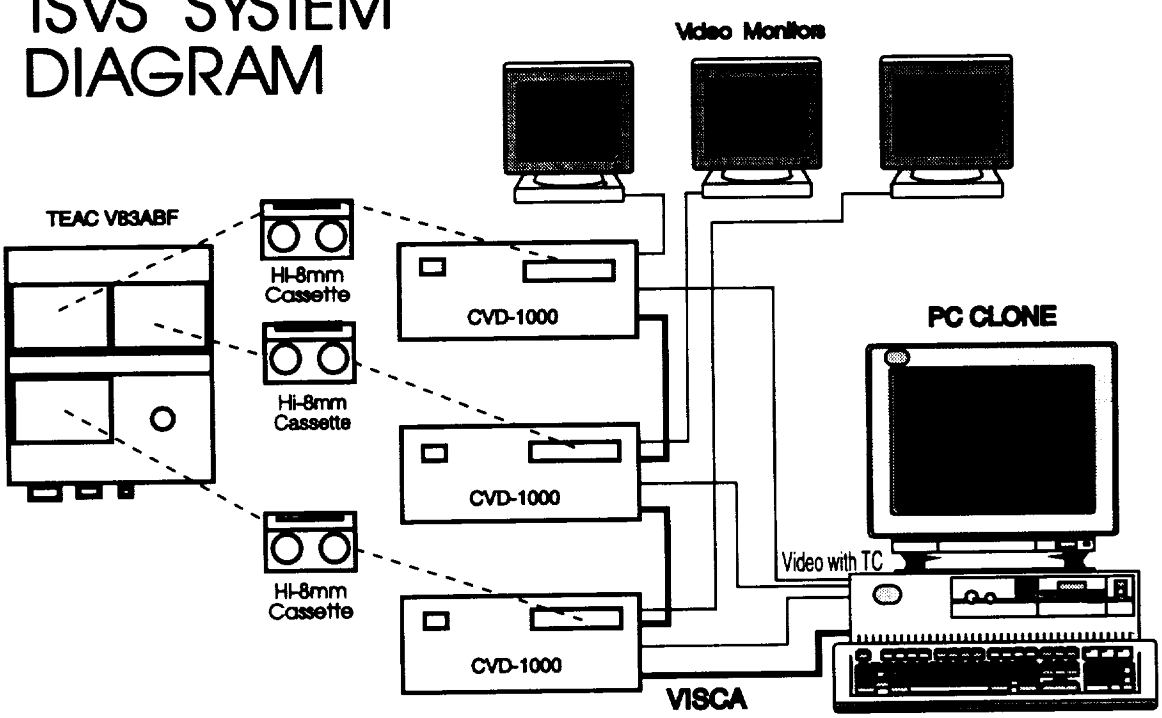
CONCLUSION

The system above may be used in a variety of environments from testing to training. Multiple video images from an entire squadron may be reviewed in sync to access any aspect of training and readiness. The cost of such systems has been reduced to a level that is normally associated with high quality playback systems with no special features. A typical playback system of three video monitors, playback decks and timing card sells for under $10K. The rugged three channel inserter is available for approximately $2.5K. Most standard PC clones (486 recommended) running Windows will accommodate the control over the playback system. This system is currently in use at Pt. Mugu, Naval Air Warfare Center.



RECORDING SYSTEM DIAGRAM

TSVS SYSTEM DIAGRAM



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Hydrogen Maser Clocks in Space for Solid–Earth Research and Time–Transfer Applications: Experiment Overview and Evaluation of Russian Miniature Sapphire Loaded Cavity

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Abstract

The Observatoire Cantonal de Neuchâtel (ON) is developing for ESTEC a compact H–maser for space use based upon a miniature sapphire loaded microwave cavity, a technique pioneered at VNIIFTRI.

Various contacts between West–European parties, headed by ESA, and the Russian parties, headed by RSA, led to the proposal for flying two H–masers on Meteor 3M, a Russian meteorology satellite in low polar orbit.

The experiment will include two masers, one provided by ON and the other by VNIIFTRI. T/F transfer and precise positioning will be performed by both a microwave link, using PRARE equipment, and an optical link, using LASSO–like equipment. The main objectives of the experiment are precise orbit determination and point positioning for geodetic/geophysical research, ultra–accurate time comparison and dissemination as well as in-orbit demonstration of operation and performance of H–masers.

Within the scope of a preliminary space H–maser development phase performed for ESTEC at ON in preparation to the joint experiment, a Russian miniature sapphire loaded microwave cavity, on loan from VNIIFTRI, was evaluated in a full-size EFOS hydrogen maser built by ON. The experimental evaluation confirmed the theoretical expectation that with a hydrogen storage volume of only 0.65 liter an atomic quality factor of 1.5×10^9 *can be obtained for a -105 dBm output power. This represents a theoretical Allan deviation of* 1.7×10^{-15} *averaged on a 1000 s time interval. From a full-size design to a compact one, therefore, the sacrifice in performance due to the reduction of the storage volume is very small.*

Introduction

Following many contacts between West–European parties, headed by ESA, and Russian parties, headed by RSA, a proposal for a H–maser experiment was conceived in the form of an opportunity flight on a Russian meteorology satellite in low polar orbit[1, 2, 3]. Meteor 3M is a Russian meteorology satellite built by NIEEM, Moscow. The satellite will be launched end of 1996 on a sun–synchronous orbit.

Altitude :	925 km
Inclination :	99.1°
Eccentricity :	0.001
Orbital Period:	103 minutes

Total mass is 3,000 kg and 200 kg are available for the opportunity experiment. The meteor spacecraft is designed for a three year lifetime.

Twenty–five spacecrafts of the Meteor 2 type have been launched so far, as well as five spacecrafts of the new Meteor 3 type. The launch vehicle utilized for the Meteor satellites is the Tsyclon launcher and the launch base is Plesetsk, north of Moscow[4]. Meteor 3M is the first of an enhanced version of Meteor 3, optimized to serve as a multipurpose space platform.

The H–maser joint experiment is meant as a scientific experiment. With two very stable spaceborne clocks and the associated microwave and optical T/F transfer equipment it is expected to push back the limits of precise positioning for geodynamic and solid–Earth studies applications as well as for precise time transfer. Complementary scientific applications will possibly be added[3]. The joint experiment is also meant as a technological demonstration of the spaceborne Hydrogen masers and related T/F transfer equipment. It is as well an opportunity of cooperation between scientists, space agencies and industries of Russia and western Europe.

Development Status of the Spaceborne Hydrogen Masers

A compact hydrogen maser for space based on a miniature sapphire loaded microwave cavity is now in the preliminary design phase at ON. Present activities are concentrating on the breadboarding and testing of the critical maser elements. A proton irradiation test was performed on a fully operating EFOS hydrogen maser at the proton irradiation test facility of the Paul Scherrer Institute. The test, performed under ESTEC contract, has shown that on the Meteor 3M orbit the shielding effect of the microwave cavity and of the magnetic shields is sufficient for protecting the Teflon wall coating in the storage bulb from the damaging effect of space radiations. The test of the miniature sapphire loaded microwave cavity on loan from VNIIFTRI was performed under the same ESTEC contract.

VNIIFTRI, on the other hand, has already a long experience with ground based compact hydrogen masers[5, 6] including the use of bulk getter pumping for hydrogen. Its task is now to adapt the existing design for space use.

Embarked Equipment

The Meteor 3M spacecraft will carry two hydrogen masers, one provided by ESA and the other by RSA. A local T&F comparison system will measure the relative frequency stability of the

H–maser clocks and downlink the stability data to the ground.

The two way microwave link for T&F transfer between the satellite and ground will be based on the PRARE system[7, 8]. PRARE (Precise Range and Range Rate Experiment) uses pseudo–noise coded microwave signals in a fully coherent design. The two–way link uses two carrier frequencies in S and X bands and allows correction of the ionospheric delay by evaluation of the total electron content through the dispersion effect. Figure 1 illustrates the basic PRARE operating principles.

The optical link will use LASSO–like equipment[9, 10], i.e. a corner reflector and a detector on the spacecraft. The laser pulses from the ground are reflected by the corner reflector and the two–way delay is measured at the ground station. Simultaneously the arrival of the laser pulses on the detector is time-tagged with respect to the spaceborne hydrogen maser clock using an embarked counter. Figure 2 shows schematically the optical link. Figure 3 shows the main equipment necessary for the joint experiment.

Complementary equipment such as a DORIS system, a GLONASS/GPS Receiver and an ultra sensitive accelerometer may be added depending on the complementary scientific applications now under study at ESA and RSA. Figure 4 shows the embarked equipment as it could possibly be expanded.

Evaluation of The VNIIFTRI Miniature Microwave Cavity

During a previous feasibility study ON determined that the best compromise between size and performance for a spaceborne hydrogen maser is by the use of a miniature sapphire loaded microwave cavity such as the one used in the VNIIFTRI "Saphir" H–maser[11]. A collaboration between ON and VNIIFTRI was started in the perspective of using the VNIIFTRI cavity in the ON design. Dr. Gaygerov of VNIIFTRI visited ON in August 1993 with one of the sapphire loaded cavities used in the "Saphir" maser. The VNIIFTRI cavity was installed into an EFOS hydrogen maser and evaluated.

A view of the VNIIFTRI miniature cavity, as mounted in the EFOS–13 full size maser, is shown on Figure 5. For the purposes of the experiment, the molybdenum plate that normally holds the quartz storage bulb in the EFOS maser was replaced by an aluminium interface plate on which the VNIIFTRI cavity was mounted. The interface plate was placed on top of the standard EFOS aluminium cavity baseplate. A special interface tube with o–rings was used to connect the neck of the sapphire storage bulb to the internal vacuum vessel of the EFOS maser.

Table 1 shows the main geometrical parameters of the VNIIFTRI sapphire loaded cavity. Note that from the microwave point of view this cavity does not have a fully cylindrical symmetry because of the sapphire covers that close the sapphire storage bottle. A photograph of the sapphire storage bottle standing on the Titanium cavity bottom plate is shown on Figure 6.

Table 1 Geometrical Parameters of VNIFFTRI Sapphire Cavity	
sapphire I.D.	80 mm (r1 = 40 mm)
sapphire O.D.	93 mm (r2 = 46.5 mm)
sapphire length	172 mm
inner length of sapphire bulb	130 mm
thickness of sapphire covers	6 mm

Table 2 VNIIFTRI Cavity Modes in Air at Room Temperature as Measured at ON Theoretical Modes Computed by ON				
ν_0 [kHz]	approx. Q	Mode	theor. ν_0	theor. Q
1,118,394	4,500			
1,421,214	55,000	TE011	1.4212 GHz	48,000
1,517,714	17,000			
1,650,470	46,000	TE012	1.6442 GHz	66,000
1,883,549	5,600			
1,883,882	5,600			
1,940,788	43,000	TE013	1.9398 GHz	87,000

Table 2 shows the resonant modes of the cavity as measured by ON in air and at room temperature. The theoretical resonant frequencies were computed by ON by assuming a fully symmetrical symmetry, i.e. a sapphire cylinder without covers, and by adjusting the external diameter of the sapphire cylinder in order to obtain the right frequency for the TE011 mode.

Figure 7 shows the experimental determination of the TE011 mode thermal coefficient. Table 3 shows the experimental temperature coefficient of the TE011 mode as determined by a best fit of the slope on the plot of figure 7. The theoretical thermal expansion coefficient of Titanium, and sapphire as well as the temperature dependence of the dielectric constant of sapphire are also shown. It appears that the dominant factor in the temperature dependence of the TE011 mode is due to the variation of the dielectric constant of sapphire.

Table 3 Parameters of Theoretical Model for Thermal Coefficients	
Normalized thermal coefficient of TE011 mode [1/C]	3.3×10^{-5}
Thermal Expansion Titanium [1/C°]	9.4×10^{-6}
Thermal Expansion Sapphire [1/C°]	5.4×10^{-6}
Dielectric Constant Sapphire [1/C°]	6×10^{-5}

The atomic quality factor was measured for different hydrogen pressures in the dissociator. The slope

$$s = \frac{\Delta f_{\text{atomic}}\ [\text{Hz}]}{\Delta f_{\text{cavity}}\ [\text{Hz}]}$$

produced by the cavity pulling effect is proportional to the γ_2 relaxation rate. Both the relaxation rate and the slope s are proportional to the atomic linewidth and increases proportionally to the hydrogen flux because of the spin–exchange line broadening effect. The slope without the spin–exchange contribution is obtained by extrapolating to zero the slope versus hydrogen pressure curve. An extrapolation by linear regression yields

$$s(\mathrm{p} = 0) = 1.76 \times 10^{-5}$$

and therefore the atomic quality factor without spin–exchange broadening is

$$Q_{\mathrm{atomic}}(\mathrm{p} = 0) = \frac{Q_{\mathrm{cavity}}}{s(\mathrm{p} = 0)} = \frac{47,000}{1.7584 \times 10^{-5}} = 2.67 \times 10^{9}$$

The VNIIFTRI storage bulb collimator is

4.2 mm diameter
60 mm length

The time constant of the storage bulb is

$$T_b = \frac{4V}{K v_v A_h} = 1.01\ s$$

where

$V = 0.65 \times 10^{-3}\ \mathrm{m}^3$ is the volume of the storage bulb,
$K = 0.0797$
the Clausing factor in molecular flow for a 60/2 length to radius ratio,
$v_v = 2564$ m/s
the average velocity of atomic hydrogen at 45 C° and
$A_h = 12.57 \times 10^{-6}\ \mathrm{m}^2$
the cross–section of the collimator.

The escape rate is therefore

$$\gamma_b = \frac{1}{T_b}$$

and the storage bulb contribution to the quality factor

$$Q_b = \frac{\pi \nu_0}{\gamma_0} = 4.51 \times 10^{9}$$

Neglecting the contribution of magnetic relaxation, the atomic quality factor with spin–exchange broadening removed is the sum of the escape rate and wall relaxation contributions.

$$\frac{1}{Q(\mathrm{p}=0)} = \frac{1}{Q_b} + \frac{1}{Q_w}$$

Therefore the Teflon contribution to the quality factor is obtained by removing the contribution of the storage bulb escape rate.

$$Q_w = \frac{1}{\frac{1}{2.67\times 10^9} - \frac{1}{4.51\times 10^9}} = 6.51 \times 10^9$$

This figure can be converted into an equivalent EFOS Teflon quality factor by taking into account the surface to volume ratio which is

$$\frac{A_b}{V_b} = \frac{4.22 \times 10^{-2}\ \mathrm{m}^2}{6.54 \times 10^{-4}\ \mathrm{m}^3} + 65.38\ \mathrm{m}^{-1}$$

in the case of the VNIIFTRI storage bulb and

$$\frac{A_b}{V_b} = 33.14\ \mathrm{m}^{-1}$$

in the case of the EFOS storage bulb.

The VNIIFTRI Teflon used in an EFOS storage bulb would yield

$$Q_w = 6.53 \times 10^9 \times \frac{65.38}{33.14} = 1.29 \times 10^{10}$$

This value is very high and is comparable to the quality factor obtained in the most recent EFOS storage bulbs. This indicates that the VNIIFTRI Teflon coating has a relaxation probability per collision similar to the Teflon coating used at ON in recent EFOS masers.

The operating quality factor of the VNIIFTRI cavity is 1.5×10^9 for a -105 dBm output power as measured 10.8.93. Figure 8 shows the atomic quality factor versus the maser output power. The circles indicate the experimental values while the solid line represents the theoretical model. The model is the same as in [11] and the theoretical parameters are set to the values of Table 4.

Table 4 Parameters used in the Theoretical Model	
V_b	= 0.65 liter
β	= 0.1
Q_c	= 47,000
η'	= 0.45
γ_b	= 0.988 s^{-1}
γ_w	= 0.683 s^{-1}

The correspondence between experimental values and the model is very good. note that the filling factor of a dielectric loaded cavity is larger than the assumed $\eta' = 0.45$. However, the fitting of the model is not improved if the value of η' is increased.

The frequency stability of the hydrogen maser is determined by the atomic quality factor and by the signal output power.

Assuming that there is an isolator between the cavity and the receiver, the theoretical Allan deviation of the maser is given by

$$\sigma_y(t) = \sqrt{\frac{3f_c kt}{2\pi\nu_0^2 P_0}\left(\frac{\beta}{1+\beta}+\frac{F}{4}\right)\frac{1}{\tau^2}+\frac{kT}{2P_0Q^2}\left(\frac{\beta}{1+\beta}\right)\frac{1}{\tau}}$$

where f_c is the bandwidth of the measurement, P_0 the maser output power, b the coupling factor of the cavity, F the noise figure of the receiver and Q the quality factor of the atomic line. Assuming the parameters of Table 5 that correspond to the conditions of the frequency measurement of 10.8.93,

Table 5 Operating Parameters of Measurement 10.8.93	
Q	= 1.5×10^9
P_0	= 3.16×10^{-14} W (-105 dBm)
F	= 2
f_c	= 1 Hz
β	= 0.1

the fundamental limit to frequency stability is shown in Table 6 and Figure 9. Note that the theoretical limit does not include the flicker noise floor and other environmental effects.

Table 6 Theoretical Frequency Stability Limits for Operating Parameters of Table 5	
tau [s]	Allan dev.
1	1.5×10^{-13}
10	2.2×10^{-14}
100	5.5×10^{-15}
1000	1.7×10^{-15}
10,000	5.4×10^{-16}

Conclusion

The experimental evaluation confirms the theoretical expectation[11] that with a hydrogen storage volume of only 0.65 liter an atomic quality factor of 1.5×10^9 can be obtained for a -105 dBm output power. This represents a theoretical Allan deviation not very far form what is normally obtained in a full-size hydrogen maser. From a full-size design to a compact one, therefore, the sacrifice in performance due to the reduction of the storage volume is very small.

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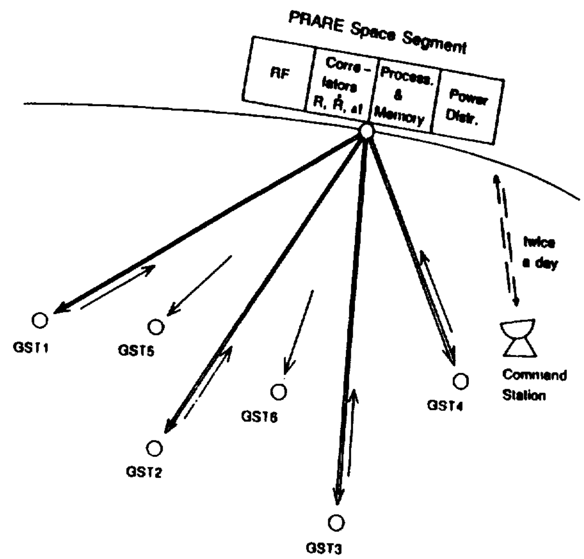
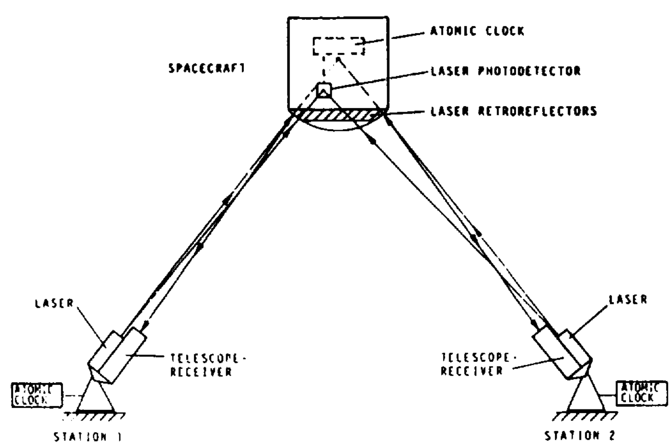


Figure 1
Basic PRARE Operation



Schematics of Time Synchronisation Experiment

Figure 2
Basic Optical Link Operation

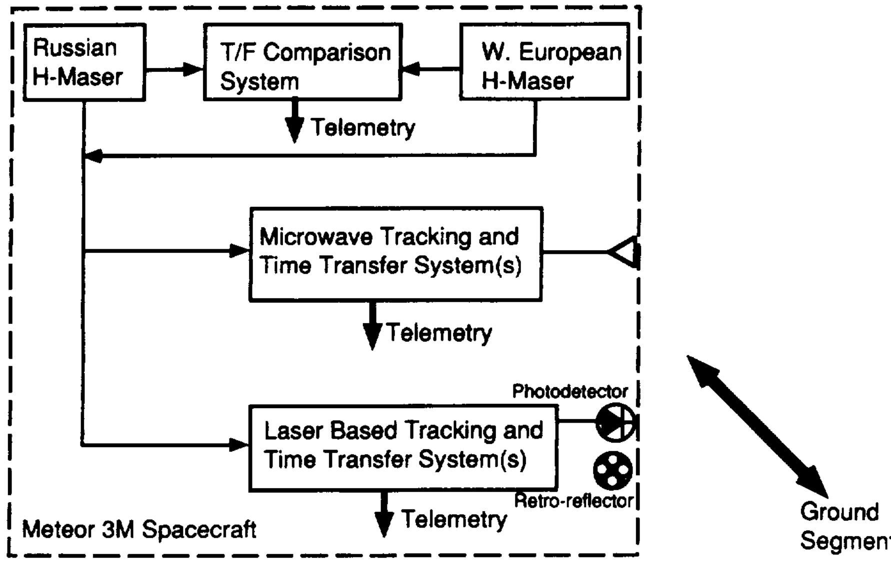


Figure 3
Main Payload for Joint Experiment

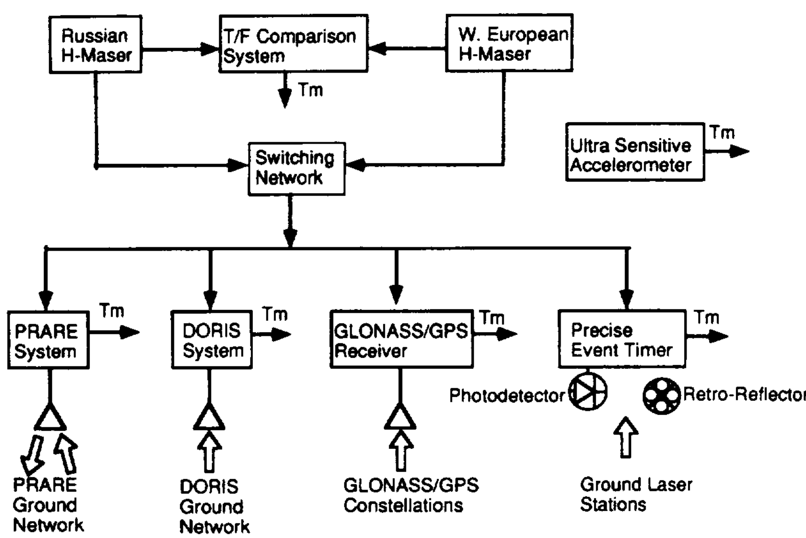


Figure 4
Extended Payload for Joint Experiment

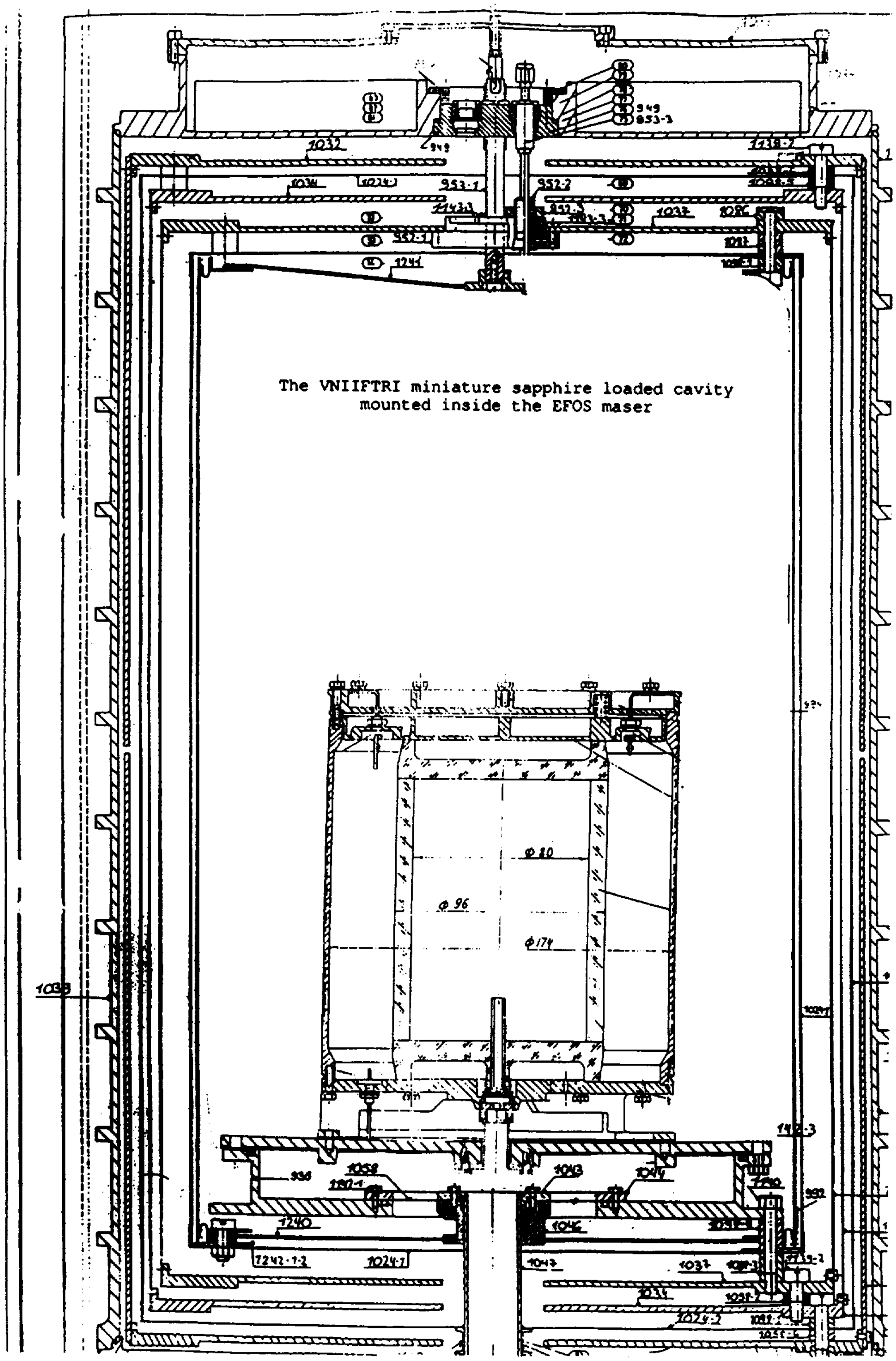


Figure 5
VNIIFTRI Miniature Sapphire Loaded Cavity
Mounted Inside the ON EFOS Hydrogen Maser

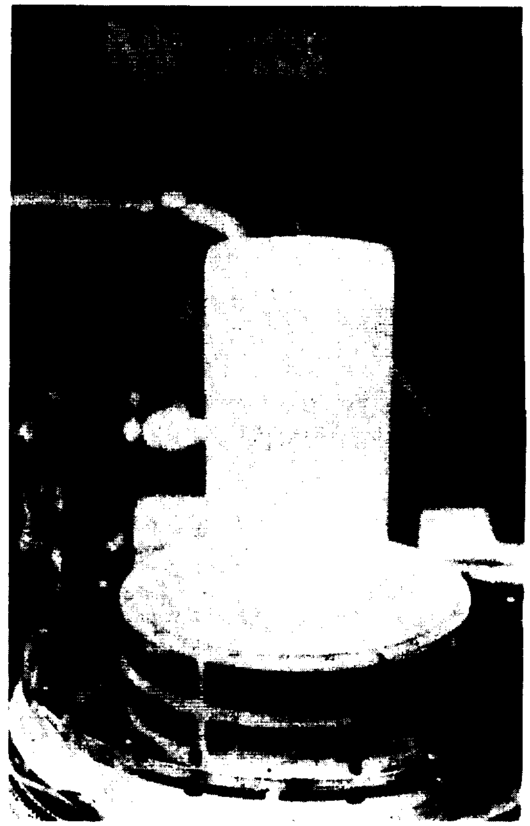


Figure 6
VNIIFTRI Sapphire Storage Bulb on the Titanium Cavity Base

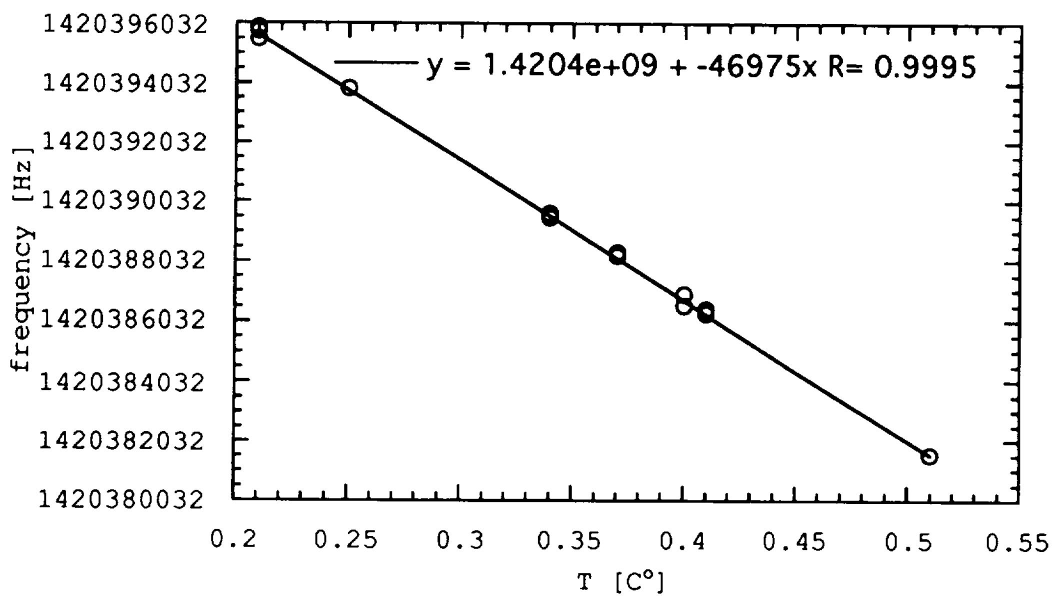


Figure 7
Determination of TE_{011} Mode Thermal Coefficient

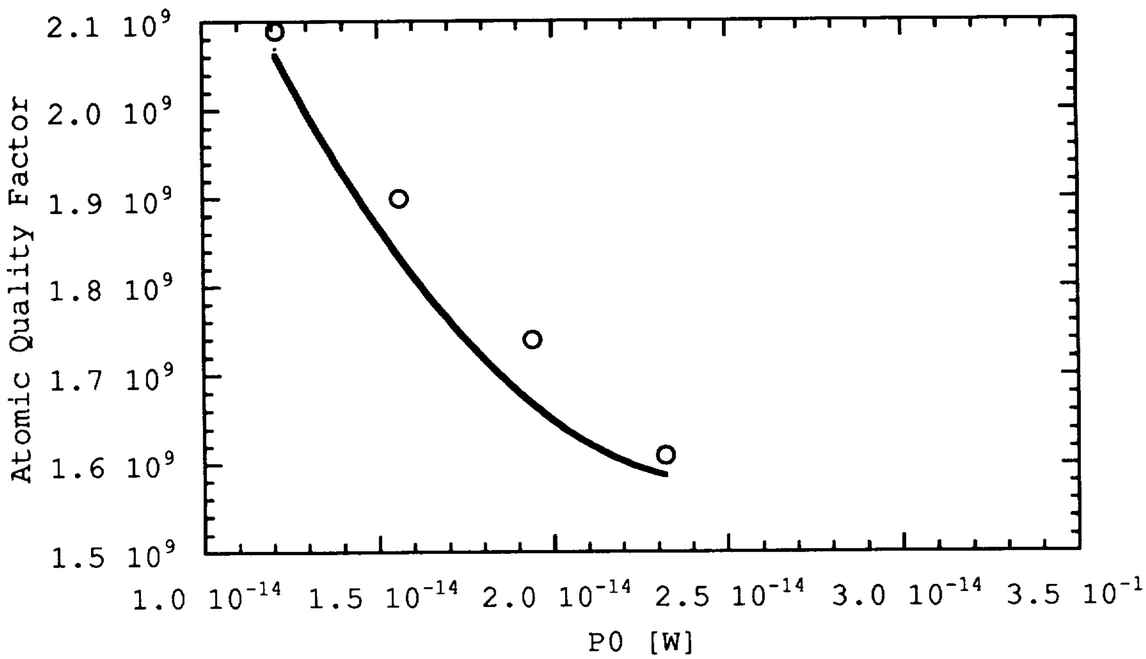


Figure 8
Atomic Quality Factor versus Output Power
Theoretical Model and Experimental Values

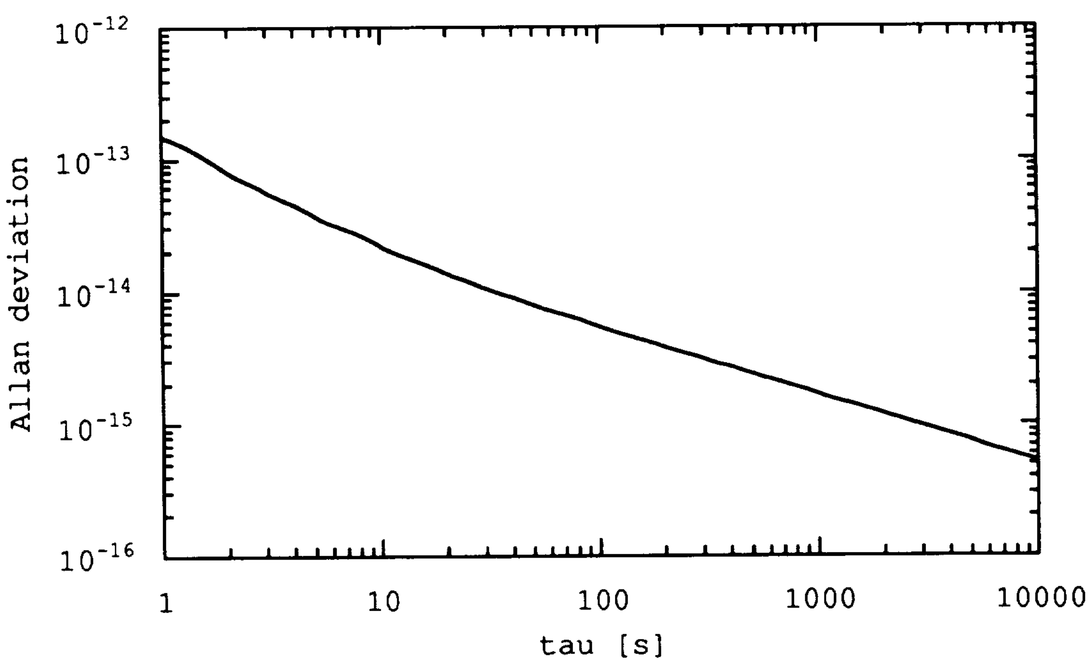


Figure 9
Theoretical White Phase Noise and White Frequency Noise Limits
Associated with Parameters of Table 5

PANEL DISCUSSION ON WORKSHOPS

Ron Beard: Moderator
United States Naval Research Laboratory

Ron Beard, Naval Research Lab: What I thought we would do is have the people who led the workshops summarize what went on in the different sessions; and after a bit of discussion by the panel, we would open it up to the floor for any other discussion or comments that people would like to make. The first person will be Sam Stein and what went on in the discussion on "Ensemble Management."

Sam Stein, Timing Solutions Corporation: Thank you very much. The session on "Ensemble Management" focused on goals, objectives for both performance and operation; there was also very substantial discussion on what sorts of improvements are needed in technology and software in order to enable people to achieve those performance goals and objectives. I was quite surprised when I saw that those people who attended the session came from organizations that were actively involved in operating clock ensembles. I estimated that more than three–quarters of the people were from those institutions.

The uses of ensembles were varied. Those organizations used the time and/or the frequency internally or delivered it to external customers. Some of them were involved in synchronizing remote sites or providing frequency to remote users. In general, the objectives of operating ensembles were far more to maximize the reliability and availability of the service being delivered to customers than they were to improve the performance characteristics of the time or the frequency. Finally, fairly universally all the people involved were quite interested in delivering UTC and not any other form of time.

In terms of performance objectives, one of the salient comments that was made was that people who are in the delivery business are very, very concerned with no doing harm, to minimize the probability of delivering bad signals; and, for instance, they preferred to deliver no signal for time than to deliver the wrong information.

Frequency stability improvement: it seems to be a rather minor goal for ensemble management. And I think that is quite natural, given that in general the improvement that one gets over one's good clocks is, at best, inversely proportional to the square root of the number of the clocks and the cost increase is proportional to the number of the clocks. So we are all much better off with developing better clocks than buying large numbers of them, for that purpose.

Another thing that came up that I think is important – and we don't often think about it – is that this is an example of a case where the peak errors are far more important than the RMS errors. It doesn't do a lot of good to be exquisitely fine in ones frequency or time capability and be occasionally terrible, if that single instance of being occasionally terrible occurs during a critical period. I think that has implications on how we need alternative methods for characterizing performance clocks under those circumstances. Given that performance objective, outlirr detection and methods of dèaling with outliers become very important. One thing to point out is that the process of dealing with outliesr is a process of trying to detect without outside information when the measure result does not come from the source that one's normal measurements come from. It is perturbed by something other than what we expect. On the other hand, we don't have a signal line that comes in and says, "Oh by the way, this bad event occurred." So we are guessing. When you reject the measurement in order to preserve the integrity of the system, when the timing receiver says that the time changed by a second, and when cesium clocks say that it didn't, and you reject that measurement, you can do a great deal of good. However, when you reject a measurement that is a few ns out of your expectations – and it was real – you do a minor bit of harm. The resultant in time or frequency that one computes from a group of clocks is a less good reflection of what the clocks actually did than had you included the data. Once again, we prefer not to maximize performance in the RMS sense in order to protect ourselves from the peak errors.

Finally, there was quite a large discussion about the topic of producing real time outputs from clock ensembles and particularly the steering of physical clock signals so that they reflect a computed group ensemble time or frequency. And how big those frequency steers should be, whether or not the users of these real time signals would prefer tight time tracking or smooth frequency. And I think one of the things that we realized was that those questions were answered a long time ago; decisions were made, people operate in a certain way, and there perhaps is a need to revisit the question – we don't know the answer, but at least to revisit the question in the light of great changes that have occurred in the nature of time synchronization. People's operational objectives are pretty simple, like 100 percent automation of systems, with considerable ability for operator oversight. People in general require guru-free operation. Whatever happens, you must be able to deal with the situation without the need for a true expert.

I think I would finally say that at the present time, people are not in general always taking advantage of the capabilities of ensemble systems for the production of real time signals, because right now of fear of what might happen and a fear of delivering very bad signals for extended and noticeable periods of time. For example, people are often not steering, or not steering automatically for that reason. So kinds of improvements are needed. There are actually improvements needed in the available hardware to do this job, particularly in the area of producing real time signals. One of the things that is needed in such a clock system is a low-noise way of steering the clock without perturbing the clock's innards. Today we have cesium standards that can be steered in frequency in this manner, but these frequency standards cannot really be steered in phase without affecting their frequency. Phase steering would be useful and it is desired. We also require highly deterministic steering. And that is the time at which the steer takes place and the exact value, both in phase and frequency, need to be known.

Another aspect of the steering mechanism that is I think often neglected – it has been pointed out to me before and it was pointed out again at this meeting – is that when one is steering, and in particular when one is steering frequency to remove phase errors, there is a danger that the system might stop in the middle of the process. And so if we have intentionally offset the frequency standard in a degree in excess of the noise of the ensemble, in order to change a large amount (perhaps 100 ns, or 10 ns, or one ns), and the computer chooses that moment to stop, we would leave in this large offset – perhaps several parts in 10 to the 14 or several parts in 10 to the 12 – and steer off into Never–Never Land unintentionally. So that the intelligence of knowing what the long–term steering target is needs to be built into the steering mechanism in a way of determining that in fact has to return to the nominal steering value; it has to be built into the steering mechanism.

Finally, an important thing that came out of this is the large desire on everybody's part to be able to steer to UTC. That has large implications on the desire for the availability of UTC in real time; so improvements in the time at which we can access UTC – and a great deal is being done now in the way of providing that. There was a paper by Claudine Thomas, a discussion of UTCP and how we will in the future have better access and more timely access to a UTC replica.

Ron Beard: Thank you, Sam. There are some interesting points there that we can follow up on. And I think a lot of what has come out of ensemble management today was a result of some of the good R&D and sales being done by various companies. So why don't we pass on to Jack and see what came out of that session. Jack?

Jack Kusters, Hewlett–Packard Labs: Thanks, Ron. Our workshop was not quite as technical, since we were dealing more with opinions and feelings and observations. In particular, we were looking at a way of improving communications between R&D groups, sales groups, and support groups in an organization. And indeed this is a problem that has been around for a long time; the "Harvard Business Review" articles have termed it the "silo effect." And if you think about it, a silo is a very tall building with no windows in it. And if indeed the various functional areas in the company are in their silos, the communication between silos is virtually nil. They reached a peak at the Ford Motor Company in the late fifties where the R&D people and the marketing people were kept separate. And the only communication allowed between them was through their vice–presidents. You can imagine how effective that was (I think that is when they brought out the Edsel).

So we were looking at several areas. Number one, what were some of the problem areas that we saw that were caused by a lack of communication? And secondly, we spent time looking at some of the suggestions from the group, more of sharing opinions and experiences than good concrete ways of solving the problem. These tend to be highly organizational–dependent. For example, those companies who are engaged as a direct supplier to the U.S. military have an entirely different set of problems and an entirely different set of interactions with their customers than those of us who engage in strictly commercial activities. And so it became very interesting to share opinions as to what we saw were problems in our organizations.

Even though the area that we were asked to concentrate on was strictly internal, the group insisted on talking about customers. And so it sort of flowed into the other workshop area. In particular, they felt that one of the biggest problems in effective communications between sales and R&D was that the customer didn't know what they wanted. And there were several areas that were brought out: customer uncertainty, customer education, costing problems, problems in funding. And the people especially engaged in military activities pointed out that many programs that are many years in extent become very difficult in dealing with the customer, because the customer is changing personnel while the program is going on. On the commercial side, we tend to face large groups of customers. So the effect of one customer moving on to another area becomes sort of minimal.

In the external focus on customers, some of the suggestions that were made to improve the communication – and again, this is getting communication from the customer all the way down to the engineering support people that are actually responsible for building the final product – by providing customer education through seminars, technical papers, articles, workshops. Anticipate customer needs; learn enough about your customer so that indeed you can determine what the customer's needs really are. This may mean unsolicited proposals; it may mean a lot of other activities.

There were some revolutionary comments: sharing data with customers, even proprietary data, if necessary, to really teach the customer what the customer needs to put in his specifications. As one individual pointed out, it is very helpful to help the customer write the final specification, because that way you would know exactly what to bid. Make the customer part of the solution through a joint definition of the specifications and joint product development, if that becomes necessary. And, encourage customer visits, both from the field – people from the factory going to see the customer – and customers coming to the factory. In that same area, there was quite a bit of comment on staff education. Too often the sales people are the only people directly contacting the customer. But also in many companies, the sales people don't necessarily have the in-depth technical knowledge to ask the right question of the customer. And indeed if that is the only contact, there is a possibility of the communications chain internal to the company ending up with some very interesting interpretation of what the sales people thought the customer really wanted. So there was a fairly good consensus that direct contact with the customer by the R&D and engineering folks would be important to really understand and to really communicate properly what needed to be done.

Strong encouragement of staff rotation. Let the R&D guys go out and talk to the customer; let the engineering people get involved in a lot of these activities. QFD – that stands for "Quality Functional Deployment" – is a technology that is starting to show up in companies. It is a methodology whereby you gather tremendous amounts of information on a customer's viewpoints. It tends to be more appropriate either in interfacing on very large programs or on developing products that go to a wide variety of customers. Because you are dealing with one individual for one particular product, the types of questions that you have to ask in the in-depth interview that you have to do are just not appropriate. I can strongly recommend QFD in terms of trying to find out what customers may wish and to build that into your product.

A very strong emphasis came from a number of people on core teams. Involve more than just the sales people in calling on a customer. Set up a team that involves not only the sales people, but the R&D people, the manufacturing people, the QA people, the systems people, the test people; so that indeed the program operates without any misunderstanding or any surprises as it goes down the chain and into production.

We spent a lot of time talking about the internal problems. What are some of the things that we saw internally between Sales, Marketing and Engineering? Several areas that were identified were cultural differences – we don't have a common language, in general; the people that are associated with sales or marketing tend to talk in different terms than the people in engineering. There is a joke that has been going around my company that a engineer and a marketing person is asked "How much is one and one?" The engineer says "two" and the marketing guy says "What do you want it to be?" I think that there is a slight change in the cultural emphasis in the two areas.

Quite often there is no control on the final specs. Things are not properly defined. There is no ownership of a particular program or a particular product. And there is no product champion. Some of the areas that were identified as possibly improving these were, number one, to abolish the silos. I tend to look at them as bunkers, because at times we are far more defensive of our functional areas. Some of the solutions, again, establish core teams; combine meetings – again, as an extension of core team; concurrent engineering – get the manufacturing people involved in the R&D program; make sure that as the product comes out into the manufacturing floor that the engineering people who have to support have been a part of the problem and have been a part of the solution. One thing that we found very effective is colocation; make all those guys sit together. It is strange how much communication can improve if indeed the R&D and the sales people are sitting next to each other. It is amazing how much you overhear when your peer in the next cubicle talks to a customer and makes comments that you know full well are wrong. It helps improve the communications there. Self-elected planning groups: make open environments such that people can indeed move from one area to another. Self-empowerment of the engineers to help make those decisions early. Interactive brainstorming in all aspects of sales, engineering and R&D. Combine unstructured brainstorm sessions, but with a very carefully-defined goal.

Some of the other ideas that people came up with were not directly related to problem solving, but are areas of concern. These are testing, human engineering, reaching the right person, TQM ("Total Quality Management"), which immediately segued out into a long discussion on ISO-9000; that faces a lot of us now in terms of trying to understand our own internal processes. Certainly in my company the interaction between the various engineering groups regarding ISO-9000 has been a real experience for all of us trying to understand what we are really doing.

The final area that we talked about was brought up by one the individuals in the workshop. He said, "Why is it that when I order something, I don't get something that just meets my requirements, I get something that is a total overkill that I have to pay too much for?" It is a question of "perfect versus good enough." And some of the problems and comments we received on that: number one, it is a perfect example of product of evolution, or creeping futurism. The problem is that we don't really know what the customer wants. And again, we have not communicated with the customer on options. We have not verified with the customer our impression of what he asked. And, we have not communicated that customer preference down through our structure. It is partially also a problem of not having adequate specifications. It is also a problem in commercial companies of designing for multiple customers. If you are designing for one customer, that's a lot easier; if you are designing for multiple customers, the temptation is to be all things to all people. And indeed, we end up putting in so many different hooks and options that we lose sight of what the real direction is. What happens is that the product ends up costing too much and has too low of a customer value.

The bottom line from the group: the strong consensus was number one, consider customer costs when you are putting out a product. And the last comment from one of the manufacturing people there was "make sure that everything is designed for manufacturing." "One of the fundamental ways of lowering cost is to make sure that the manufacturing process is taken into account." And, "Make sure the manufacturing engineers are a part of the core teams." That about sums about an hour and 40 minutes of very active discussion. My compliments to the group and my thanks to those of you who participated. It turned out to be a very interesting afternoon.

Ron Beard: Thank you, Jack. Well from what I learned from visiting the various groups, it sounds like many of things that you brought up in your session, Jack, were also raised in the other session on communication itself, in trying to work with the vendor to determine what his requirements really are; and arrive at a price that was commensurate with what he was doing. And that is a difficult problem in today's environment with the people who are putting together these systems and trying to develop some new capabilities, really defining what they need to do that; and then effectively working with the vendors to get what he needs, and at an affordable price. And communications is a difficult problem.

A number of points came up out of these other groups, and I would like to open it up to the floor now. Does anyone one want to comment or elaborate, or do you have any questions on what we've discussed so far?

John Gehrhard, Rockwell: I have a question regarding that session on customer interface. The future of time and frequency equipment, are they going to go VXI for that equipment? And are you going to have modular boxes where you buy a console and then you plug in like a counter or plug in a volt meter so you don't buy an instrument that has excessive range capability, etc?

Jack Kusters: Well there certainly is a trend in that. We didn't actually cover that in the workshop because we were not looking products, just at just specific items. But out in the exhibit area certainly several of the manufacturers are heavily engaged in doing just that, providing VXI, VME, MMS modules to go into predefined chassis. Again, it depends on what you are trying to do. If you are looking for a single counter or a single product, it may not be as cost–effective; but if you are building a system, there are somewhere around 170 companies (the last time I looked) involved in providing VXI solutions. And certainly there is a tremendous amount of products out there right now. I don't know if that answered your question, but I certainly see that as a path that many people are taking in the future.

Ron Beard: I'll ask Martin now to summarize what went on in his session and bring you up to date a little bit. In the other session on R&D, it appears that communications was one of the larger subjects they talked about, essentially between the vendors. So I think that is a problem area that everyone is concerned about.

Martin Bloch, Frequency Electronics, Inc.: I think communication was the main topic in my workshop. It was basically the idea of the need to understand and to communicate between the user and the supplier, and also to identify the non–value added functions that happen in hardware and in testing. There was a lot of discussion about telemetry needs and getting data from spacecraft on hardware that we launched. And, of course, the scientists need to get data for future improvement from knowledge and, of course, the cost associated with having all this data available; I think everybody's conclusion on that was that we need telemetry, but we have to really thoughtful in what we record because the reams of data, in many cases, really mask the actual knowledge that we need.

I think one of the other important items is the concept (this may be mine more than the participants) is that in the next decade in order to be successful, we have to be able to do things smarter; and we need a lot of cooperation between industry, government and the universities to really meet the challenge of new hardware, to make it cost–effective and the quality and reaction time. I think one of the other key points that came out is that it is imperative for the system designer to get together with a hardware supplier early in the game in order to be able to specify the magic bullet for a solution; because otherwise a lot of non–value added specification and testing comes, significantly increasing the cost of the hardware.

Ron Beard: Thank you, Martin. Well it appears as though communications is certainly a key in a lot of these things; plus, the developer really being able to determine what he needs. And I think a large part of that function is being able to determine the requirements of his system. And in time and frequency, that has been a difficult area over the years. We'll open it up again to discussion.

Shiela Faulkner, USNO: I have a question for Jack. He said something about writing specifications for the customer. I am under the impression that is a fine line there. I think recommending what the specifications be – while I don't purchase the type of equipment you do, I do work in the field; and when I have purchased other related equipment, I have been told that that's not really acceptable; you can tell me what the specifications are, but writing them would be kind of hazy. Am I correct or incorrect?

/bf Jack Kusters: Not being in the military business, I am not exactly sure, and I may have used incorrect terminology there. But certainly in providing the customer with specifications.

Ron Beard: The intent, of course, is to get the correct specifications; from the government point of view, that is not really permitted, at least not in my agency.

Dr. Winkler, USNO: Jack mentioned – and, in fact, in some conversation with Marty Bloch – the big problem came up of phasing out of the defense business to almost entirely commercial business. And I wanted to add that even those parts of the defense business which remain will be under a very high pressure to buy off–the–shelf line items, instead of custom engineering, instead of making specific specifications for specific purposes. The push is on and it will be assisted by the change which is coming in the procurement regulations. That will make it very easy to procure an off-the-shelf item, particularly if it is under $100,000, as compared to specifying something which has to be custom made. And I think this will increase the pressure on the manufacturer to come up with items which will be more generally useful, and to lower the burden of developing such items will be much greater I think.

Martin Bloch: Dr. Winkler, I think that that is a necessity for the future. And there are risks and rewards. If John Vig were here, he would tell his favorite Dutch Navy story where they went out and bought a commercial light bulb for a dollar instead of $10; and the first time they fired all the guns, all the lights on the ship went out. So they replaced all the bulbs and then fired all the guns again. All the bulbs went out and they returned to port. So the use of off–the–shelf hardware, I think, is the thing of the future and it is very economical and necessary. And we have to fight the bureaucracy on it every step of the way. I think what is important, though, for military use is to make sure that the environmental requirements of the hardware is tested properly and it does meet. And there is no conflict of interest. You can have commercial off–the–shelf hardware that will exceed the environments, but we cannot overlook, by buying something without making sure that the end user is protected in the environment that he is going to have to live in. And I think that is a risk factor.

Ron Beard: Doesn't this get back to the point that it will give the user exactly what he needs?

Dr. Winkler: That is exactly the point. I think there has been some gap of communication between the two of us. I think in that example of these light bulbs, it would be up to the manufacturer to understand that they will need bulbs which will be able to withstand that, and have that as a line item. That is the problem.

Martin Bloch: There is education on both parts. The manufacturer must understand the user's need and his environment. And the user has to protect himself in some way to make sure that he gets what he needs.

Ron Beard: In many of the military applications, they are operating in environments and stations and things like that that are very comparable to commercial operations. And many of the off–the–shelf items that he needs is perfectly adequate.

Marc Weiss, NIST: Mr. Kusters and Mr. Bloch both have talked about getting the customer what he needs. I think that concept is a little oversimplified; because, as people develop new technology, the in–house engineers and staff work with their own creativity to come up with new technology, new ways to do things. And then customers are out there coming up with systems trying to find ways to solve problems. It is really an interactive problem. The system designer may know what he needs in terms of old capability, but if there is new technology being developed that didn't even exist before that solves problems or actually creates new capabilities, there is a whole communication and a synergy between the customer and the developer and the salesperson, if you will.

Martin Bloch: I think we all agree – I'm sure Jack and I do on a hardware basis – that communication between the end user and the equipment designer is imperative and very cost-effective. From my personal experience, if we can get in early enough in system requirements, then we can come up with a magic bullet at approximately half to 70 percent of the cost. And if you unilaterally design what you need for your system and come to us and impose on our boundaries – which to you is simple, and to us are major cost drivers, and to Jack makes it almost if not being available since he is more of a catalog–type of sales, we are more custom; so to him, you don't deliver; to us, you increase the cost.

Ron Beard: I think this is a good point. It kind of presumes that the customer knows exactly what he wants. And the fact that there are many things that may exceed or actually augment the capability that he needs that he simply doesn't know about.

Jack Kusters: Yes, from my viewpoint, the way to make money is to have a customer who is willing to buy and has a problem; and indeed that the problem you are trying to build solves this problem. But that doesn't happen accidentally. The world isn't perfect, and indeed there tends to be – or there should be – a tremendous amount of interaction so that the manufacturer has an idea of what the customer really needs, perhaps before the customer knows he needs it. How do you lead the technology? How do you understand what is really going to be needed down the line? That is a problem that we all face.

Martin Bloch: I think an example of probably the highest cost driver item that we came across in procurement – we specialize in oscillators that work under dynamic conditions on aircraft and ships for lower 'G' sensitivity. And that is one of our products. And we find that nine out of ten customers will specify aesthetic phase noise which is basically pushing the state of the art with their concept that under vibration and shock that there is going to be a deterioration from the static phase noise to what it does under dynamic conditions. And that is enormous cost drivers. You are talking about, in many cases, doubling the cost of the product. And in reality, it is amazing in the industry how few very sophisticated engineers and scientists understand that the two behaviors are totally unrelated. And what a clock does under environmental conditions is their 'G' sensitivity; and what it does under phase noise is the cue of the resonator on how long it annoys the circuitry.

So if we could just communicate on that level we could do a better job in reaction time and really be more competitive. I feel that both user and supplier have to be on the same side. The 1990s are going to put enormous pressure that we have to be competitive and cost-effective in order to really stay in business and be able to compete with the rest of the world. So we are looking to communicate; we are not looking for an adversarial relationship. It has to be almost like a partnership.

Ron Beard: I think that is a really good point in being able to communicate to the customer. Some of the things that are available today I think what has brought ensembling more into light these days is that the users traditionally have thought of reliability and maintainability in systems by having hot spares and what not that they simply switch in when they have failures that they somehow detect. And ensembling provides a means of maintaining a continuous reliable signal to the user, which he had never really thought of before. And now it is becoming more available.

How do we effectively communicate what is being developed in these areas to the user such that he can define his requirements better? Or, have a bigger appreciation of what is available to build into his system, perhaps at a much lower cost than he would have thought through traditional thinking? That is a difficult problem. Does anyone have any thoughts on that?

Martin Bloch: It is difficult, but you have to start someplace. And I think these interactive workshops would be very effective if we could get the system designer to attend and participate. And that is about the best way that I know of communicating, if you do it on a one-to-one basis; with about 1000 users, especially during this time when there is an enormous transition from the experienced individual that is being phased out of industry to the newcomer who is coming in. And how to get the information to him is going to be a challenge, but we must.

Dr. Hellwig, AF Office of Scientific Research: I am going to help you on this issue of how you communicate. And I think this relates what Gernot said about commercial practices. I think when you develop new hardware or customize existing hardware, specs have to concentrate on the interface specs, on the black box specs, and not on how you build it or how you achieve those performances. I think that is crucial. And that does relate to procurement reform. But quite frankly, a lot can be done (from my experience) without procurement reform. And I don't see enough effort in that direction, personally. That is what I recommend as a tool to help communications.

Dr. Winkler, USNO: I think it is an extremely important item, so we should not stop here. Because, I think the customer is not always right. The customer is not right when it comes to these internal specifications or internal requirements which define the equipment as such. The customer is right, however, in the applications, in the needs of the applications, and so on. So there is a very sharp demarcation. And it is necessary that of course the communication exists between that thing. But it is also extremely dangerous if a manufacturer would go out and build just exactly what the customer wants. Usually this is very bad and very expensive.

Dr. Van Melle, Rockwell: A couple of points. One that Shiela brought up, a lot of unsolicited proposals come to, in our case, the Air Force. I don't know who started GPS, whether it was the Air Force or Rockwell – well whoever started it, they planted the seed. Like all the secondary payloads, I think Rockwell tried to get that and that helped salvage GPS contracts.

Another thing, the Air Force has a tendency to over–spec – like in the clocks, for example. We have got minus 54 degrees to survive, we have turn–on at minus 19 degrees C. The clock has never, ever seen in its whole lifetime anything below plus 5 degrees C. But you have to talk about margins – you know, how much margin do you want to put in specs? So that drives up the cost. There were a lot of vibration specs we didn't need, and we could go on and on down the line. But who comes up with these specs? Should we have told them that these payloads will never reach the requirements that you are trying to tell us to do?

Martin Bloch: Van, I think there is a misunderstanding on what is margin. Sometimes people extend the temperature range or increase the vibration levels, increase the temperature cycling; and they think that this gives margin. And that has to be very carefully analyzed. Our experience is, for the most part, that it adds cost on this without really giving the necessary margin. I can cite an example: recently someone came up with the requirements for fighter aircraft that a precision crystal oscillator has to build up in approximately 100 millisecond start–up time. If you had a five–megacycle three–million Q crystal, you immediately have to deteriorate the Q considerably in order to meet these requirements. This was like a "do or die" spec. And it is in three major programs. I took it as a personal challenge to find out what the requirements were, because I know the warm–up of the system is a couple of minutes; and I found that a guy in the power supply decided that he wants to have a status of "get well" on this within the first 100 ms; and he needed a clock reference in order to be able to drive his chip over there. That drove the spec and it literally tripled the cost of the clock and the complexity.

So these are items that you need to fight. You can't find the universal solution. I think what is important is to communicate and express. And the supplier has been very remiss; in our enthusiasm to make the sale, we really are afraid to challenge the customer in what is difficult and what is expensive. And I think we need to do that.

Jerry Norton, Johns Hopkins Applied Physics Lab: We frequently see multiple margins built in. The systems engineer will add three dB to cover his tail, if you will. The systems people, the test people, everybody wants three dB, just in case, and frequently those three–dBs more than double the cost every time, when it is not necessary at all.

Ron Beard: Aren't they really striving for reliability, trying to get the most out of what they are getting? That is really what they are attempting to do, aren't they?

Jerry Norton: There are points of diminishing return though. I mean, the first dB may be pretty easy; the second dB is going to be much more difficult; and the third one may be impossible. And the cost may be tripled or quadrupled while you are doing that.

Martin Bloch: Our experience, Jerry, is the same. We had a major system that put a four–dB margin on phase noise and the specification was 170 dB floor because of the error in the measuring instruments. And that basically decreased the yield by 50 percent. So yes, I don't think it added reliability. Maybe it made it convenient for somebody on a data review. But the cost was just overwhelming.

Jerry Norton: Frequently, you know, as things get tough down the line, people start relaxing those things. And if they had just been honest and up–front about it, it would have saved everybody a tremendous amount of trouble and cost.

Philip Talley, Aerospace: My experience has been over quite a few years that the problem is people are forced into specifying military standards. And military standards called for these particular limits and it takes an act of Congress to get it changed. And this is a big factor in the cost; and I think it is something that needs to be worked on. But everybody wants to have standards; and if you have standards, then everybody has to comply to them. But still there appears to be a logical work–around by having the designer say, "Okay, that is the standard. But for this application, you need to do so–and–so and take exception to that standard and logically defend it." I think that is the only solution that ever came about.

Ron Beard: Aren't a lot of these standards actually tailored when you get right down to it? And it gets back to a point I think that Jack made on generic solutions, trying to generically solve it for all applications; and that is very difficult.

Marc Weiss, NIST: Mr. Kusters, you used the word "leadership." And I think that is primarily the issue; I think that is at the heart of what we are talking about; who provides leadership for developing new technology? Who provides a leadership for trimming things that have been over–specified? I think we need not to be afraid to say that they are specifying too much, that we don't think you need this much. As a supplier you can say to a user that it is a risk. You need to step out and say "I think this; I have some expertise and this is what I think." At NIST, in the other direction, we come up with services before people need them. We need to anticipate people's needs and say that this is a primary frequency standard that nobody needs and we're going to start building it today; because by the time we build it, people are going to need it. Here is a timing service that nobody needs, and we come out with it; and then suddenly people need ten times better than what we are supplying. So there is a leadership there, also, where you come out and say here's a product that we think will be useful but that nobody needs right now. And there is a risk in that.

So leadership is a balance between leading and providing value that is not useful.

R. Michael Garvey, Frequency & Time Systems: I think one way to tie all this together, in my experience it is relatively rare to find a customer who will say that they don't need that if they think they are going to get it and they think they might need it; or if they are ignorant and don't know if they need it, they will remain silent. And a big part of the challenge, I think – and we talked a little bit earlier about communication and educating our customers and so forth – is that there is a fairly common tendency in the industry to bring on a person, let the vendor educate him, and then move him somewhere else. And then you have got a new person and a new education process. I hesitate to say this, but it is a sort of standing joke that if it takes longer than two years to teach it, then the customer may never learn it. And so I think it is particularly important for the customer to realize if there is going to be an education process, he has to dedicate the person or persons, let them be educated and let them make intelligent decisions throughout the process. Because, it is a big load on the vendors to dedicate a high-level person to teaching one customer after another within the same organization, on the same program – be it six months or two years at a shot.

Martin Bloch: Mike, are you resenting that you have nine program managers over a four-year period from a customer? I'll tell you one of the problems – it sounds so simplistic, but we experience it over and over again. And I once wrote a thesis on the generation of a system requirement for a clock. We did the right thing, we got together with the system designers when the study was done, and came up with a two-page requirement for the clock; and it was very simple. It then went to the M&P people, and they added 14 pages. It then went to the EMC people, and they added another 20 pages. And then it went to the components people, and quality control. By the time we were finished – and this was a 100-page document and the basic requirements for the clock – it was basically subservient, compared to all of the other requirements that were put on by this other organization. And I don't know a solution for it; the bureaucracy cuts in on existing organizations that make it very complicated, especially on major weapon systems and satellite clocks.

The commercial people have found a much smarter way of doing it: 'Here is a two-page spec" and everything else is implied. And to the customer it is the supplier's responsibility to make sure that all the implied specs are met.

Ron Beard: I think that is really showing that there are problems on both sides: there are problems on the generation of these things and understanding what the people want, or what they really need in putting their system together; effectively communicating, whether it is with the sales department or directly with the engineering department, such that they can really interpret and give them the product that they want after they wade through the 450,000 pages of the specifications; and citing all the different specs and tailored specifications and other things that they are attempting to add to the procurement in order to get a reliable product that is going to do the job

that they want within the scheme that they have to work on. And in the government, that is applying government standards, military standards and specs.

Ralph Partridge, Los Alamos National Laboratory: I want to take a small amount of exception to something you said, Martin, about implied specs. Our experience has been that you cannot use implied specs. What the vendor states he will supply is exactly what he will supply, and not one bit more. And if you assume that there is more there than there really is, you are going to be in deep trouble.

The other point that I wanted to make is more of a general point, and that is a plea for more QC in off–the–shelf items. We have six GPS receivers in our place – so we are small compared to some of these other people; of those six, exactly one worked properly out of the box the first time. Others would have a hardware trouble that showed up within a month (or something like that). Manufacturers are happy to fix it, of course, under warranty; but that doesn't change the fact that it didn't work. And others, you will find that the software doesn't work, and they will have to fix up the software too. One out of six is a pretty poor result.

Martin Bloch: It is definitely a real problem. And the solution, in my opinion, is quite simple. Don't buy from this supplier again and it won't happen, and he'll improve the quality. And somebody is going to come in its place. That is what the commercial users are doing. There is no tolerance for not delivering a high–quality product in the commercial environment. And the punishment is simple: you don't have lots of specs, lots of QC, and lots of area; the guy is eliminated from being a future supplier. That is a very effective weapon that the customers have in trying to force the quality and force the proper suppliers to stay in line and the marginal ones to really disappear.

Ron Beard: This has been a rather interesting discussion. I hope that you have gotten as much out of it as I have. I think communication has been an age old problem. Hopefully in this current age where we want systems to be more efficient and affordable and to do more reliable things, we are going to need to communicate more between the vendors, the developers, and to really get the systems we will need for the future.

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Ionospheric Corrections to Precise Time Transfer using GPS

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Abstract

The free electrons in the earth's ionosphere can retard the time of reception of GPS signals received at a ground station, compared to their time in free space, by many tens of nanoseconds, thus limiting the accuracy of time transfer by GPS. The amount of the ionospheric time delay is proportional to the total number of electrons encountered by the wave on its path from each GPS satellite to a receiver. This integrated number of electrons is called Total Electron Content, or TEC. Dual frequency GPS receivers designed by Allen Osborne Associates, Inc. (AOA) directly measure both the ionospheric differential group delay and the differential carrier phase advance for the two GPS frequencies and derive from this the TEC between the receiver and each GPS satellite in track. The group delay information is mainly used to provide an absolute calibration to the relative differential carrier phase, which is an extremely precise measure of relative TEC. The AOA Mini-Rogue ICS-4Z and the AOA TurboRogue ICS-4000Z receivers normally operate using the GPS P code, when available, and switch to cross-correlation signal processing when the GPS satellites are in the Anti-Spoofing (A-S) mode and the P code is encrypted.

An AOA ICS-Z receiver has been operated continuously for over a year at Hanscom AFB, MA to determine the statistics of the variability of the TEC parameter using signals from up to four different directions simultaneously. The 4-channel ICS-4Z and the 8-channel ICS-4000Z, have proven capabilities to make precise, well calibrated, measurements of the ionosphere in several directions simultaneously. In addition to providing ionospheric corrections for precise time transfer via satellite, this dual frequency design allows full code and automatic codeless operation of both the differential group delay and differential carrier phase for numerous ionospheric experiments being conducted. Statistical results of the data collected from the ICS-4Z during the initial year of ionospheric time delay in the northeastern U. S., and initial results with the ICS-4000Z, will be presented.

INTRODUCTION

The ionosphere can be the largest source of error in GPS time transfer, positioning and navigation. Radio waves propagating through the ionosphere suffer an additional time delay

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as a result of their encounter with the free electrons in the ionosphere. This total electron content (TEC) is a function of many variables including geographic location, local time, solar ultraviolet radiation, season and magnetic activity. Accurate information on the behavior of TEC is important to satellite navigation and time transfer systems that correct for the time delay effects of the earth's ionosphere.

The GPS dual-frequency system provides the opportunity to measure absolute TEC with a high degree of accuracy. Absolute TEC values are obtained by measuring the differential group delay of the 10.23 MHz modulation on the dual-frequency L-band signals. Relative TEC values are obtained by monitoring the differential phase of the two GPS carriers. By combining both the relative measurements of the differential carrier phase with the absolute TEC obtained from the differential group delay, excellent absolute TEC measurements can be made.

Many ionospheric experiments are currently in operation using this technique. A recent study on the seasonal variability of TEC was conducted at Hanscom AFB, MA. The results of this study will be presented here together with the method used to calculate precise measurements of TEC using the dual frequency GPS system. Ionospheric measurements for this study were made using the AOA 4-channel ICS-4Z Mini-Rogue GPS receiver. It has a high-performance, all-digital design and is capable of tracking four satellites simultaneously using the P codes on both frequencies, L1 and L2, in addition to the C/A code on the L1 frequency. Precise measurements of the L1 and L2 carrier phase are also derived. This paper also will describe some measurements made using the AOA TurboRogue receiver, Model ICS-4000Z. This is an 8-channel receiver that has an improved cross-correlation capability. This allows the receiver to recover sufficiently accurate measurements of TEC when the precision ranging codes (P codes) of the GPS transmissions are encrypted (i.e., with Anti-Spoofing activated).

IONOSPHERIC MEASUREMENTS USING GPS

The GPS satellites transmit coherent radio signals at two L-band frequencies, L1, at 1.575 GHz and L2, at 1.228 GHz. Since the ionosphere is a dispersive medium, the two signals experience different amounts of time delay. The difference between the L1 and L2 transmit times is the differential group delay. This differential delay can be related directly to the total electron content along the line of sight between the satellite and the receiver. The value of 1 ns differential group delay represents 2.852 TEC units (1 TEC unit = 10^{16} electrons/meter^2). One ns of group delay at the L1 frequency is equivalent to 1.85 TEC units.

Figure 1a illustrates an example of the differential group delay measurement for one full satellite pass recorded on February 24, 1993. Note that the time delay is given in units of nanoseconds at the L1 frequency; however, the differential time delay is the actual measured quantity in Figure 1a. These measurements represent absolute values of TEC, but they also include the effects of multipath and receiver noise. Multipath is strongly dependent on the local environment and is more evident at low elevation angles, as can easily be seen near both ends of the pass. Note that the approximate elevation and azimuth of the pass are given, for different times during the pass, in Figure 1b.

L1 and L2 signals also experience different carrier phase advances caused by the ionosphere.

The difference between these carrier phase changes, in units of time, is referred to as the differential carrier phase advance. An example of differential carrier phase, expressed in units of nanoseconds of delay at the L1 frequency, is illustrated in figure 1b, together with the approximate elevation and azimuth angles to the satellite. This is a more accurate ionospheric measurement than differential group delay since it is affected much less by multipath and receiver noise. However, it is only a relative measurement because of inherent carrier cycle ambiguities. That is, the number of full phase cycles along the line of sight between the satellite and receiver is initially unknown.

Absolute values of ionospheric time delay (or TEC) generally are determined from these two GPS measurements by using a technique first suggested by Jorgenson (1978). This is accomplished by calculating an arithmetic mean fit of the absolute, but noisy, group delay data, to the relative, but precise, differential phase data. This fitting procedure is done only over the higher elevation portions of the satellite pass, minimizing the error caused by multipath from the differential group delay measurements. Figure 1c illustrates the results of this fitting procedure. There is a possibility of cycle slips in the differential carrier phase, giving potential problems in the fitting of the carrier phase throughout an entire pass to the differential group delay. In practice, however, cycle slips are a relatively rare occurrence with the ICS–4Z receivers, and even rarer with the ICS–4000Z, occurring on the order of less than one cycle slip for each day of data recorded. Nevertheless, a program has been written which finds and corrects for these rare events automatically in virtually all cases.

There are several sources of error in determining the absolute values of ionospheric time delay. The most significant being the additional time delay induced by the receiver hardware and the individual GPS satellites (Klobuchar, et. al. 1993). The receiver hardware is easily calibrated to a fraction of a nanosecond differential delay. The individual space vehicles introduce a much greater error. These errors, or biases in the transmitted time offset between the 10.23 MHz phase of the L2 minus the L1 modulation, are called T_{gd}. They are different for each space vehicle, and they could possibly vary with time, though the evidence for their temporal variations is not compelling. Estimates of T_{gd} indicate that they can be as high as 10 TEC units (3.5 ns differential time delay). A bias this large is intolerable, since it can exceed the maximum TEC observed during solar minimum conditions. These biases have been studied by Lanyi and Roth, 1988; Coco, et. al., 1991; Gaposchkin and Coster, 1993; Wanninger and Sardón, 1993; Wilson and Mannucci, 1993; and others. These studies have revealed many inconsistencies in results of the T_{gd} measurements. A summary of the published T_{gd} values, and the potential problems in deriving them, was given by Klobuchar, et. al, (1993). In this paper, the biases reported by Wilson and Mannucci, (1993), have been applied to the data. Their bias estimates are based on a multi–site fitting technique that exhibits a small day–to–day scatter. The Wilson and Mannucci study of the biases is based on a very extensive data base recorded in March 1993 and is likely the most reliable set of bias estimates available to date.

DATA BASE

The GPS data used in the TEC variability study was recorded at Hanscom AFB, MA for a full year, from May 1992 through April 1993. Figure 2 illustrates the satellite paths of the various

GPS satellites over Hanscom for one day during this period. Elevation angles of 0 through 60 degrees are represented by the concentric rings centered around the station. Satellite signals received from widely spaced azimuth and elevation angles pass through greatly different regions of the ionosphere. Therefore, simultaneous measurements of ionospheric time delay (or TEC) along different lines of sight generally are not the same.

VARIABILITY STUDY RESULTS

Figure 3 displays the observations recorded on February 24, 1993. The slant absolute delay measurements have been converted to equivalent vertical time delay in ns at the L1 frequency. That is the measurement at the geographic position directly below the point where the satellite intersects the centroid of the electron density distribution with height, typically taken to be at 400 km. In order to display the diurnal variation of ionospheric time delay, the data is plotted versus local time at this sub–ionospheric intersection point. At any local site, the ionization generally peaks in the mid–afternoon local hours, and drops rapidly at night. The differences between measurements made at the same local time are attributed to the ionospheric gradients encountered by satellite paths intersecting the ionosphere at different latitudes.

Ionospheric time delay is also highly variable by season. Figure 4 illustrates the statistics of ionospheric time delay for three seasons during the daytime hours of 1100–1700 local time. The daytime TEC values were computed and grouped together by season, summer (May through August), winter (November through February), and the combined equinox periods of March, April, September and October. The ionospheric time–delay measurements are plotted against their cumulative probability so that the percentage of occurrence above and below certain probability levels can be observed. A straight line on this type of statistical plot indicates a Gaussian, or normal, distribution. The slope of the line is a measure of the standard deviation, and departures from a straight line are simply departures from a normal distribution. This figure indicates that the median daytime values of ionospheric time delay are highest in winter, followed closely by the equinox period. The summer values are the lowest. The winter season exhibits a significant departure from a normal curve above the 99% probability point. Departures like this are often due to the effects of magnetic storm activity.

Figure 5 illustrates the statistics of ionospheric time delay at L1 during the nighttime hours of 2300–0500 local time. Here, it is evident that the summer nighttime values are higher than those for the other two seasons. Winter and equinox have a more nearly normal distribution than summer. Summer begins to depart significantly from a normal distribution above the approximate 95% probability level. The negative numbers below the 1% probability point are probably due to incorrect satellite biases. There is some evidence that the biases vary with time, (Gaposchkin and Coster, 1993), and other evidence that they do not vary with time (Wilson and Mannucci, 1993). Our indications of the apparent "fewer than zero" number of electrons in the ionosphere, seen in Figure 5, for less than 1% of the time during the equinox season and for less than approximately 0.5% of the time during the summer season, are likely due to incorrect values for the T_{gd} for at least some of the GPS satellites.

The ionospheric time delay is primarily a function of solar ultraviolet radiation. A reasonable surrogate measure of the amount of ultra–violet radiation produced by the sun which is responsible for ionizing the earth's atmosphere, and producing the ionosphere, is the number of sunspots visible on the solar surface. Figure 6 illustrates the last two solar cycles with the period indicated during which the GPS measurements were made. This period was in the declining phase of the current solar cycle, therefore, the ionospheric time delay values measured are approximately half the values expected at the peak of the solar cycle.

The data set used in this ionospheric variability study is the first continuous, well-calibrated, dual-frequency GPS ionospheric data set large enough for statistical research. The TEC parameter, however, has been studied for over twenty years using measurements of the Faraday rotation of linearly polarized radio waves transmitted from geostationary satellites. For comparison with the GPS TEC data study, Figure 7 is included to represent the daytime cumulative probability of equivalent vertical ionospheric time delays at the GPS L1 frequency, as determined from the Hamilton, MA 1981 Faraday rotation data. This data is from a high solar activity year and should represent near-worst-case ionospheric time delays encountered in the mid-latitude region. A comparison of the 1981 results (Figure 7) and the recent GPS daytime statistics (Figure 4) illustrate an agreement in seasonal behavior with summer producing the smallest daytime values and equinox exhibiting the greatest day-to-day variability. It also illustrates the ionospheric time delay dependence on solar activity, with the 1981 data producing median values that are nearly two times those encountered during the 1992–1993 period.

IONOSPHERIC MEASUREMENTS USING THE TURBOROGUE ICS-4000Z

A few weeks of ionospheric measurements using GPS dual-frequency signals were recorded recently at the AOA offices at Westlake Village, California using the TurboRogue Model ICS-4000Z receiver. This receiver has the capability of tracking eight satellites simultaneously. Figure 8 illustrates the equivalent vertical time delay, in ns at L1, measured for one day during that period. This receiver provides much better spatial coverage with up to eight satellites visible simultaneously. In the data collected, a minimum of five satellites were visible at any one time. The passes showing large positive temporal gradients, seen particularly between approximately 0900 and 1700 hours local time were observed from satellites viewed at low elevation angles to the south of the receiver. These are manifestations of the latitude gradients in the ionosphere as viewed from a single station. From a single station the ionospheric time delay can be measured at latitudes up to 15 degrees away from the station.

An advantage of the Rogue-type receivers is their ability to automatically switch to a codeless mode of tracking when the P-code on any satellite is encrypted by Anti-Spoofing (A-S). In this mode, continuous ionospheric measurements are made possible by cross correlating the L1 and L2 signals, (Srinivasan, et. al., 1989). Because of the inherent lower signal to noise ratio obtained by the receiver when the satellites are in the A-S mode there is a higher level of system noise. However, this higher noise level does not greatly affect the normal attempts to measure ionospheric time delay values.

A comparison of P-code and codeless ionospheric measurements is shown in Figure 9. For this comparison, the receiver was set to simultaneously track the same satellite on separate channels using both the fully coded and the codeless, cross–correlation techniques. Figure 9a shows the differential group delay and phase delay obtained with P–code tracking. The approximate elevation and azimuth angles of the satellite are printed under the curve. Figure 9b shows similar results with data obtained by codeless tracking. Here, system noise provides the greatest error, particularly at elevation angles lower than 30 degrees. However, no difficulties were encountered in fitting the codeless differential carrier phase data to the codeless differential group delay data, despite the obviously much higher noise for codeless group delay case. Ten–second sample rates were used for both the code and codeless channels. Since the receivers make measurements at 50 per second, at a 10–second sample rate a total of 500 measurements are averaged per point.

Figure 9c illustrates the difference in delay between the coded and codeless data. A constant difference of approximately 1.1 nanoseconds at L1 is apparent throughout the pass. That difference is due to the asymmetry in the correlation function, and the difference in the correlator in the code versus the codeless mode in this version (2.8) of TurboRogue firmware. This difference between code and codeless tracking in the TurboRogue has been corrected in receiver firmware versions 3.0 and beyond. The noise in the resultant ionospheric time delay measurement at L1 in the codeless mode is comparable with that found by Meehan, et. al., 1992. It is much less than one nanosecond with ten–second averaging.

CONCLUSIONS

The GPS dual–frequency system provides an accurate source of ionospheric time delay measurements. The general results of the TEC variability study agree with prior studies using the Faraday rotation technique to measure TEC. From this study, it is obvious that reliable GPS measurements greatly depend on the accuracy of the receiver and individual satellite biases. The receiver biases can easily be calibrated, but the GPS satellite T_{gd} biases still have an uncertainty of approximately 1 to 3 differential nanoseconds.

The Mini–Rogue and TurboRogue receivers used in this study proved to be reliable in making highly accurate relative measurements of ionospheric time delay, only limited by the GPS satellite T_{gd} offsets. The receivers ability to automatically switch into cross–correlation mode when A–S is turned on insures continuous ionospheric measurements in the presence of Anti–Spoofing. In this codeless mode, the TurboRogue continued to provide accurate measurements of the ionosphere with ten–second time resolution.

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QUESTIONS AND ANSWERS

Marc Weiss, NIST: How do you know that the noise that you see in the group delay is measurement noise and not actual physical fluctuations of the ionosphere?

R. Snow: Primarily because of the smoothness of the carrier phase. The carrier phase is a much more precise measurement. And that doesn't show that rapid fluctuation. If there were real noise you would see fluctuations in the carrier phase or in the signal to noise ratio, which you do not see. Most of that noise is due primarily to multi-path and measurement noise in the receiver; but primarily multi-path. That is why it grows so much at low elevations.

Claudine Thomas, BIPM: You showed some graphs with vertical delays due to the ionosphere. How did you get these because you are measuring the line of sight to the satellite?

R. Snow: Yes, I'm sorry I didn't go over that. What is done is we convert the equivalent delay that we measure through the line of site to the local vertical delay by using the secant of the angle. The measurement that we are using, we are determining the centroid of the ionosphere which is about 400 kilometers above the earth; so the point with that ray path intersects the centroid of the ionosphere is converted to a local vertical by using a secant of the angle.

Claudine Thomas: Yes, you just choose the elevation of the satellite and nothing else.

R. Snow: Well, we are actually using the angle. Yes, it is a combination of the elevation.

Claudine Thomas: Well, I don't know if it is complete, if this is a complete process to do that. The other point is that I don't know why you need the $T - gd$ with the P–code receiver. I don't think you need the T_{gd}.

R. Snow: T_{gd} tells you the time difference between when the two signals are transmitted. If this is not correct then it will add as an error source to what you measure.

Claudine Thomas: Yes, for sure. But when you use a P–code receiver, like the TTR4P, you don't need the T_{gd} I think.

R. Snow: No, I think you do. You need to know when the L1 and L2 P–codes were transmitted. And the T_{gd} tells you that difference. If you don't know that, it can be off by three ns; that three ns adds to your delay. So you must know the time at which they started the transmission as well as the arrival time. And they are not totally synchronous at the time of the transmission. The offset is the T_{gd}. If they were totally synchronous, if the T_{gd} were zero, we wouldn't have a problem.

Claudine Thomas: Yes, I know about that. Because when we have compared your TTF4P with another receiver, we had to deal with that T_{gd}. But I think in the TTF4P there is no values for the T_{gd} which I introduced.

R. Snow: The values are in the navigation message.

Claudine Thomas: Yes, but they are not decoded and introduced.

R. Snow: No, they are not used in real time, that is correct. All of the data which I showed you was done post–mission, not real time.

Dr. Winkler: I have a quick question. In your reduction to the vertical, you are using only elevation but not azimuth. Shouldn't you account for the azimuthal variation also? Wouldn't that be useful?

John Klobuchar, AF Phillips Lab: Well of course you should take into account the azimuth as well as elevation. But you have to know the gradients in order to that. And you in general don't know the gradients well enough. So to first order, we just take into account the thickness parameter which is a function of elevation angle.

I would like to make another comment on the T_{gd}. Perhaps you don't understand what T_{GD} really is. If there were no ionosphere at all, you would measure some "equivalent" ionosphere just because the satellite doesn't transmit those L1 and L2 10.23 MHz modulated signals in phase. So consider the case of no ionosphere where you see a perfectly calibrated receiver would still measure some apparent number of electrons. In fact, sometimes they might measure fewer than zero electrons. And this is the most serious problem; it has nothing to do with the receivers. The receivers are calibrated properly; it has to do with the satellites. And each satellite has a different offset between the L1 minus the L2 modulation phase. It is unknown; it may be changing; it is a difficult thing to measure now that they've been launched; and there is still a lot of question about that down to the last, as Robert said, three to six ns of equivalent delay at 01(?).

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The NIST Internet Time Service

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Abstract

We will describe the NIST Network Time Service which provides time and frequency information over the internet. Our first time server is located in Boulder, Colorado, a second backup server is under construction there, and we plan to install a third server on the East Coast later this year. The servers are synchronized to UTC(NIST) with an uncertainty of about 0.8 ms RMS and they will respond to time requests from any client on the internet in several different formats including the DAYTIME, TIME and NTP protocols.

The DAYTIME and TIME protocols are the easiest to use and are suitable for providing time to PCs and other small computers. In addition to UTC(NIST), the DAYTIME message provides advance notice of leap seconds and of the transitions to and from Daylight Saving Time. The Daylight Saving Time notice is based on the US transition dates of the first Sunday in April and the last one in October. The NTP is a more complex protocol that is suitable for larger machines; it is normally run as a "dæmon" process in the background and can keep the time of the client to within a few milliseconds of UTC(NIST).

We will describe the operating principles of various kinds of client software ranging from a simple program that queries the server once and sets the local clock to more complex 'dæmon" processes (such as NTP) that continuously correct the time of the local clock based on periodic calibrations.

Introduction to the Internet

The current internet is based on the ARPANET, a small network started in the 1960s and originally funded by the Department of Defense. The network has grown dramatically in the last decade and now connects thousands of sites worldwide. One of the important reasons for the success of the network is its support for a group of relatively simple message protocols whose structure is largely independent of the details of the underlying transmission medium. Two of the most widely used protocols are the User Datagram Protocol (udp) and the Transmission Control Protocol (tcp); both of these are in turn built on a common base called the internet protocol (ip) and hence are usually referred to as udp/ip and tcp/ip.

An important concept supported by the internet protocols is that of a logical connection – a connection between two processes on two different machines so that messages sent by one

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are received by the other without either end–point needing to be concerned with the details of the physical realization of the network or the topology of the intervening path. A machine may have more than one of these logical connections active at the same time, with two independent processes transmitting and receiving messages over the same physical connection. This multiplexing requires a hierarchical address – both the source and destination addresses must contain not only the address of the machine, but also some identification of the process on the machine that is the source or destination of the messages. This end-point is usually called a port, and it is identified by a port number. A process that wishes to communicate over the network must logically connect to the port to send and receive messages.

The protocols also support the concept of a server process – a process on a machine that is continuously "listening" for connections and performs some action whenever a connection request is received. There are often several such processes on any machine; they may each be actively listening for connections or they may designate a super–server that listens on behalf of all of them. The response is basically the same in either case – a request to a specific port on the machine logically activates the server process that has advertised its willingness to respond to that type of request. Once the server process has been activated, the communication between it and the client proceeds transparently through all of the intervening layers in both machines – both of them see the connection as if it was a dedicated physical circuit with full–duplex capabilities.

If a server process is to be useful, the client must know which port it is listening to, since the port number must form part of the request for service. A group of standard "well–known" port numbers have been assigned to address this issue, and all machines on the internet are expected to conform to these standard assignments. The mail–server, for example, is expected to be listening for connections on tcp/ip port 25; other well–known services have similar port assignments (Comer, 1991, pages 167 and 201).

Three ports have been assigned for time services. Port 13 is for the "daytime" service using either the tcp/ip or udp/ip protocols; port 37 is for the "time" service using either tcp/ip and udp/ip protocols, and port 123 is for the Network Time Protocol (NTP) using udp/ip only. This paper describes a server whose time is synchronized to the NIST clock ensemble; it will respond in the appropriate format to time requests on any of these three ports from any client on the internet.

Time Formats

In addition to defining a standard port number for each service, it is equally important to define a standard message format. These formats are specified in a series of documents called "Requests for Comments" or RFCs. The RFC documents are numbered sequentially in chronological order; revisions to a protocol are usually assigned a new number so that many of the lowered-numbered documents have been superseded and are obsolete. The RFC documents are available in several formats from the Network Information Center (Comer, 1991, Appendix 1). The daytime protocol is specified in RFC–867, the time protocol is in RFC–868 and the Network Time Protocol in several documents including RFC–1119, RFC–1128, RFC–1129 and RFC–1305.

1. The Time Protocol

The time protocol is the simplest one to use. The server listens on port 37 and responds to a request in either tcp/ip or udp/ip formats by replying with the time in UTC seconds since 1 January 1900. The response is an unformatted 32–bit binary number; the conversion to local civil time (if necessary) is the responsibility of the client program. The 32–bit binary format can specify times over a span of about 136 years with a resolution of 1 second; there is no provision for finer resolution or for increasing the dynamic range. The transmitted time will wrap–around through 0 in the next century and, if the protocol is still in use at that time, there will be a 136–year ambiguity in the transmitted time thereafter.

The strength of this protocol is its simplicity – many computers connected to the internet keep time internally as the number of seconds since 1 January 1970 (or sometimes since 17 November 1858) and a conversion between the received time and the internal format is a simple matter of binary arithmetic. This strength must be balanced against several serious weaknesses:

a. There are two difficulties with the handling of leap seconds – a practical one of what time to transmit at the leap second and a conceptual one of how to specify the time afterwards. The choices depend on whether or not the clients are assumed to know that a leap second is currently being inserted and whether they can remember all of the previous leap seconds to correct the transmitted time afterwards. The simplest solution is to adjust the time on both the server and the client at the time of the leap second, which is equivalent to pretending afterwards that the leap second did not happen. This raises difficulties when a client tries to compute the time interval between two epochs on opposite sides of a leap second, but this difficulty is a generic one and is not limited to computer clocks.

b. The protocol is awkward for machines that keep time internally as time of day plus the date (PCs fall into this category) since the conversion of the received message to the internal format in the client requires a full knowledge of the vagaries of the calendar and the time–zone system and of the transitions to and from daylight saving time.

c. There is no provision in the message for additional information such as the health of the server, and the protocol cannot be easily expanded without the risk of breaking the software in some clients.

2. The Daytime Protocol

The daytime protocol has many of the advantages of the time protocol and addresses many of its short–comings as well. The server listens on port 13 and responds to a request in either tcp/ip or udp/ip formats by replying with the time and date as a line of text whose exact format is not specified in the standard beyond the requirement that it be composed of human–readable standard ASCII characters. We have chosen a format for the daytime service which conforms to the very broad requirement of RFC–867 and which addresses many of the short–comings that characterize the time format we have just discussed. Our message format is very similar to the format used by our ACTS system (Levine et al., 1989). A typical message is shown below:

MJD	YY–MM–DD	HH:MM:SS	D ST	L S	H	Adv.	
49302	93 – 11 – 11	17 : 30 :42	00	0	0	50.0	UTC(NIST) *

The message consists of a single line of text; the identifying characters in the legend above the line have been added here to show the significance of each field. The first number is the Modified Julian Day. It is included for those systems that keep time as the number of seconds since some epoch, since the conversion between a Modified Julian Day number and such formats is a simple matter of binary arithmetic and does not require a knowledge of the calendar. The next 6 numbers are the UTC date and time as shown by the legend and can be directly understood by a human observer and easily used by machines that use the date and time system internally. (Although this format can transmit the time during a leap second in a natural way, I discuss below a number of reasons for not doing this.) The DST flag and LS flag give advance notice of the transitions to and from daylight saving time and of the imminent occurrence of a leap second, respectively. The format is the same as in the ACTS system:

If DST is 0, then the US is currently on Standard Time; if DST is 50 then the US is currently on Daylight Saving Time. If DST is between 49 and 1 a transition from Daylight Saving Time to Standard Time is imminent. The DST value is decremented at 0000 UTC every day and the transition will arrive at 2 am local time when the counter is 1. If dst is between 99 and 51 a transition to Daylight Saving Time is imminent. The DST value is decremented at 0000 UTC every day and the transition will arrive at 2 am local time when the counter is 51.

If LS is 0 then no leap second is imminent. If LS is 1 then a leap second is scheduled to be added after 23:59:59 UTC on the last day of the current month. That second will be called 23:59:60, and the next second will be 00:00:00 of the next day. If LS is 2 then a leap second is scheduled to be dropped at the end of the current month. The second following 23:59:58 will be 00:00:00 of the next day.

The server itself transmits UTC and therefore experiences no internal discontinuity during the transitions to and from Daylight Saving Time, but there is likely to be a discontinuity during a leap second. As pointed out above, there is an ambiguity in what to transmit during and following a leap second depending on whether or not the client is assumed to know of its existence and whether or not it knows how to parse a time of 23:59:60. After the leap second has occurred, this ambiguity is resolved in the server by adjusting the time of the server and pretending that the leap second did not happen. There are many reasons for making this adjustment gradually by slewing the clock rather than suddenly by stepping it. This adjustment will therefore take a finite time to complete, so that the time of the server may be ambiguous while it is going on. The client software will face the same problem during leap seconds and may also have a much larger version of it each Spring and Fall when Daylight Saving Time starts and ends if its internal clock is set to local time rather than to UTC. The client, too, must choose between slewing the clock and adjusting it in one step. The first alternative results in a clock that is wrong for a significant period of time, and the second may play havoc with many of the time–dependent processes on the machine. Many implementations of the client software choose the single–step alternative in both the leap–second and Daylight–Saving–Time situations; the leap–second adjustment could be implemented by parsing both 23:59:59 and 23:59:60 as 23:59:59.

The H parameter gives an estimate of the health of the time server, with a value of 0 indicating fully healthy. Positive integers indicate increasingly poor health; both the magnitude of the possible time errors and the uncertainty with which they are known increase as this parameter increases from 0. Users who need the time with an uncertainty of less than 1 second should not use the message if the health parameter is non–zero and those who need the time with an uncertainty of 3 s or less should not use the message if the health parameter is greater than +1. A value of +2 indicates a time error of up to 5 minutes and values greater than this indicate an internal failure in which the time error may be small but cannot be determined.

The final parameter gives the time advance in milliseconds. The entire packet (not just the terminating on–time marker) leaves the server early by this amount to compensate approximately for the delay in the travel time through the internet. Within the continental US, travel times on the internet range from about 30 ms to 150 ms, so that the packet is likely to arrive within 100 ms of the correct time anywhere in the US. This parameter is fixed at the present time since our experience with ACTS indicates that this accuracy is sufficient for most users, but future enhancements to the server software may estimate this parameter dynamically as is done with ACTS at the present time.

The message ends with an asterisk for compatibility with the ACTS format, but this character has no special significance as an on–time marker since the entire message will most likely be transmitted and received as a single network packet. The time advance parameter applies to the entire packet for this reason.

3. NTP – The Network Time Protocol

NTP is the most complex and sophisticated of the time protocols, and it can provide the highest accuracy to a time client as a result. It normally runs continuously on the client as a "dæmon" (background) process; it periodically queries the server and makes small adjustments to the local time based on the data that it receives. The server responds to each query with a packet in a special NTP format that is built on the udp/ip network protocol (Mills, 1991). The client software can also be configured to query several servers and to average the responses in a statistically robust manner. In particular, it evaluates the response of each server against the average and is prepared to consider the possibility that one of the servers is broken. NTP must receive its calibration data via the noisy internet, and it will be limited by the un–modeled noise in the transmission medium. It is most likely to have problems at intermediate periods of a few hours or so, because the internet noise in this period regime is likely to have low–frequency divergences (which would appear in an Allan variance analysis as Flicker or Random–Walk Frequency Modulations) that are difficult to estimate because they are not amenable to improvement by averaging.

Server Synchronization

Our server was initially synchronized to UTC(NIST) using periodic calls to the ACTS system. We found that the time of the server could be kept within 0.8 ms RMS of UTC(NIST) by calling ACTS once every 3000 s. We are currently upgrading the server so that its clock is phase–locked to a 1 pulse/s signal received directly from the clock room. This signal is stretched to 125 s and is connected to the machine in such a way as to generate an interrupt every second. These interrupts can initiate the phase–lock task which in turn adjusts the internal clock so that its time is an exact even second. Periodic calls to ACTS are also scheduled, since the phase–lock process cannot detect a slip of an integer number of seconds. This process can keep the internal clock within 100 s RMS of UTC(NIST). The improvement in the accuracy and stability of the reference time of the server is unlikely to be noticed by the users, since the uncertainty in the received time is dominated by the uncertainty in the travel time across the network.

Both synchronization methods have advantages and disadvantages: the phase–lock system is easier to implement but requires a direct 1 pulse/s signal; the ACTS system requires much more complex software but can be used to implement a stratum–1 clock anywhere a telephone line is available. We plan to use both of these methods in the future in constructing additional time servers. This could greatly reduce the jitter due to the network delay for many users since the distance between them and a server would be much smaller.

Access to the Server

Our primary network time server is named time_a.timefreq.bldrdoc.gov, and its internet address is 132.163.135.130. A backup server named time_b.timefreq.bldrdoc.gov is being constructed; its address is 132.163.135.131. The times of both servers will be synchronized to UTC(NIST) using the phase–lock method we have outlined above.

We have written example software that can be used to set or check the time of a client machine by parsing the "daytime" format response of the server. The client software includes a routine to convert the received message to local time, if necessary; conversion to daylight saving time is also supported. This software can be adapted to run in most software and hardware environments, requiring only a network connection and standard interface software to send and receive messages on the internet. It provides a time capability similar to the ACTS system (but at lower accuracy) without the need for making toll calls. The example software is publicly available via anonymous ftp from the primary network time server in directory /pub/daytime. Both the source code and the documentation are in this directory.

We have also written example software to access the time service, but this service provides less information than the daytime service with no appreciable increase in accuracy, and we do not recommend its use. This service is often used by time programs that are supplied with commercial network software for PCs. These programs usually require external environmental information to specify the time–zone of the user and what to do about daylight saving time. Examples of how to specify this information are in the documentation in the directory specified above.

The software for the Network Time Protocol is widely available, and is often bundled with the operating system itself. It is normally distributed in source code with instructions for how to build it for many different environments.

Conclusions

The NIST Network Time Service provides time information to internet users that is directly traceable to UTC(NIST). The information is provided by a time-server located in Boulder; the server will respond to requests for time in several different formats. The simpler formats are well suited to the needs of small computers with modest accuracy requirements, while the more complex formats can provide substantially better accuracy at a substantial increase in both the size and complexity of the client software.

One of the synchronization algorithms we have developed for the server itself uses periodic calls to our ACTS service to synchronize the time of the server; it could be used to construct a stratum-1 time-server needing only a standard voice-grade telephone line for synchronization. This server might be connected to a local network that is disjoint from the internet or it might be used as a stand-alone machine wherever accurate time-stamps are required.

Acknowledgements

I am grateful to David Mills of the University of Delaware, the designer of NTP, for many helpful discussions. This work is supported in part by grant NCR-9115055 from the National Science Foundation through the University of Colorado.

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QUESTIONS AND ANSWERS

Dr. Winkler, USNO: This is a remarkable experiment. We have for the last half year or so made regular timings between our station at Richmond and Washington. And we find that in that network, through that connection which we have, delays are vastly different from second to second. They are in fact traffic-dependent. It is a packet-switch network and in this packet–switch network each node of course retransmits the packets, depending on its own local traffic. So for that reason the actual noise which you see is a function of time of day. So that is why we have abandoned that, actually, as a practical missile for the dissemination of time, of timing between stations; and we are also looking at circuit boards with GPS receivers which is much more economical and more precise.

J. Levine: I agree with you 100 percent. May I show another slide? What I did was say let's measure the delay between Boulder and Washington; and let's measure the outbound delay and the inbound delay. So here you have it. Boulder or Washington go through 16 gateways: Denver, St. Louis, Chicago, Cleveland, New York, etc. The delay is 59 ms. This is measured kind of average. Back delay: Washington to Boulder turns out to be a very strange delay, because it goes through NIST Gaithersburg and then in one step it makes it to NIST Boulder. The delay: 55 ms. The answer is the difference is a few ms; it is remarkably the same. Of course four ms, that is the kind of the noise you are going to get; or four, or ten or 12 or some number like that.

Dr. Winkler: May I add just one thing? During these experiments we have not advanced by 50 milliseconds but one-half of the round-slip delay as measured at that moment.

Tom Becker, Air System Technologies: Is this transfer done on a transactional request basis? Or are these two machines essentially logically connected continually?

J. Levine: All of the protocols have to put up a request to the server for the time. In the case of the time and the daytime protocol, you do it by hand; in the case of NTP, NTP schedules itself with a variable time ranging from a few minutes to a few hours. If you don't ask, you don't get.

Tom Becker: Yes, it would seem that if it were a continuous process and there were very many people doing this, the network would be overloaded just by time transfer information. What happens then in–between requests? What would a local machine do to maintain accurate time?

J. Levine: Well again that depends on what your client software is. If you have NTP, then NTP is a dæmon and it is making small adjustments to your client software. If you are using the other protocols, then nothing happens and your clock is free running.

Tom Becker: NTP does or does not run on PCs?

J. Levine: NTP is probably too big for most PCs. There is no reason why it couldn't run in principle; it is mostly a matter of size.

Tom Becker: But you are not aware of an implementation of NTP for PC?

J. Levine: It is written in C; it should run on a PC if you didn't run on a hardware speed first. But I really don't know the answer to the question.

REPORTS ON OTHER CONFERENCES

FREQUENCY CONTROL SYMPOSIUM

Jack Kusters, Hewlett–Packard:

Good morning. I have been asked to talk on the Frequency Control Symposium. One thing that has happened since the symposium became part of the IEEE is that our name has gotten much longer. It used to be the "Annual Symposium on Frequency Control;" it's now the IEEE International Frequency Control Symposium.

The 1993 symposium was held in Salt Lake City. We had 129 paper summaries that we received; we accepted 104. Many papers were combined, and that is one of the reasons that it perhaps looks like we had many more rejections than we really did. But there were 12 tutorial sessions, four separate tracks, three sessions per track; and we now have the auspices of Dave Allan as essentially a permanent tutorial chair to make sure that our tutorials end up having some coherence from year to year. Rather than giving the same talk over and over again, we can actually now plan out several years in advance. We think it is quite effective.

The attendance last year was 297 people, down slightly from 1992. I think we had 308. We had thirty–six complementary attendees; four were students. And one of the most important things we have been doing in the last couple years is funding a number of foreign visitors, primarily eastern Europeans. There have been also some people from the People's Republic of China coming to give talks. Those people, for the most part, need virtually full funding, especially for transportation to and support while in the United States. So it turns out to be a rather substantial expense. We have been very lucky to have monies coming from the various agencies that are associated with the Frequency Control Symposium, and companies that are donating money. We had 87 people for the tutorial sessions, up from 1992.

Some of the other activities that are somewhat of interest: this past year we took a survey of conference attendees, specifically asking them to evaluate six things, such as a potential change in date. Frequency Control has always been almost exactly out of phase with PTTI, we're almost exactly six months apart. So that was done by design and it seems to work out extremely well. We tested the flavor of the symposia attendees, and for the most part there is no desire to change meeting dates. Apparently this six–month time lag seems to work extremely well as far as the two symposia are concerned. However, 75 percent were in favor of occasional foreign meetings – and you see that as we get down into this slide. The 1994 meeting is in Boston at the Westin Copley Place; it promises to be at least an interesting place to have a meeting. The Local Arrangements Chairman is Mike Garvey. In 1995, it is at the Fairmount

Hotel in San Francisco. I am the Local Arrangements Chairman. If you wish any information on any of these, contact one of us.

1996 – whereas this is PTTI's 25th anniversary, in 1996 we will have the 50th anniversary of the Frequency Control Symposium. And this will be our first excursion off the continental United States. Our plan is to hold this in Hawaii. The local chair is John Vig. 1997 is Orlando, Don Malocha will be the Local Arrangements Cochair. 1998 will probably be a West Coast meeting, we don't know where yet. 1999 – we are talking about holding a joint meeting with the FTF in Europe. You will probably hear more about this when the person from EFTF gives his report. We're looking at setting up an arrangement such that we can periodically hold meetings in the United States and in Europe with the FTF. The periodicity may be about five years. But there is still a lot of logistic things to be worked out, such as responsibility for the conference and financial as well as sponsorship by organizations. And so this is something that we're working on. And beyond 1999, right now there are no concrete plans.

That is a very quick report of the status of the Frequency Control Symposium. It continues to draw around 300 people; we continue to get a very good, wide selection of technical papers associated with technology and theory. And it looks like the symposium is still healthy and going well. Any comments or questions?

QUESTIONS AND ANSWERS

John Gerhard, Rockwell International: I am Chairman of the Board of the Measurement Science Conference. And you mentioned that you fund travel for foreign attendees, primarily from China and the Soviet Union –

Jack Kusters: Well, the Eastern European countries; we have people from Bulgaria, the former Czechoslovakia, the former Yugoslavia – I'm not going to remember where they are actually from these days.

John Gerhard: Yes, we've had requests from the Japanese and other people for funding, and I didn't know if other conferences did that as part of a budgetary thing; and whether they get a really good return on their investment. Because travel is expensive.

Jack Kusters: Travel is very expensive. And we have been able to do some fairly decent arrangements. We've been able to work out deals with airlines to handle that in a certain direction. We have been doing it for two years now. Do we get a return investment? Certainly in the technical areas that are associated with the Frequency Control Symposium, specifically in the material areas. There are activities going on today in Russia that far surpass anything that is happening in the United States. And without having this kind of interchange, we wouldn't be as well versed in it as we are now.

So I think there is virtue. Do all of the people who come here to present papers give us this kernel of knowledge? No. It is like any other series of papers that we receive. But we get far more submissions from Eastern Europe than we can possibly handle. So we cherry–pick; we try to find the best ones. And I think we have been reasonably successful.

Dr. Winkler: Yes, I agree.

Jack Kusters: There are several other members of the committee here and I think we are content with where our money is going.

EUROPEAN FREQUENCY AND TIME FORUM

Laurent–Guy Bernier, Observatory de Neuchatel: Good morning. This report will be very short. My goal is to give some of the people here the urge to go through the proceedings and dig out what is important for them. I can only give only a rough idea of what happened at the European Frequency and Time Forum.

It was held in Neuchatel, Switzerland in March of this year. And there were 20 percent more attendees than the year before, so you see that it is still growing. Fifteen percent of the papers were from non–European countries. And there were 11 invited papers, 67 contributed papers, 45 posters, for a total of 123. And there were 15 papers from Eastern European countries. So that gives you an idea of the proportion. Many of these papers came from Russia, but some of them were from Rumania, Poland, and Czechoslovakia. An interesting thing is that from the Eastern European countries some papers were from government agencies. But there were a few papers from industries in Russia that produced quartz crystals and instruments. So these statistics give you an idea of the health of the European Time and Frequency Forum.

For the first time, there was a tutorial on the day before the beginning of the forum. And there were three working sessions on quartz crystals, their applications in control loops and appropriate measurement techniques. And with more than 50 participants, this first tutorial was quite a success.

The opening session was marked by the excellent insight of the keynote speaker, John Vig, with his paper about driving forces affecting precise time and frequency. And another two invited papers focused on space application and telecom application. And this is a really expanding thing in the forum. There was also a paper by Dr. Reed of British Telecom about timing of digital signals and telecommunication network synchronization. And Dr. Andreyanov, from the Astro Space Center of the Lebedev Physics Institute in Moscow, gave a paper about time and frequency synchronization in the Radioastron Space VLBI satellite.

There was a full session devoted to telecom applications, and two sessions for space applications. And one interesting paper was about a European GPS overlay system for the use of GPS in civil aviation. Other sessions included information about oscillators, quartz crystals, frequency control competence, etc. There were also sessions on time scales and instrumentation; time transfer and telecom. There were reports on the use of H–masers in time scales, as compared to their cesium counterparts. Of course there were reports about time transfer using GPS and GLONASS. There were two full sessions devoted to primary cesium frequency standards. One important thing is that in Germany at the PTB, they are now operating a fourth primary standard. And all four standards agree to plus or minus 1.8 to the minus 14 accuracy.

There was significant progress in the understanding of Majorana transitions, which may be of importance in conventional as well as in new cesium frequency standards. There were several avenues to better understanding of the biases in cesium beam standards that were discussed, the configuration of the RF field, the new configuration of magnetic fields, among other things.

There was a report on optical pumping of cesium at NIST. There were reports about the new atomic fountains, especially the fountain operated at Oxford University. They obtained a two–Hz bandwidth in this fountain. There were reports also on cryogenic H– masers and

H–masers for space application.

The last thing that I will mention is that there was a session about new development in frequency standards. There is an Ytterbium ion trap operated in Germany that obtained a very narrow line, and Xenon for future optical frequency standard. Thank you.

INSTITUTE OF NAVIGATION

Ron Beard, Naval Research Laboratory: I would like to give a brief report on the Institute of Navigation's – actually the Satellite Division's meeting – on the Global Positioning System, which was held in Salt Lake City on the 21st through the 23rd of September of this year. This was the sixth international technical meeting of the Satellite Division, so it was a relatively young meeting. However, it is a very fast–growing meeting. At the first meeting, I think the attendance was on the order of this meeting, or perhaps a little less (at the first meeting); the sixth meeting, this last September, I think the attendance was around 1300 people. It has grown enormously.

There were 21 sessions in three days, three of which were running simultaneously for most of the sessions, except the beginning session which was a plenary one. It was held at the convention center in Salt Lake City and took up a large fraction of the center; so it is a large meeting. It was proceeded by two days of tutorials given by the Navtech Information Company, who did a very extensive tutorial session on GPS and the various applications of it.

One session, Session 2–C, was the Range Applications and the PTTI session. It was combined with Range Applications from the prior year because of the lack of papers. However, this year PTTI dominated the session. There were six papers given and they were all on PTTI. Overall there were 203 papers given in the conference, eight of which came from students. They have a student competition that students can compete in when coming to the conference at ION expense and membership in ION and that sort of thing. Twenty five abstracts were submitted, of which eight were chosen and presented at the meeting.

If you compare the ratio of papers, four percent of the papers given dealt with PTTI. That is interesting, considering PTTI was probably your first operational use of GPS and is one of the strongest support for that system. However, the applications of GPS are so diverse and are being integrated into so many systems that it is difficult to keep up in all these different areas. For example, the sessions ranged from geographic information systems to spacecraft orbit trajectory, GPS receiver technology, military applications, attitude determination, marine navigation, unique or unusual applications, differential navigation, integrity, ionospheric observations, observing the earth, vehicular navigation. The applications of GPS seemed almost endless.

The contributions of PTTI into this conference I think is somewhat disappointing, considering the low percentage of participation on that score. So I would encourage anyone here – and I know a number of people here were also at that meeting – to submit more papers. The planning committee for this meeting is concerned about that, as to whether to even offer it as a session during their meetings, because of a lack of papers. I would encourage everyone to submit papers on this so that we can really show what the contribution of PTTI and use of GPS really is in this area. Thank you very much.

CIVIL GPS SERVICE INTERFACE COMMITTEE MEETING

David Allan, Allan's Time: Good morning. This report will be very brief. I think we all know of the tremendous contribution that GPS has made to the time and frequency community. As of January of this year, an official memorandum of agreement was signed between the DoD and the DoT which effectively establishes it as a permanent service through the year 2005, to be used by DoT and the civilian sector. And so we have, as you might say, an opportunity to utilize this; and certainly it has been, but it is a matter of recognizing the tremendous momentum that exists in the civilian community, utilizing the service that GPS can provide.

The committee, CGSIC, is a civil GPS interface committee. It was set up specifically in agreement between DoD and DoT so that information can flow – it is really an information-flow organization – from the military to the civilian users, about the status of GPS. Within this CGSIC, there are three subcommittees. One is an international cooperative, pulling different nations together in terms of their political concerns, as well as utilization of the system. The other one is essentially differential GPS for position determination. The Coast Guard is one of the main drivers for this; they are very actively using differential GPS off the coast with information about the SA signal so that non–secure receivers can be navigated at about a 10–meter accuracy level at some hundreds of kilometers off the coast. And that is not a very active system.

The third committee is the Timing Subcommittee, and that is the one that I can report about as chair. Dr. Lewandowski cochairs that with me, and this slide shows the cover page for the last meeting, which was held in conjunction with the meeting just reported about the ION conference in Salt Lake City. We met two days prior to that conference and there is about a half inch of summary records of the minutes. If anybody wants to get those, you can access them from the Coast Guard. Specifically the Timing Subcommittee serves a variety of functions and organizations in a broad sense. The generation of international atomic time and UTC is critically dependent nowadays on GPS common view, as was reported yesterday. We also serve the international timing centers generally to make sure that they have as best information as we can give them from DoD about GPS performance. The Deep Space Network for JPL is integrally tied to GPS in the common–view mode. Direct access to GPS is becoming more and more utilized by the telecommunications industry; our committee is often represented by people from Telecom Solutions, from AT&T, and they are very active participants in this Timing Subcommittee.

The power industry has come on board in the last year or two. We heard an excellent paper yesterday on the utilization of GPS in BC Hydro and Power Authority. NIST has provided a global time service now for about a decade in which we use GPS common view to provide the very accurate time and frequency from the U.S. Frequency Standards Lab and Time Scale at Boulder, Colorado. In 1984, we set up a system at Arecibo. Other places as well are using GPS to time the very predictable millisecond pulsar timing signals of which now there are about a dozen such pulsars being studied. This has an incredibly high interest level. Those of you who follow physics know that Professor Taylor at Princeton just received the Nobel Prize for his work in this regard. This promises to be one of the potential candidates which may detect actual gravity waves and document their existence in a terrestrial sense.

There are other precise timing systems that I won't take time to go into. But anyway, this committee is quite active; and we feel it is service–oriented in providing a useful service because of the tremendous potential that GPS provides for the civil sector.

Let me just share a couple of results. Dr. Lewandowski presented some of the same things that he reported to you yesterday. We do comparisons with GLONASS, look at the accuracies of GPS, the effects of coordinates, the effects of the ephemeris ionosphere. I will not repeat those, as you saw those yesterday. The one thing that has been very useful in terms of telecom and the power industry and some of the civil users who don't want to do common–view is the realization that one can characterize the spectrum, as we showed last night, in a very simplistic way, using the $\sigma - x(\tau)$; you probably can't read this very well, this is the square root of the time variance that we developed last night. This would be 10 ns, 100 ns. And we see this very typical behavior on all of the satellites. It kind of random walks away; there is a decorrelation time of the order of 300 seconds or so; and then it behaves normally tau to the one-half, which would be modeled by white phase modulation process. And once you develop this model and you can do similar to what Dr. Thomas showed yesterday, some averaging, and effectively average out most of the SA. From a theoretical point of view, it looks like you can average it out so that, in fact, it would be as good as if SA were not there.

So from a civil point of view, this is extremely useful. We studied it both across all the satellites and as a function of several passes. I showed this graph last night. This is over a sequential five–day period. This is the square root of TVAR, you see max at tau; and again, we peak up integration times at the order of 300 seconds. It changes slightly from day to day, but one can make a very nice model and mask for this and design algorithms appropriately.

So I think we have a very encouraging direction for the civilian users in this regard. We have a very active committee and it is fulfilling its purpose as a service organization. Thank you.

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RUSSIAN NATIONAL TIME SCALE LONG–TERM STABILITY

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Abstract

The Institute of Metrology for Time and Space NPO "VNIIFTRI" generates the National Time Scale (NTS) of Russia — one of the most stable time scales in the world. Its striking feature is that it is based on a free ensemble of H–masers only. During last two years the estimations of NTS longterm stability based only on H–maser intercomparison data gives a flicker floor of about $(2 \rightarrow 3) \times 10^{-15}$ *for averaging times from 1 day to 1 month. Perhaps the most significant feature for a time laboratory is an extremely low possible frequency drift - it is too difficult to estimate it reliably.*

The other estimations, free from possible inside the ensemble correlation phenomena, are available basing on the time comparison of NTS relative to the stable enough time scale of outer laboratories. The data on NTS comparison relative to time scale of secondary time and frequency standards at Golitzino and Irkutsk in Russia and relative to NIST, PTB and USNO using GLONASS and GPS time transfer links gives stability estimations which are close to that based on H–maser intercomparisons.

INTRODUCTION

The time and frequency standards and time scales long term stability characteristics are of great importance especially for the national time keeping centers which usually deals with averaging time up to several years. Then one may use such stable time scales itself for frequency comparisons with primary Cs standards or as reference for fundamental researches.

The lions share of advanced time laboratories usually do not use output signal of individual, even extremely stable, clocks as the laboratory's time scale, but use a so–called "paper clock", which constitutes the set of time and frequency corrections applied to the output signal of individual clocks. These corrections originate from a time scale algorithm which use as input information clock ensemble intercomparison data. The sophisticated time algorithm may significantly improve characteristic of the "paper clock" compared to individual contributors, and may even produce a time scale which is better than every individual clocks, but nevertheless correlated frequency drift of the time keeping instruments can not be detected based on time comparison inside an ensemble only. That's why in order to estimate confidently and accurately time stability of individual clocks and "paper clock" one needs an additional comparison data

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relative first of all to primary Cs standards or at least stable enough time scales of outer laboratories.

STABILITY ESTIMATIONS BASED ON INTERCOMPARISON DATA

To begin with some words about operational H–masers. Nowadays our laboratory possess 10 commercially manufactured H–masers, four of them of similar design are installed at separate room and have operated since 1989, the other part consist of two groups of instruments: four instruments of quite different design the physical package of which is installed in a refrigerator at temperature about 0 °C started operation at the middle of 1992 and are located at two separate rooms. Two last instruments have the same design as first group, and have operated since this spring and locate together with their elderly brothers.

We present here, Fig. 1 and Fig. 3, a portion of H–maser intercomparison data for four elder masers (No. 47, 49, 50, 51) and one instrument which locates in refrigerate (No. 53). Due to some problems in data collection system the only actually available data for long term analysis are 1 pps time differences between H–masers at one day basis with resolution about 1 ns. One may find more detailed information on intercomparison technique details in [1].

Fig. 1 shows not original intercomparison data but ones with removed deliberate constant frequency difference between instruments and cut and pasted to remove all detected time steps. The Allan variance plot, Fig. 2, shows typical flicker floor for H–maser's time difference under consideration at level about $(2 \rightarrow 3) \times 10^{-15}$ for ten day averaging time. Somewhat worth results are depicted for shorter averaging time, but this is effect of inadequate resolution 1 pps signal measurements. Measurements with significantly better resolution using phase comparing technique confirm stability of every H–maser at a level about $(2 \rightarrow 3) \times 10^{-15}$ for averaging times from 1 hour to 1 day. Along with it the worth estimation of possible frequency drift gives value about $(5 \rightarrow 6) \times 10^{-17}$ per day for 49-51 difference. Because of the limited number of samples (432 samples at 1 day basis) confidence of Allan variance for 100 day averaging time is not high and the above mentioned estimation of frequency drift also is not reliable enough.

Next pair of Figures 3 and 4 depict H–maser comparison data relative to TA(SU) for the period about 1000 days starting the begin of 1991. The original data were subjected to the same processing as previous ones. Important remark – there is no difference between TA(SU) and UTC(SU) but constant bias and leap second embedded into UTC(SU). Perhaps the most striking feature of Fig. 3 is the obvious frequency drift of H–maser No. 51. As a matter of fact it does not pose significant problem for time scale generation because, as one sees, this is well predictable process. For example one may estimate value of this drift at one year basis and then get the clock reading prediction using second order model. The gained error for one year forecast is less than 300 ns, this value comparable with gained time error of non–drifting instruments.

The Allan variance plot depicted at Fig. 4 confirms the long term stability of individual H–masers which was presented in Fig. 2. Because of the limited number of 10 day samples (N = 101) the confidence level of estimations for 300 day averaging time is not too high. Nevertheless

H–maser No. 51 linear frequency drift estimation gives the same value as previously, about $(5 \rightarrow 6) \times 10^{-17}$ /per day. The other instruments under consideration do not show detectable frequency drift. Basing on at presented data of individual H–maser stability one may expect improvement of TA(SU) based on these 4 clocks up to factor two. Since as it was mentioned it is possible to predict more or less reliably frequency drift of H–maser No.51 one may expect stability level for TA(SU) about 3×10^{-15} for time intervals up to 1 year.

All presented estimations are based on H–masers intercomparison only, even results relative to TA(SU) which in turn is based on H–maser intercomparison data also. That is why it is interesting to compare these estimates relative to time scale of independent laboratories.

STABILITY ESTIMATIONS BASED ON TIME SCALE COMPARISON WITH REMOTE LABORATORIES.

Fig. 5 presents Allan variance plot for time scale difference between TA(SU) and atomic, that means uncorrected and based on H–maser intercomparison data only, time scales of two other laboratories inside Russia. These laboratories are Golitzino, which is located about 50 km from Mendeleevo and Irkutsk which situated in East Siberia in the vicinity of Baikal lake. Each laboratory is equipped with an ensemble of H–masers consisting of at least four instruments. Time difference data originates from GLONASS common–view manual sessions. For one month and more averaging time presented plot reflects time scale characteristics namely and shows the best relative stability level may be better than the 1×10^{-14} level.

Apart from internal estimates we would like to present here stability data relative to some world known time scales. For this presentation we have two sources of data. First of all this is BIPM Time Section official publications – Circular "T". Starting in 1992 time information in it concerning UTC(SU) and TA(SU) is based on GPS common view sessions data under international time comparison schedule. This publication gives us any time difference we like at ten day basis. We have chose four time scales from three laboratories. The other source of data is direct comparison with PTB basing on original GPS common–view session data exchange between two laboratories starting 1993. This last source gives us information on one day basis.

Allan variance plots for time differences between TA(SU) and some laboratories originate from above mentioned time transfer links are depicted at Fig. 6. First of all some commentaries to result based on Circular "T". Dependencies referred to TA(NIST) and TA(PTB) look qualitatively different from those for TAI, TA(NISA) and TA(USNO) – TA(SU) manifests white FM relative to TA(NIST) and TA(PTB) and somewhat similar to random walk frequency fluctuations relative to other scales.

Qualitative similarities in estimations based on TA(NIST) and TA(PTB) do not look astonishing because of these time scales are syntonized to cesium SI second – the first (TA(NIST) in software way[2] and the other in hardware. The difference between them and TA(NISA) and TA(USNO) is also obvious - each of the latter is based on a free ensemble of clocks.

Despite these remarks presented data show for averaging times of one month and more the best stability estimation of TA(SU) is about $(2 \rightarrow 4) \times 10^{-15}$. This value is quite similar to that based on H–maser intercomparison. We would like to underline that estimates based on direct comparison between two laboratories IMVP and PTB give similar results. The last result seems us to be very important because of this is comparison of time scales based on different physical processes – TA(SU) is based on a free ensemble of H–masers and TA(PTB) on continuously operating primary Cs standard.

TA(SU) as time scale of free running ensemble of H–masers looks in many extends similar to EAL (Echelle Atomique Libre, i.e. free atomic time scale) which is produced by BIPM Time Section and which is based on readings from more than 150 clocks located at various laboratories[3, 4]. Fig. 7 shows corresponding stability estimations of TA(SU) referred to TA(PTB) and EAL referred of Cs2 PTB. Due to many similarities in TA(PTB) and Cs2 PTB especially for 1992–93 one may consider Fig. 7 as very successful presentation of modern high stable H–maser's ability to contribute significantly to the EAL at least for moderate averaging time. One may see that possible value of TA(SU) frequency drift doesn't exceed corresponding value for EAL (about 2.5×10^{-17} per day) and we hope to obtain in the coming years additional data to get more confident estimation of its actual value.

Acknowledgements

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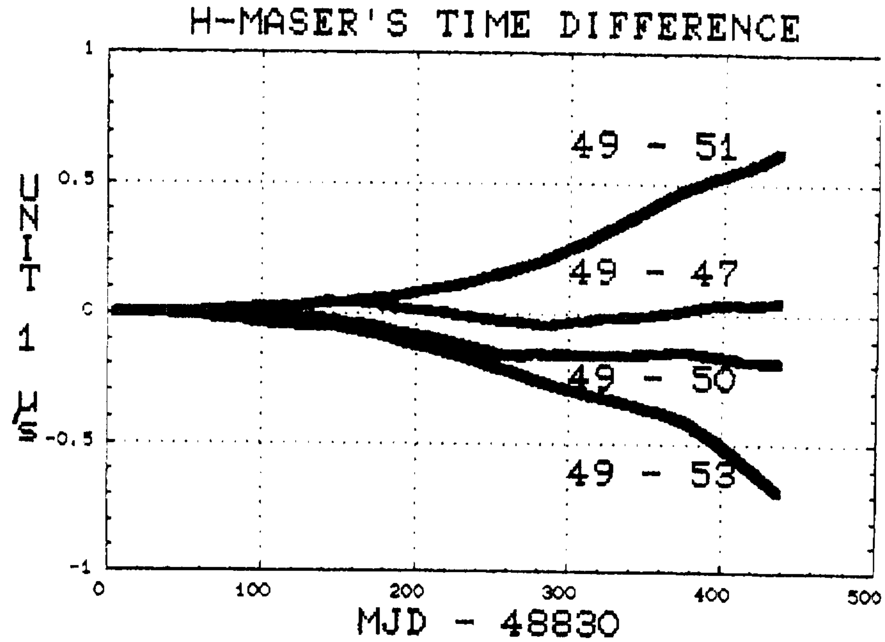


FIGURE 1

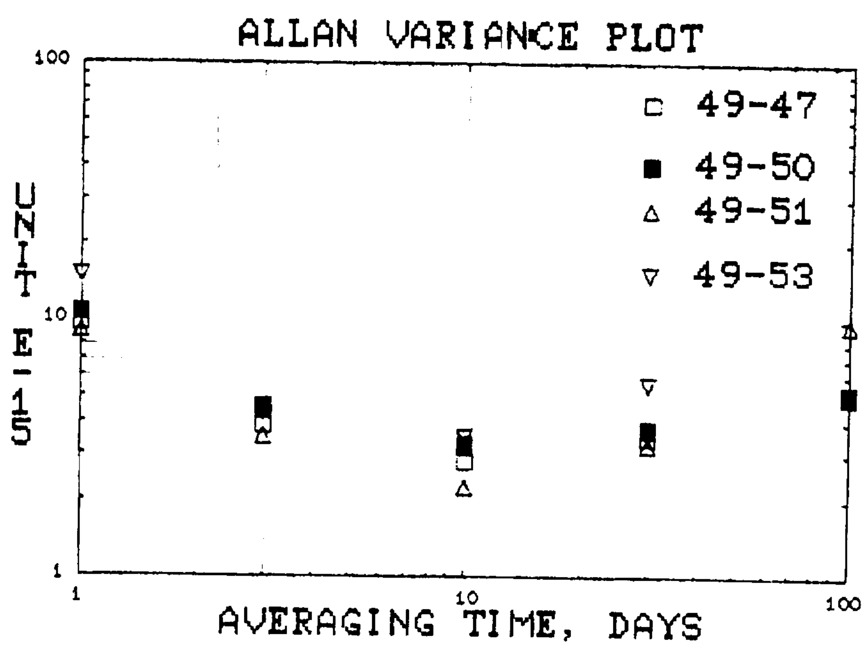


FIGURE 2

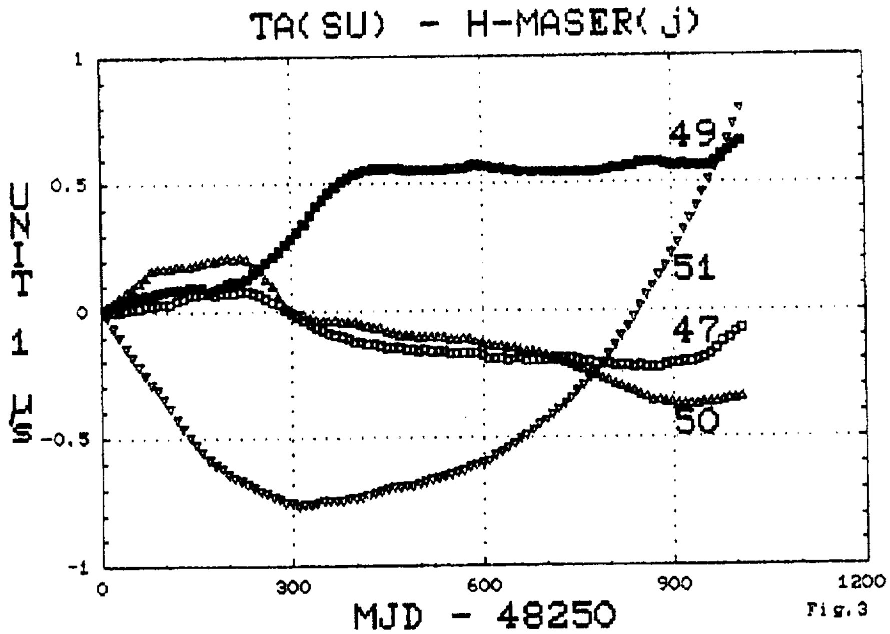


FIGURE 3

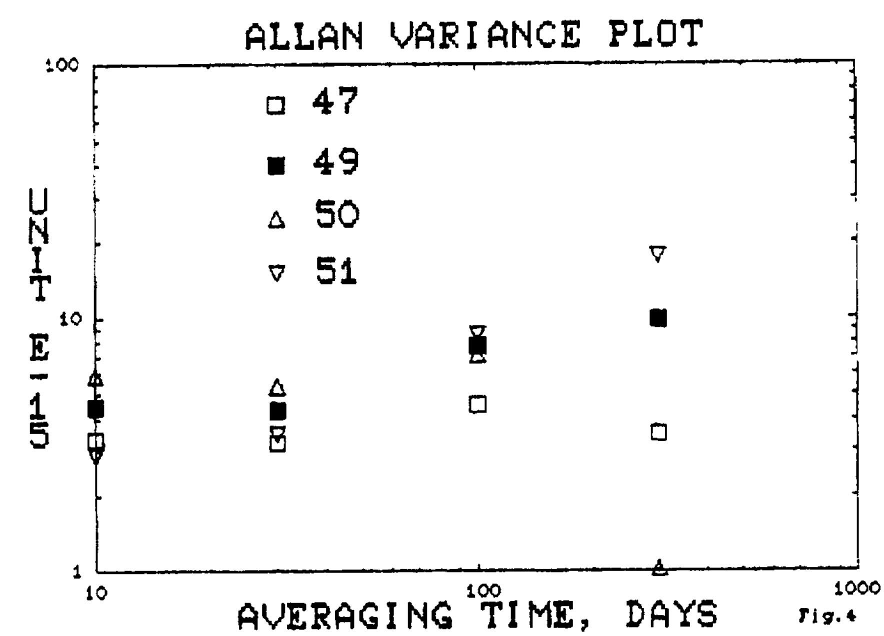


FIGURE 4

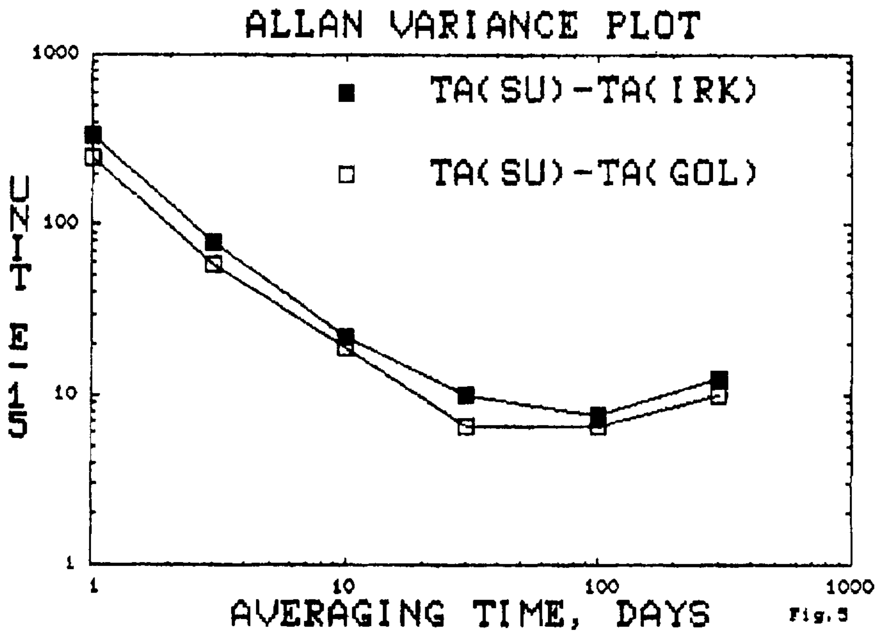


FIGURE 5

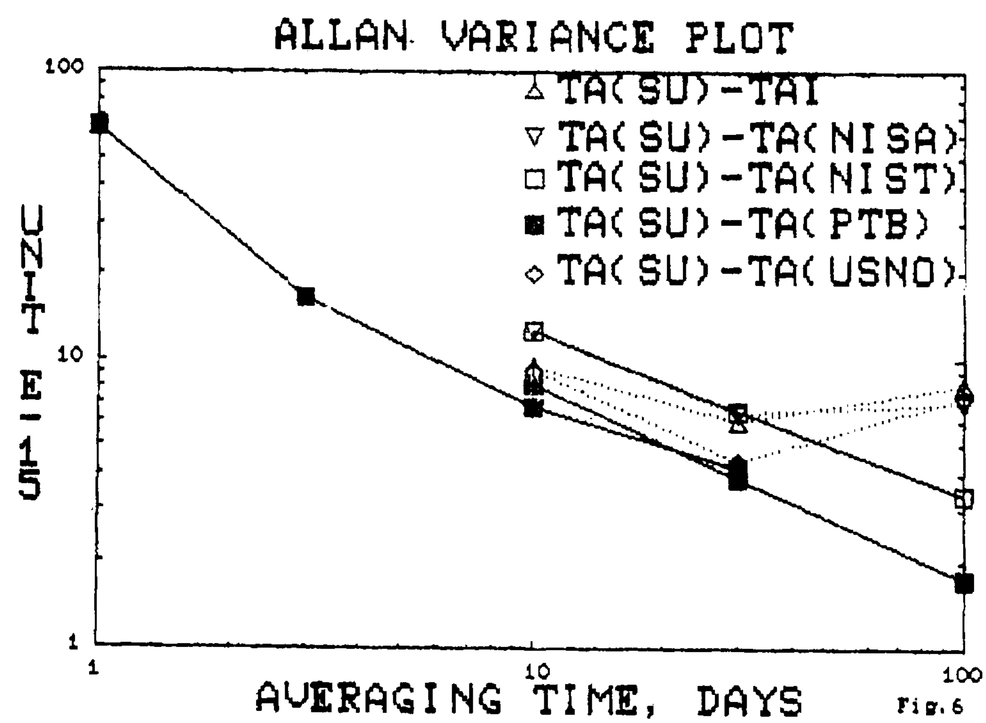
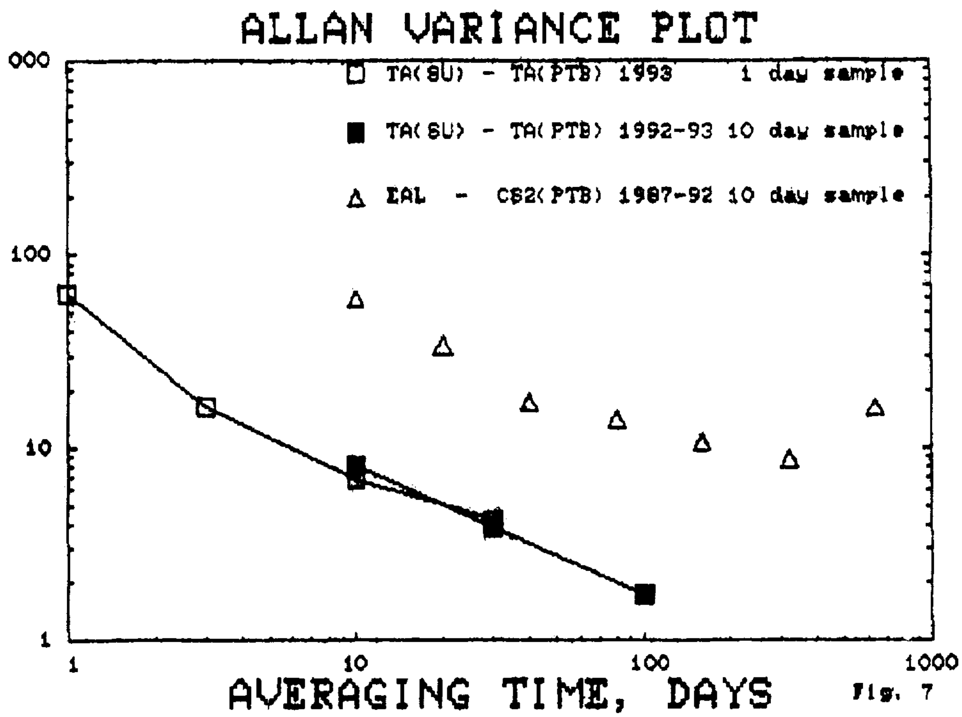


FIGURE 6



ALLAN VARIANCE PLOT
TA(SU) - TA(PTB) 1993 1 day sample
TA(SU) - TA(PTB) 1992-93 10 day sample
EAL - CS2(PTB) 1987-92 10 day sample
000
100
10
1
1
10
100
1000
AVERAGING TIME, DAYS
Fig. 7

FIGURE 7

QUESTIONS AND ANSWERS

Dr. Winkler, USNO: Have you seen any evidence that they have abandoned the meteor trail synchronization which they use between Moscow and Irkutsk and other stations in Siberia?

Mr. Allan: They, as near as I can tell, are still actively using the meteor trail technique.

Dr. Winkler: In addition to GLONASS?

Mr. Allan: Yes, it is quite embedded. I suspect with time, as GLONASS satellites become more and more prolific – they don't have a full constellation yet. And so I suspect until they do it will be a gradual transition. But it is quite embedded in their system and meteor trail technique.

J. Levine, NIST: Would you mind putting that slide back up? I just want to make sure I understand it. Does that mean that the red is TA(SU) minus TA(NIST) and it is better at 100 days than against TAI?

Mr. Allan: That's right.

J. Levine: This scale is free–running?

Mr. Allan: Yes. That is their claim.

J. Levine: Okay, that is not what I would have thought would happen.

Claudine Thomas, BIPM: You showed us two Allan variance plots. One, between a TA(SU) and Irkutsk, I think. And we see a minus one slope noise. And then something which is surely due to the performance of the hydrogen masers themselves or the time scales, which is, as I understand, about one part in ten to the fourteen.

Mr. Allan: Right.

Claudine Thomas: And then you showed us another Allan variance plot which was obtained in Moscow and Medeleevo between the different hydrogen maser charts. And then the number is much smaller.

Mr. Allan: Yes.

Claudine Thomas: It goes until only one or two parts in ten to the fifteen.

Mr. Allan: That's correct.

Claudine Thomas: Do you think that it means that the hydrogen masers we chart in Moscow are more or less correlated in the long–term or middle term?

Mr. Allan: You cannot rule out correlation. That is certainly true. Unfortunately the FAX machine cut off the data for longer integration times. They do have data out here and it does behave still in the same vicinity. But that doesn't say they are not correlated. So to answer your question, I don't know that you can rule out correlations.

Claudine Thomas: Yes, so we don't know the answer about that.

Mr. Allan: We really don't.

Claudine Thomas: Because, you know it is a concern for the BIPM because we are receiving all these hydrogen masers which are active hydrogen masers with an autotuning mode, but we are not sure that the autotuning mode is somewhere, and it helps to correlate them. And our concern, of course, is to have independent clocks. So this is the first time that I have seen these plots. The question is open.

Mr. Allan: The PTB number, which would be quite independent, you see that the PTB number and the NIST number are –

Claudine Thomas: Yes, TA(PTB) is PTB Cesium 2.

Mr. Allan: Yes, this is Cesium 2 and would be an independent clock. And that would maybe rule out correlation. So this number would agree with the laboratory numbers to some degree.

Claudine Thomas: TA(SU) is a very simple average of four or six hydrogen masers. And TA(PTB) PTB Cesium 2 – what can you conclude? I don't know if we can conclude something about that value. It is the last value for 100 days. It seems to be smaller than the stability coming from PTB Cesium 2 itself. So I don't know if we can conclude anything about that.

Mr. Allan: Well the question is maybe there is nothing with long–term data with which to compare it. But this would indicate that maybe there is validity to the very good long–term stability of the maser. PTB is independent.

Al Kirk, JPL: Did they give you the mechanism that causes the frequency of some of the masers drift negative and others as positive?

Mr. Allan: That drift is very tiny. I don't think they know. They do have servo–cavity tuning.

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USING GLONASS SIGNAL FOR CLOCK SYNCHRONIZATION

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p. 8

Abstract

Although in accuracy parameters GLONASS is correlated with GPS, using GLONASS signals for high-precision clock synchronization was up to the recent time of limited utility due to the lack of specialized time receivers. In order to improve this situation, in late 1992 the Russian Institute of Radionavigation and Time (RIRT) began to develop a GLONASS time receiver using as a basis the airborne ASN-16 receiver. This paper presents results of estimating user clock synchronization accuracy via GLONASS signals using ASN-16 receiver in the direct synchronization and common-view modes.

INTRODUCTION

At present the use of satellite navifation system signals is one of the most high-precision ways to clock synchronization on global scale. Various aspects of time synchronization via GPS signals are discussed in diverse references, for example [1, 2]. Over the last 2 - 3 years, several experiments of time synchronization via GLONASS signals were also held [3, 4]. But using GLONASS signals for clock synchronization was limited for a long time because the lack of commercial time receivers. Therefore RIRT carried out a number of experiments to estimate the possibility of using the commercial airborne ASN-16 receiver as the GLONASS time receiver. Results of these experiments and its analysis are presented in this paper. This results demonstrate that the use of ASN-16 gives the clock synchronization accuracy about 20 ns for one day in a direct synchronization mode and about 10 ns for one day in a common-veiw mode. To provide the automatization of the measuremets and their processing the interface between ASN-16 and PC was held.

BRIEF ANALYSIS OF GLONASS

The full-deployed Russian GLONASS should consist of 24 satellites placed witnin three orbital planes by 8 satellites each plane [5]. The orbital planes are separated by 120°. Satellite orbits are the circular ones with eccentricity less than 0,01, revolution period of 11 h 45 min, altitude of 19100 km and inclination of 64.8°.

Now the space segment consists of 12 - 15 healthy satellites disposed in first and third orbital planes. The satellites are equipped with a cesium time/frequency standard with daily frequency instability no more than $5 \cdot 10^{-13}$ [5]. This provides accuracy of satellite time synchronization relative to System Common Time (SCT) about 15 ns (σ) with uploading time and frequency corrections (TFC) to the satellite twice a day.

SCT is generated on the basis of main synchronizer (MS) time. Hydrogen frequency standards with daily frequency instability no more than $5 \cdot 10^{-14}$ are used as a part of MS. The difference in SCT and UTC (SU) should be less then 1 ms. The accuracy of SCT corrections uploaded to the satellite once a day should be less than 35 ns (σ).

When UTC (SU) is corrected by an interger number of seconds, the time of all system components including SCT are corrected too. However, there exists a constant offset of 3 h between SCT and UTC (SU) due to GLONASS monitoring specific features. Full deployement of GLONASS is scheduled on the end of 1995 [6]. Besides flying tests of modernization satellite named GLONASS-M will start in 1994. The main characteristics of this satellite will be an increased satellite life (span up to 5 years) and use of a new spaceborne time/frequency standard with daily frequency instability no more than $1 \cdot 10^{-13}$. This enables to realize a synchronization of satellite times with an error not worse than 10 ns (σ) with uploading TFC to the satellite once a day. No special measures to degradate the GLONASS signal are planned.

CLOCK SYNCHRONIZATION VIA GLONASS SIGNALS

There are four main methods of clock synchronization via satellite navigation systems signals: direct synchronization, common-view, clock transportation and very-long base interferometry (VLBI) Techniques Over Short Baselines [1]. But the methods of the most utility are the first two ones, which priciples are shown in Fig.1.

The direct synchronization method is the most simple. It provides the global coverage and requires no other data than those received from satellite navigation message. The time difference between the user clock and the SCT or UTC (SU) is given by the relationship (1):

$$\Delta T = S - (D/C - \tau_{ion} - \tau_{trop} - \tau_{rec}) + \Delta T_{sat} + \Delta T_{sct} \qquad (1)$$

where S - measured pseudorange between the satellite and the user, i.e. the difference between two identical codes, one received by the receiver, whereas the other one generated by the receiver; each of these codes is synchronized by its own clock;

D - range from the satellite to the user;

C - speed of light;

τ_{ion} - propagation delay due to the ionosphere;

τ_{trop} - propagation delay due to the troposphere;

τ_{rec} - receiver delay;

ΔT_{sat} - difference between satellite clock and SCT;

ΔT_{sct} - difference between SCT and UTC.

The range from the satellite to the user is computed on the basis of broadcasted ephemerides X_i, Y_i, Z_i and the known coordinates of the receiver antenna X_A, Y_A, Z_A. The difference between satellite clock and SCT is determined on the basis of TFC τ_i, γ_i. The difference between SCT and UTC is directly contained in the navigation message as a SCT correction τ_S.

Since GLONASS navigation messages doesn't include model's parameters for consideration for the ionosphere delay, the ionospheric correction is computed by the user on the basis of parameters which are autonomously stored in the receiver. The tropósperic delay is determined in a similar way.. The receiver delay is calculated by means of its periodical calibration. It follows from the relationship (1) , that the clock synchronization accuracy while using direct technique is defined by the following components:

- the error of pseudorange measuring;
- the instability of receiver delay;
- the error of ionospheric and tropospheric influence consideration;
- the uncertainty of the antenna coordinates;
- the error of the satellite ephemerides;
- the error of the satellite clock;
- the error of SCT correction.

The last three components are dictated by GLONASS's characteristics. That's why the clock synchronization accuracy via GLONASS signals in a direct synchronization mode doesn't exceed tens of nanoseconds.

The common-view method is a technique of a mutual clock synchronization. It presupposed simultaneous measurements at the points of clock location via one of the satellite's signals and further exchange of the results of the measurements. In this case, mutual difference of clock times is determined from the relationship (2):

$$\Delta T_{A-B} = \Delta T_A - \Delta T_B \qquad (2)$$

where $\Delta T_{A,B}$ - the result of determination of each clock's offset relative to SCT or UTC (SU) in conformity with (1).

It is obvious that, due to the elimination of several components, stipulated by GLONASS characteristics, which are common for A and B clock, its mutual synchronization accuracy increases. Therefore characteristics of the receivers which determine the potential clock synchronization accuracy are of great importance.

USE OF ASN-16 RECEIVER FOR CLOCK SYNCHRONIZATION

In order to estimate the possibility of using the commercial airborne GLONASS ASN-16 receiver as a time receiver, a number experiments was carried out in RIRT. The measurements were held simultaneously using two ASN-16 receivers on the basis of RIRT's secondary time/frequency standard (STFS). The uncertainty of the antenna coordinates was approximately 5 m.

The ASN-16 unit, designed by RIRT, is one-channel one-frequency navigation user equipment. While solving the time task it provides the operation via one chosen satellite with output of 1-Hz and the result of determination of the time difference between this signal and UTC (SU). That's why for clock synchronization via GLONASS signals using of ASN-16 an additional counter of a 1-Hz signal difference in ASN-16 output and user's clock is requied. In order to eliminate this defect, one of ASN-16 reciever was reworked to provide a time task solving relative to the external signal of 1-Hz. As a result of this, the ASN-16 reciever takes part of a time receiver. The experiment configuration is shown in Fig.2.

The procedures of experiments were as follows. The 15-minute sessions of measurements were held every half of hour during the day. The data registrations took place every 15 seconds. Then average value $\Delta \overline{T}$ and root-mean-square value δ of the offset between STFS and UTC (SU) were estimated for each session, for every day and over all the interval of the measurements (the drift of the offset between STFS and UTC was eliminated). Simultaneously, the data received had been used for estimation of a mutual clock time difference measurements accuracy using ASN-16 as an average value $\Delta \overline{T}_m$ and rms value δ_m for each session, for every day and over all the interval of the measurements. The results for each session of measurements are given in Table 1, for every day and whole intervals - in Table 2.

The average value of time synchronization accuracy via GLONASS signals in the direct synchrenization mode was 6,8 ns for session, 20.6 ns for one day and 23.3 ns for 5-day intervals for the serial ASN-16 receiver and 7.1 ns; 20.8 ns and 24.4 ns respectively for the reworked ASN-16 receiver. Practically absolute coincidence of the results proved that accuracy characteristics of ASN-16 had not become worse due to the reworking the receiver.

The systematic error of mutual synchronization of the clock with the two ASN-16 receivers was close to zero for a day, and the random error was 6.1 ns for a session, 10.3 ns for a day and 10.0 ns for the whole interval.

An approximate coincidence between the random error of the mutual synchronization of the clock for a session and that of the clock synchronization in direct synchronization mode can be explained by the fact that within one session the influence of the parts, stipulated by receivers characteristics, prevail upon the parts, stipulated by GLONASS characteristics. So there were no essential synchronization accuracy increase. However, for the averaging over a day, the clock synchronization accuracy in a common-view mode is twice better then for direct synchronization mode.

PROSPECTS FOR ASN-16 RECEIVER USE

In order to provide a wider use of ASN-16 as GLONASS time receiver the task of its interfacing with a PC was solved. This provides fully automatic process of measuring and data processing. Module of data exchange between ASN-16 and PC interface is a board installed in PC. With this interface module the setting of ASN-16 operation modes and the reception of the necessary measuring and processing data is provided. The rate of the data output from ASN-16 is 1 second with a period of change of 2 seconds.

The developed software for PC realizes as follows:

- the GLONASS state indication;
- measurements programs generating and realizing;
- data reception and registration;
- real-time time/navigation tasks solving;
- statistical processing and analysis of data;
- ASN-16 operation monitoring;
- data exchange with other users.

The creation of such a measurement system on the basis of ASN-16 receiver and PC will make possible more careful estimation of GLONASS characteristics as the time transfer system and to begin using GLONASS signals for high-precision clock synchronization.

CONCLUSION

The results of the experiments held in RIRT have shown that already at present GLONASS provides time synchronization accuracy about 10 - 20 ns. While using ASN-16 receiver, clock synchronization accuracy of 20 ns for one day in a direct synchronization mode and about 10 ns for a day in a common-view mode is provided.

The further increasing of time synchronization accuracy via GLONASS signals with ASN-16 may be realized using direct pseudorange measurements and solving a time task with PC.

ACKNOWLEDGEMENTS

The authors are pleased to express their gratitude to their colleagues in RIRT for their participation in the experiments and data analysis.

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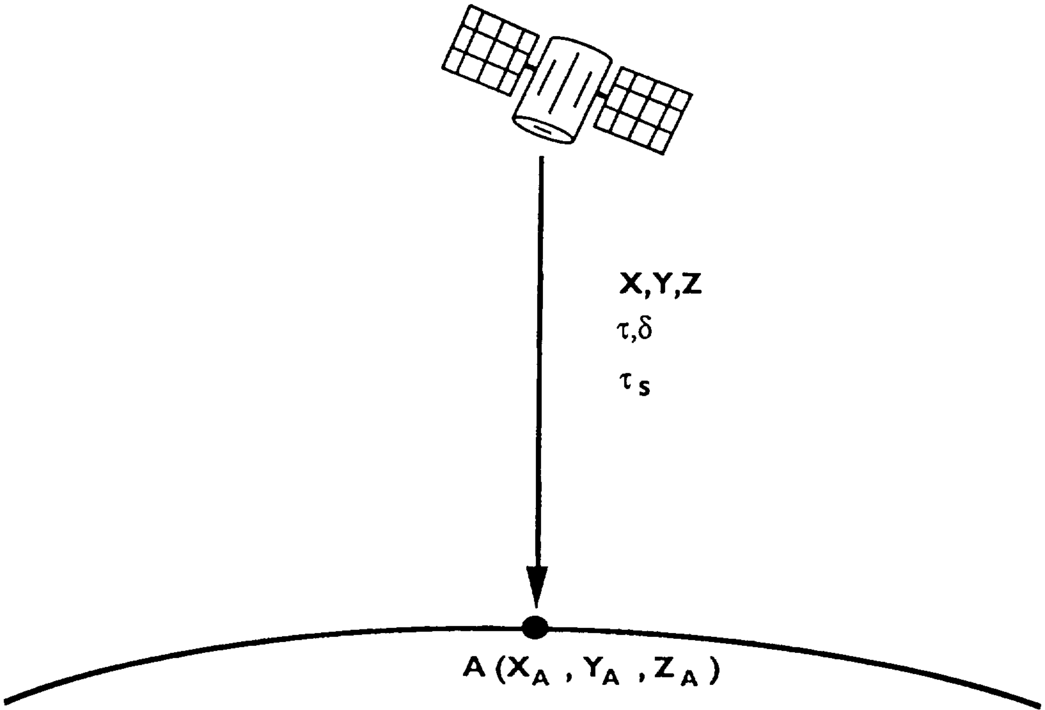
Table 1. The estimations of time synchronization accuracy via GLONASS signals for sessions

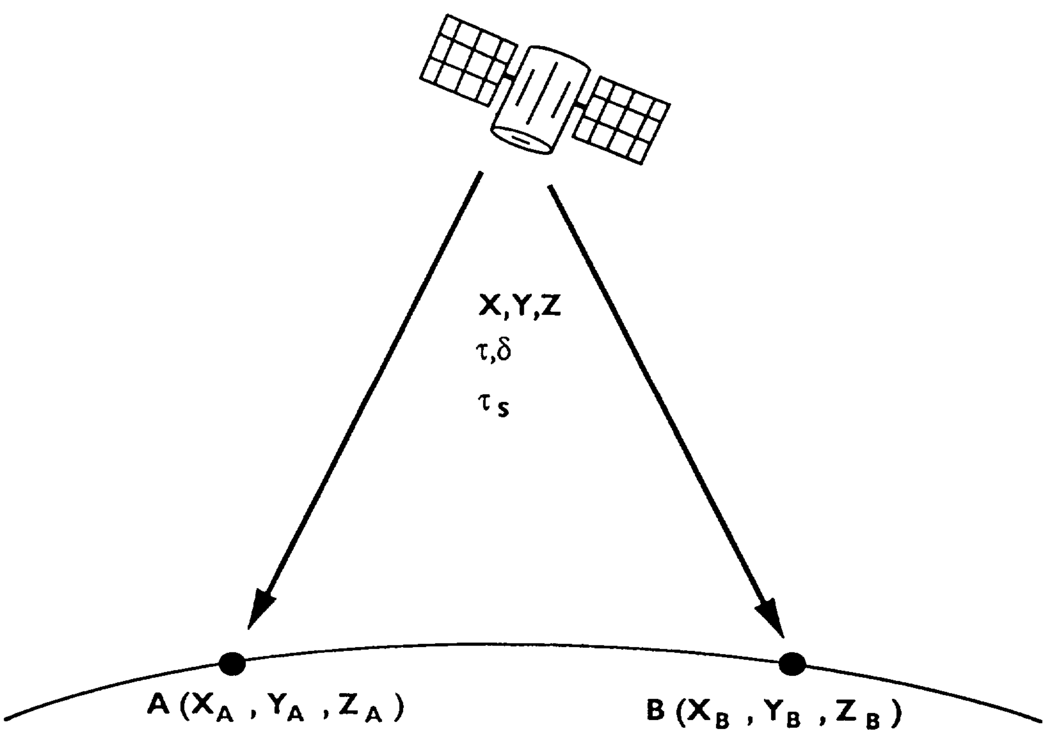
Time	ASN-16 / 1		ASN-16 / 2		common-view	
h, min	$\Delta\overline{T}$, ns	δ, ns	$\Delta\overline{T}$, ns	δ, ns	$\Delta\overline{T}_m$, ns	δ_m, ns
8.00	2522.0	3.8	2539.5	10.1	-17.5	10
8.30	2520.0	0.0	2512.0	0.0	8.0	0.0
9.00	2470.0	0.0	2465.0	7.5	5.0	7.5
9.30	2456.0	8.7	2464.0	4.4	-8.0	10.0
10.00	2520.0	9.9	2524.5	4.3	-4.5	10.3
10.30	2510.5	2.2	2507.0	4.9	3.5	5.0
11.00	2524.0	6.4	2528.5	4.6	-4.5	7.5
11.30	2455.5	5.8	2455.0	7.1	0.5	10.2
12.00	2471.5	3.7	2470.0	3.6	1.5	4.5
12.30	2491.0	3.0	2488.0	4.4	3.0	5.4
13.00	2490.0	5.6	2489.5	4.4	0.5	5.5
13.30	2470.5	2.2	2488.5	4.3	-18.5	4.6
14.00	2470.5	2.2	2468.5	4.6	2.0	4.8
14.30	2511.0	3.1	2506.5	5.1	4.5	5.0
15.00	2511.0	3.1	2508.5	4.4	2.5	4.8
15.30	2532.0	3.9	2534.5	7.4	-2.5	8.0
16.00	2532.5	4.0	2514.0	4.0	18.5	6.3
16.30	2491.0	3.0	2490.0	3.6	1.0	4.4
17.00	2572.0	3.5	2571.0	2.2	1.0	4.1
17.30	2492.0	4.1	2491.5	0.0	0.5	4.1

Table 2. The estimations of time synchronization accuracy via GLONASS signals for every day and the whole interval

Date	ASN-16 / 1		ASN-16 / 2		common-view	
h,min	$\Delta\overline{T}$, ns	δ, ns	$\Delta\overline{T}$,ns	δ,ns	$\Delta\overline{T}_m$,ns	δ_m,ns
21.12	2511.0	18.2	2511.5	17.5	-0.5	9.8
22.12	2591.0	22.1	2591.5	16.4	-0.5	9.3
23.12	2688.0	21.5	2685.5	26.8	2.5	10.9
24.12	2778.0	20.9	2780.0	22.4	-2.0	11.4
25.12	2863.0	19.5	2862.5	20.8	0.5	10.2
21-25.12	2686.0	23.3	2662.5	24.3	0.0	10.0



a) The direct-synchronization technique



b) Common-view method

Figure 1. The direct-synchronization technique and common-view method via GLONASS signals

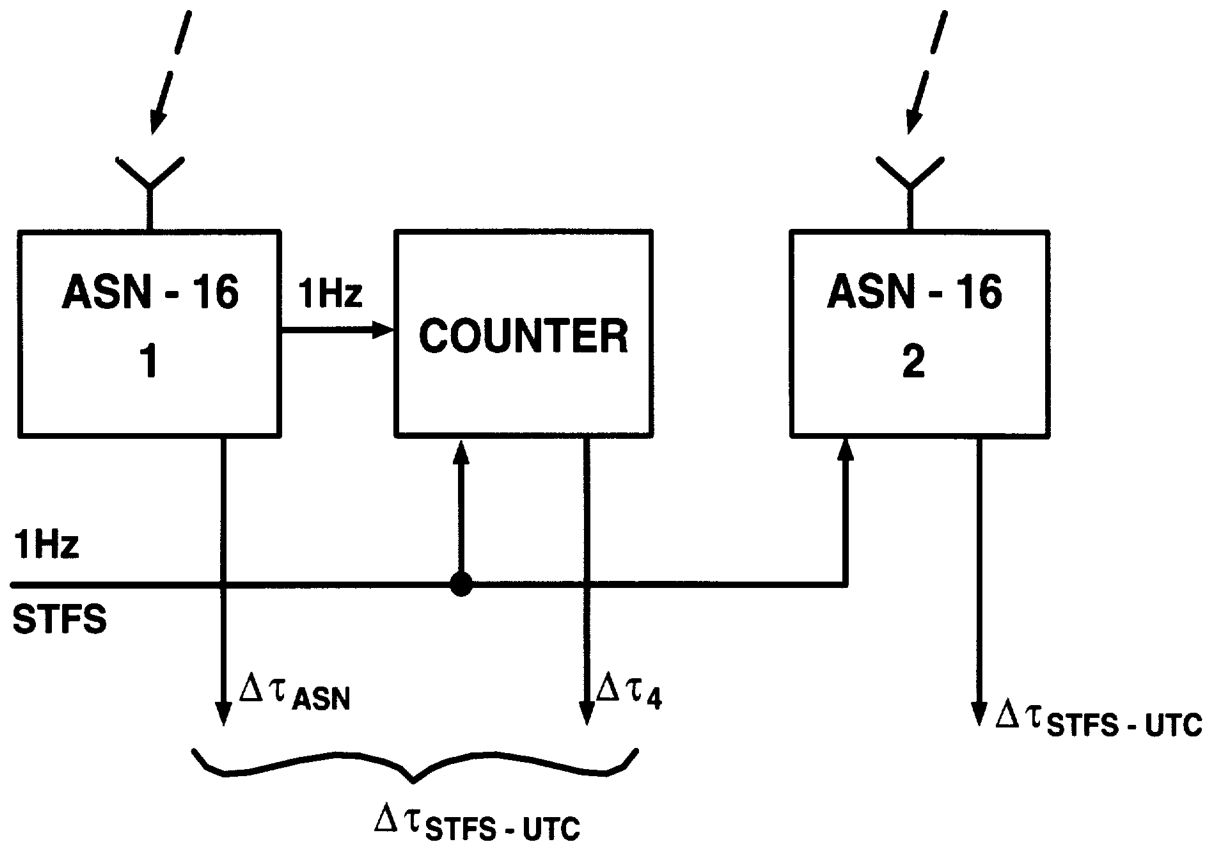


Figure 2. The experiment configuration

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A LOOK INTO THE CRYSTAL BALL, THE NEXT 25 YEARS

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Abstract

The PTTI Planning Meeting was born at about the same time as the atomic definition of the unit of time, the second. This use of the cesium resonance was made possible by advances in quantum electronics during the preceding decade which resulted in commercial availability of cesium, rubidium, and hydrogen clocks and frequency standards. Twenty–five years later these types of clocks still are the backbone of time and frequency applications; together with a variety of crystal oscillators, transmitters, and receivers, as well as signal distribution, conditioning and switching systems, atomic clocks are an essential part of the infrastructure of modern navigation and communication technology. The next 25 years undoubtedly will see a pervasive expansion of PTTI into the infrastructure that supports and leverages industrial, social, environmental, defense, and even individual human activities. Speculation as to what capabilities, services, and personal conveniences may become available, will be limited by two factors: the degree to which existing device concepts can be made more affordable and reliable, and the ability to miniaturize for purposes of compatibility with electronic integration. With regard to the latter, history teaches us that the required technological breakthrough is unlikely to originate in existing technology; thus, we may expect a paradigm shift in PTTI device concepts not unlike the shift in the 1960s from vacuum tubes to semiconductors.

Historical Perspective:

The PTTI Planning Meeting was born nearly coincidentally with the atomic definition of the unit of time, the second. This use of the cesium resonance was made possible by advances in quantum electronics during the preceding decade which resulted in commercial availability of cesium, rubidium, and hydrogen clocks and frequency standards. Twenty–five years later these types of clocks still are the backbone of time and frequency applications; together with a variety of crystal oscillators, transmitters, and receivers, as well as signal distribution, conditioning and switching systems, atomic clocks are an essential part of the infrastructure of modern navigation and communication technology. The underlying three driving forces that maintain and expand this infrastructure are performance, reliability and affordability of the products offered.

The currently deploying systems of globally networked time[1], satellite–based global navigation[2], and high data–rate global communication[3] via satellites, cable, and optical fiber are summarized in Table 1 under "present". Their demands are changing the balance of the three major driving forces that govern the development of hardware and systems: Affordability and reliability have become more important than performance, and, in most cases, either one of them is actually the dominant driving force. This should come as no surprise because time and frequency devices have graduated from laboratory applications and systems feasibility demonstrations to critical components in global networks that are essential to the functioning of modern, industrialized societies. As a further consequence, it has proven extremely difficult to introduce new products with unproven reliability and only marginal or no advantage in performance or affordability. The primary driver in networks is reliability. Once operational, the prime objective of any network is to remain operational and to never disappoint a (dependent) user. Reliability concerns may be motivated by national security, safety, business, or other factors.

Three subordinate elements of reliability are device related; i.e., they are attributes of the clock, oscillator, or receiver: MTBF, turn–on and environmental sensitivity. They can be modified by the technology used, by the design concept, and by detailed design, as well as through parts and materials, manufacturing processes, and storage and handling. The remaining three subordinate elements (redundancy, graceful degradation, and autonomy) are systems related: Redundancy can be achieved by device back–up with one or more spares and often sophisticated switchover that may have to preserve phase and/or frequency. Graceful degradation refers to a careful balance between network and device functions such that network signals can be used to interpolate or even mimic device functions should particular devices fail. Last, but not least, autonomy is a critical concept in networks allowing stand–alone operation of network subnodes, nodes, or subnetworks in case of breakdown of either devices or networks links. Local, regional or even global autonomy is the driving force for the deployment of precision clocks and oscillators within networks; a good example for this is the triple–redundant atomic clocks on board the GPS satellites.

For users, the primary driver is affordability. The user will seek alternatives to time/frequency based solutions if the required performance cannot be afforded. One must keep in mind that affordability is a relative term; e.g., the user will not acquire a clock, oscillator, receiver, or related subsystems if their acquisition or operational costs approach the cost of the host system or platform. Many years ago a proposal for an aircraft collision avoidance system floundered because the cost of a cesium clock exceeded that of some small aircraft!

Evolution of Clocks and Systems

Figure 1 depicts, in its upper part (1950 to 1990), the evolution of clocks and of the time and frequency infrastructure that support today's navigation, communication and dissemination[4, 5]. If we look further in the past, beyond 25 years, to the most significant predecessor systems, we find those depicted in Table 1 under "past". It must be noted that in the evolution of systems (Table 1), as well as in the evolution of clocks (Figure 1), substantive paradigm shifts took place: Fields of science and technology quite unrelated to the original systems and clocks became the progenitors of the new generation of clocks and systems. Globally networked time did not evolve from railroad technology, GPS is not rooted in astronomy, ISDN is not a result of perfecting telephone and radio, and atomic clocks were not conceived by astronomers nor mechanical engineers. Sextant users and pendulum clock makers of the past could not have predicted GPS and atomic clocks. Thus, we should expect another paradigm shift in the future: Although today's clocks, systems, and infrastructure will further mature and grow in scope as well as numbers, the developing intense demand for affordable, reliable, and usable devices will probably not be met by today's time and frequency technology. As in the past, scientific and engineering breakthroughs in unrelated fields will likely displace today's devices. Therefore, it may be of some use to elaborate on the promise of a few, selected technologies:

Important Technologies

a. Advanced ceramics are already of importance for essential components of time and frequency products such as cavities, resonators, and structural components. In addition, advanced ceramics are of great importance to dielectric's and dielectric substrates and thereby to all applications of electronics, especially at very high frequencies. Also, advanced ceramics can be designed to feature certain properties; thus, they offer the potential of engineered material characteristics as required by the designer of a product.
b. Microelectronics and optoelectronics, especially very large scale integration, are of enormous potential for miniaturization of time and frequency devices. Developmental circuit integration is now being pursued at feature dimensions of a tenths of a micrometers or less (quantum wells) offering complete integration of analog, digital and computer functions as well as optical interconnects on one small chip. Furthermore, optoelectronics is important for signal detection as well as signal transmission, especially with very low noise characteristics.
c. Physical and chemical manipulation at the nanometer scale has become possible through advances in lithography and microscopy (scanning, atomic force, etc.). This has led to a new technology, micro–electromechanical (MEM) device technology[6, 7] and to the ability for large scale integration of electronic, optical and even mechanical components.
d. Thin–layer technology is a pervasive generic technology for a great number of applications. These include surfaces of detectors, optical emitters, and crystals. Metalization of crystals, coatings of storage vessels, and gettering surfaces are but a few examples where a better understanding may lead to control of the interaction between solid and liquid, solid and gas, and solid and solid phases.
e. High temperature superconductors offer options ranging from low loss cavities and resonators to advanced high speed electronics and chip–size oscillators based on Josephson junctions [8]. Also, efficient magnetic shielding and shielding against electromagnetic interference as well as the exploration of nonlinear electromagnetic phenomena (mixing and multiplication) appear possible.

Based on the above, it is reasonable to predict extremely stable clocks and oscillators based on solid state or surface phenomena and/or on arrays of electronic, optical or quantum effect components, each of nanoscale dimensions. It is equally reasonable to predict extremely fast electro–optic switching as well as integrated networking with switches, amplifiers, clocks, phase shifters, transmission lines etc., at the nanoscale, mere components of an integrally fabricated system whose reliability and affordability is extremely high; at least as high as today's integrated electronic chips.

Conclusions

The next 25 years undoubtedly will see not only new devices and capabilities but also the pervasive expansion of precision time and time interval techniques into the infrastructure that supports and leverages industrial, social, environmental, defense, and even individual human activities. Reality, as to what capabilities, services, and personal conveniences may become available, will be limited by two factors: the degree to which device concepts can be made affordable and reliable, and the ability to miniaturize for purposes of compatibility with electronic integration. With regard to the latter, history teaches us that the required technological breakthrough is unlikely to originate in existing technology; thus, we may expect a paradigm shift in time and frequency device concepts not unlike the shift in the 1960's from vacuum tubes to semiconductors.

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TABLE 1 PAST AND PRESENT MAJOR SYSTEMS

- **TIME/FREQUENCY:**

  PRESENT:
  GLOBALLY NETWORKED TIME
  (10^{-14} SYNCHRONIZATION)

  PAST:
  RAILROAD SYSTEMS

- **NAVIGATION:**

  PRESENT:
  GPS, GLONASS (METER ACCURACY GLOBALLY)

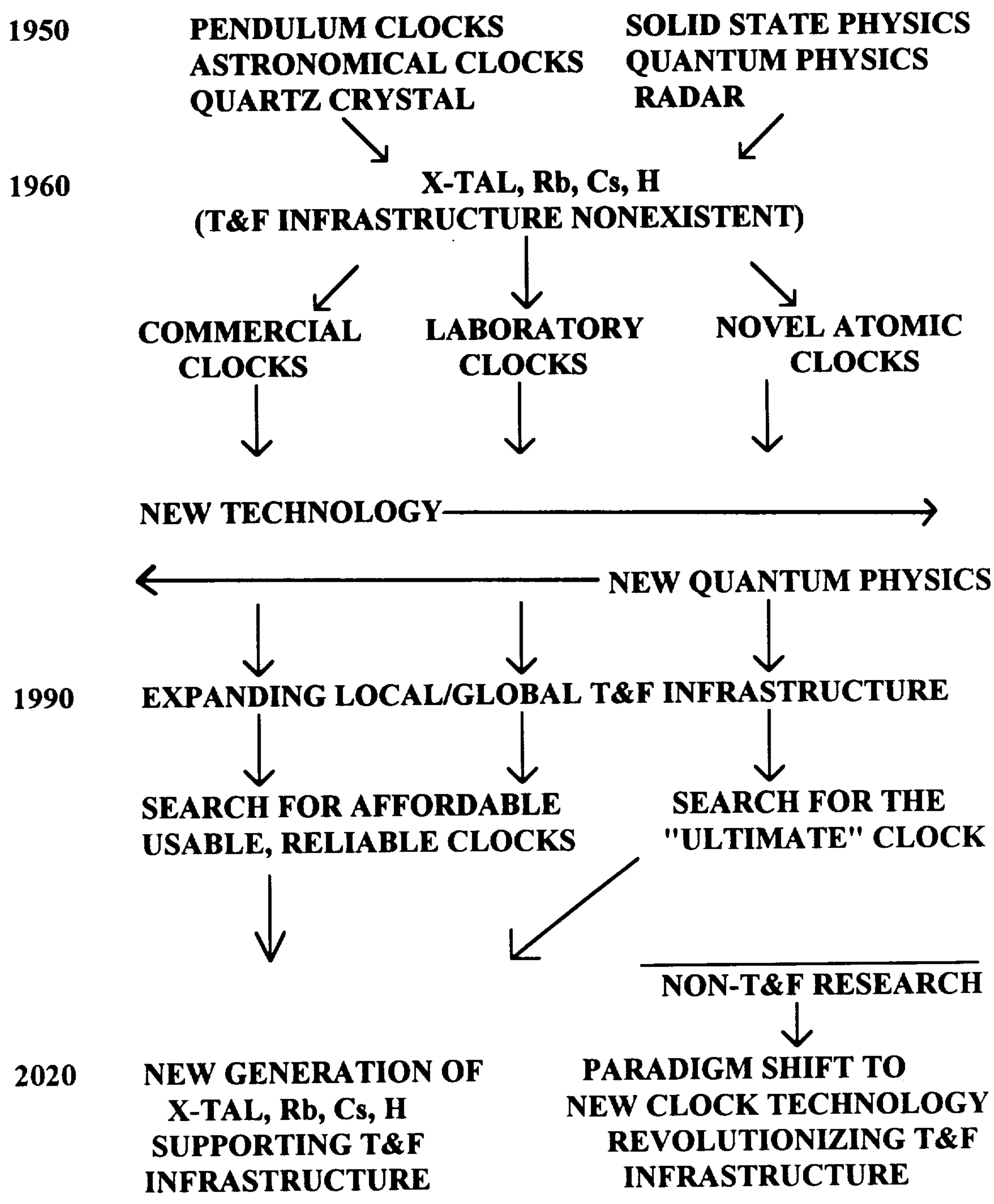
  PAST:
  STAR OBSERVATIONS (SEXTANT)

- **COMMUNICATION:**

  PRESENT:
  ISDN, SONET (GIGABIT GLOBAL NETWORKS)

  PAST:
  TELEPHONE AND RADIO (ANALOG/VOICE, MORSE, TELEX)

FIGURE 1 REVOLUTION OF CLOCKS AND INFRASTRUCTURE



QUESTIONS AND ANSWERS

Claudine Thomas, BIPM: I would just like to add one comment on something I am concerned about. I would say that I prefer that improvement in time and frequency may help communication between people rather than making war. Don't you think so?

Dr. Hellwig: I couldn't agree with you more. But if there has to be war and if there has to be a forceful dealing with bad things in this world, including terrorism, don't you agree that if you have to deal with that we will have a hard time as a world community to avoid, that it is better if we have an ability to just deal with that than with everything around it? Like blowing up the World Trade Center and things like that. I am realistic enough to say that we do need some military capability. I personally prefer military capabilities that do harm only to those who have to be harmed.

Dr. Winkler: Just a comment. In your initial draft, you showed a development of the new technology unbeknownst by the old one. I would say it was deliberately disregarded. It was not unknown. And we do the same thing today.

Dr. Hellwig: Yes, I think you have deeper insight into that. I grew up with the new technology, right. Yes, I think you were right. And you were in the middle of it back then. And that is why I am a little overly enthusiastic. But I agree with you. We are ignoring the other side now. Whether that is good or bad, I don't know. Because it would take place anyway, in my opinion.

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FREQUENCY STANDARDS FROM GOVERNMENT LABORATORIES OVER THE NEXT 25 YEARS

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Abstract

Based on a number of considerations including projected needs, current status, future trends, and status of key technologies, an attempt is made to project the future of government supported frequency standards development in the next 25 years.

INTRODUCTION

Any casual observer of prophesies made in the past regarding events to occur twenty–five years in the future is readily aware of the inevitable inaccuracies. This is so much more true about predictions of scientific and technical advances, since the outcome and the course of the future research is dependent upon future advances in a number of associated technologies which in turn are unknown. Nevertheless predicting the future of the course of science and technology, even as far as twenty–five years hence, serves to focus the present efforts and thus, in the most successful cases, may accelerate the rate of progress for at least the near term future. It is with this perspective that the present paper attempts to sketch the state of the frequency standards for the next twenty–five years.

The scope of the predictions, as suggested in the title, will be limited to the government supported laboratories. This implies that only the results of research perceived to be suitable for government support will be considered. This perception is that of the author and admittedly is subjective. It is founded on the notion that government support is to be directed for the development of technologies which do not readily point to near term commercial payoffs, and thus will be out of the scope of interest of the for–profit entities. Included in this class of technological endeavors are those that are clearly needed in support of other government sponsored projects, and thus may not be left to a chance development by the private sector. Based on this notion, the discussions in the paper will be limited to the ultra–stable frequency standards setting the limit of achievable stability. While this choice does not imply that other characteristics of frequency standards, for example reliability or cost, are not of concern, or will not be expected to be a part of government laboratories' work in the future, it is made on the basis that almost all future advances in the development of ultra–stable frequency standards are expected to be government funded. This is because of the cost associated with the fundamental

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research, and the uncertainty in short term commercial payoff, for the development of improved stability performance. The limited need for the number of such standards manufactured also places the burden of the development of the ultra–stable frequency standards on government sponsored research.

Within the boundary conditions outlined above, this paper will first present a brief review of the state of the frequency standards of twenty–five years ago, followed by a discussion of the present day and near term future capabilities. This information will then be used to extrapolate to the next twenty–five years. The extrapolation will be guided by the identification of the areas of need already known to exist. Since the pace of the future development will be strongly influenced by advances in technologies which directly affect the performance of frequency standards, several key technologies will be identified.

MOTIVATION

Before a prediction of the performance of the future frequency standards can be made the assumption that in fact they will still be needed twenty–five years from now merits some discussion. In the case of the frequency standards, the assumption of their need a quarter of a century from now is an easy one to justify. As an enabling technology for communications, the role of reference frequency signals will not be diminished in the future, and may well be expanded. This is because every received or transmitted signal in a communication system is synthesized from, or referenced to, a stable frequency derived from a frequency standard. Since the domain of communication is ever expanding, with no technological, economical, or sociological imperative to head off the expansion, it is clear that the need for frequency standards will also expand.

The second reason for expecting a persisting demand for frequency standards during the next twenty–five years is the position of frequency and time as the most precisely measurable of all physical parameters. Thus measurements requiring the most achievable precision by necessity depend on frequency and time standards. This ensures that the demand for ultra–stable frequency standards will continue in the future.

The third reason for needing frequency standards in the future is related to the above, and pertains to the fact that every theory in physics fails at some limit. That is to say, every theory in physics, including those that have been proven to everyone's satisfaction to hold true, have a finite domain of applicability. It thus becomes an important endeavor in physics to identify the boundaries of each theory, particularly those that hold so well! This exercise requires the most precise measurements possible for the highest resolution. Here again, the most precise tool of the physical metrology is the frequency standard.

I believe the above reasoning place the assumption of a need for frequency standards on sure enough a footing to justify the exercise of the prediction of their future status.

A BRIEF LOOK AT HISTORY

It is instructive to look at the state of the technology of frequency standards twenty–five years ago, and search for guidelines for making future prediction. The proceedings of the first PTTI, as well as proceedings of the Frequency Control Symposium (FCS) some twenty–five years ago, contain numerous interesting and instructive examples. Papers pertinent to our discussions may be best summarized in one of the following three categories: Those that promise of new, and sometimes bold, innovations which have since been found unfulfilled; those that predict a performance that we now find to be grossly underestimated; and those whose predictions were overestimates.

Virtually all papers making predictions fall within one of the above categories. As typical examples consider a survey paper on cesium beam frequency standards in the Proceedings of the FCS in 1971[1]. Here the performances of various Cs standards are used to develop an accuracy trend versus time, a plot that is reproduced in Fig. 1. Based on these results evidently the accuracy of the cesium standard had improved by about two orders of magnitudes every ten years (two decades per decade). Thus based on this information it wouldn't have been too unreasonable to have predicted a performance accuracy of a part in 10^{17} for a 1993 version of the cesium standard, since the accuracy in 1971 was about a part in 10^{13}. With hindsight one can easily point to reasons why this extrapolation is not justified, but such reasons were not present in 1973.

As a second example consider the paper by H. E. Peters in the Proceedings of the 3rd PTTI in 1971[2]. Here results for the performance of the NASA prototype atomic hydrogen standard NP–1 is given. Based on this example, the author argues that the maser has the potential for stability of a few parts in 10^{15}. Hydrogen masers exceeding this stability performance have since been developed by Peters and his co–workers at Sigma Tau company, and by Vessot and co–workers at the Smithsonian Astrophysical Observatory, where some have operated at about 8×10^{-16} stability. Again, it is easy to justify with hindsight why in 1971 the ultimate performance of the H–maser was underestimated.

Finally as our last example we can point to the work at Harvard in N. Ramsey's group on the large storage box maser. In a paper by Uzgiris and Ramsey in the 22nd FCS in 1968[3] the problem of wall collisions is considered and a solution is described in the form of a large diameter storage box to increase the time spent by atoms in the storage volume, thus reducing the fraction of the time atoms spend on the wall. A picture of this maser is given in Figure 2 of the paper showing the storage box, which has a linear dimension of approximately five feet long and five feet in diameter. The improvement obtained by this instrument evidently did not warrant its cumbersome size, and large storage masers did not receive any more serious attention. Thus the promise held by this innovation remained unfulfilled, despite its initial success.

In reviewing the three examples given above it is clear that advances in our understanding of the underlying physics of frequency standards coupled with innovations in the associated technologies makes the subject of future predictions a rather risky enterprise.

A Look at the Current Status and Near Term Future Developments

Recent progress in a number of scientific and technological fields has led to significant advances in the performance of ultra-stable frequency standards. In particular the advent of semiconductor and solid state lasers with narrow linewidth and suitable wavelength have resulted in significant improvements in the performance of cesium and rubidium standards. The development of novel approaches such as the linear ion trap has allowed increased signal to noise ratio for high performance lamp based ion standards. Advances in the understanding of the physical mechanism for laser trapping and cooling have led to the development of a new class of standards based on an old proposal, the cesium fountain clock first considered by Zacharias[4] Laser cooling of small clouds of ions has pointed to the possibility of developing a primary standard based on a bead of a small number of trapped and cooled mercury ions.

Laser optical pumping has virtually replaced magnetic selection in most primary frequency standards. An example of this is the recent progress obtained with NIST–7, an optically pumped cesium standard, which has yielded a short term stability of $8 \times 10^{-13}\tau^{-1/2}$[5].

Similarly progress in ion standards has led to stability performance reported at $7 \times 10^{-14}\tau^{-1/2}$, for intervals measured to about 10^4 seconds[6]. This performance is expected to persist for averaging intervals longer than 10^6 seconds.

Preliminary results have been obtained with cesium fountain clocks, using laser cooling and manipulation of atoms trapped in a Zeeman optical trap (ZOT)[7]. Stability performance of $3 \times 10^{-12}\tau{-}1/2$ has been demonstrated, which has led the researchers to predict a potential for short term stability of $2 \times 10^{-14}\tau{-}1/2$ for cesium fountain clocks.

Laser cooled trapped ions have been known to hold the potential for much improved stability. Recent advances in laser cooling of mercury ions in a miniature linear trap at NIST are expected to realize the potential for a high performance microwave standard. Stability of about $5.5 \times 10^{-14}\tau{-}1/2$ has been projected for 50 cooled mercury ions undergoing the clock transition at 40.5 GHz[8].

In the past few years room temperature hydrogen masers have demonstrated stability of about 8×10^{-16}. Several units operate at this level for relatively long time before degradation due to environmental influences set in. Recent advances in cryogenic hydrogen masers have led to projections of two to three orders of magnitude improvements compared to the performance of room temperature masers[9].

The only other ultra–stable frequency standard which is not based on an atomic transition is the cryogenic cavity stabilized oscillator. Performance of these instruments extends only to a few hundred seconds, but future improvements are expected. Stability of the Superconducting Cavity Stabilized Maser Oscillator (SCMO) has been demonstrated at about 2×10^{-15} for averaging intervals to about 800 s[10]. Higher performance is anticipated with improvements in cavity Q and stabilization of the power pumping the ruby maser.

In Figure 2 the performance of ultra–stable frequency standards of today are summarized, together with near term predictions within the next five years. These predictions are based on the author's subjective judgment as to the state of readiness of these standards, and do not necessarily agree with predictions of other researchers in the field. They are extrapolated from the current performance, and anticipated progress.

FUTURE NEEDS FOR ULTRA–STABLE STANDARDS

Clearly the progress in the development of future standards will be driven by outstanding needs for various applications. Some of the reasons why frequency standards will be needed in the next 25 years were mentioned above. In this section areas where lack of capability exists, and yet numerous applications have laid out requirements will be mentioned.

Applications of ultra–stable frequency standards in scientific investigations imply yet another class of instruments. Since environmental perturbations on earth can limit the ultimate sensitivity required for many science experiments, it is natural to design experiments that can take advantage of the relatively benign environment of space. Space experiments however must be performed within the constraints of low mass and low power available to practical spacecraft. Thus far the development of a low mass, and low power frequency standard (mass less than 4 kg, power less than 5 W) with stability exceeding a part in 10^{15} has not been demonstrated. One of the outstanding needs in the areas of ultra–stable standards is such an instrument. Future work will also be driven by ever more stringent requirements of spacecraft navigation and position location.

Small and miniature ultra–stable standards represent yet another class of needs. The concept of miniaturization is related to the needs of spacecraft standards, but yet relates to terrestrial applications as well. There are at least two reasons for pursuing work in this area. First a small frequency standard will require allow a more effective shielding of the environmental perturbations. This is because it is practically more simple to stabilize the environment in a small region of space than a large one. Thus all other things being equal, miniaturization may lead to improved stability, especially for longer averaging intervals. Furthermore, reduced shielding requirements may also lead to reduced costs for such standards.

The second reason for miniaturization of frequency standards is to extend their range of applications. Already small receivers for GPS, for example, have led to an explosion in areas of applications. An ultra–high stability standard in a "small" package will similarly find an extended range of applications, including those that resulting from simply the ease of use.

Perhaps the most conspicuous lack in ultra–high frequency standards is in the area of optical standards. The reader may have noticed the absence of a performance curve in Fig. 2 for an optical standard. This is because ultra–high stability optical frequency standards have not as yet been demonstrated. Yet advances in optical communications and scientific experiments quietly await practical optical standards. Furthermore the direct dependence of the stability of atomic standards on the line Q (the ratio of the frequency of the clock transition to the observed width of the transition) points to the optical standard as the ultimate ultra–high stability frequency standard, where the frequency of the "clock" transition is in the range of 10^{14} Hz.

Perhaps the major obstacle for the development of an ultra–stable optical frequency standard is the lack of a practical scheme for phase coherent frequency division. Optical frequency division to RF (or alternatively, multiplication of RF frequency to optical) has only been demonstrated with cumbersome chains in national standards laboratories. Development of practical schemes to synthesize optical frequency in a continuous basis is also a requirement for optical frequency standards applications. Several proposals have been made, and preliminary work in the development of optical frequency synthesis has been encouraging[11].

The areas mentioned in this section are not exhaustive, but represent the most urgent needs that developers must address in the future. Already considerable activity in these areas is underway, and progress towards meeting these needs is being made.

Emerging Technologies Influencing Development of Future Standards

Another parameter which shapes the scope and speed of the future development of frequency standards is emergence of new supporting technologies, or progress in existing ones. An outstanding example of this is the progress made in the last decade in semiconductor, and solid state lasers. This progress has been the major enabling influence for the development of optically pumped standards. Further progress in this area will also play a crucial role in the development of laser based ion and atom standards. In particular, the realization of the major potential held in trapped ion standards will clearly depend on how soon practicable semiconductor lasers and semiconductor laser based devices will yield radiation in the UV portion of the spectrum. Progress in this area will also influence efforts to reduce the size and miniaturize ultra–stable atomic and optical frequency standards.

A second technology which has direct impact on the future frequency standards is material science. New materials for high Q resonators will help the development of cavity standards with more stability. Materials with lower mass density and smaller coefficient of thermal expansion will enable progress for spacecraft ultra–stable frequency standards. Finally new materials may allow development of lower cost and higher performance standards through, for example, providing more effective shielding of environmental perturbations.

The requirement for low noise and stable electronic components is already quite stringent for present day ultra–stable standards. Progress in superconducting electronics and photonic devices will be required to extend the stability range, and the range of reference frequencies produced by standards. Advances in high temperature superconductors and photonics will undoubtedly have the greatest impact on the pace of future developments in frequency standards technology.

Two other areas already a part of the frequency standards technology hold the key to future advances. One area is progress towards the development of low noise local oscillators to support ultra–high stability of atomic standards. This is particularly true since trapped atom standards realize higher stability with larger line Q's, which in turn is obtained by extending the interrogation time of the clock transition. Thus stable local oscillators will be required to maintain stability during these relatively long interrogation times. Associated with this need is the development of effective and practical techniques to lock to the stable clock transitions, especially in the optical domain. Further progress in this area will greatly improve the speed of the development practical standards of the future.

It is perhaps unnecessary to mention that progress in science and associated technologies will certainly point to other crucial areas in frequency standards development that have not been considered here.

PREDICTIONS FOR FUTURE DEVELOPMENTS

Based on the considerations discussed in preceding sections, an attempt will now be made to predict future trends in the next 25 years in government supported frequency standards work. Within the next quarter of century ultra-stable optical frequency standards based on atomic transitions will be developed. These standards based on laser cooled ions and atoms will exhibit line Q's of 10^{15} or higher. Standards based on three dimensional arrays of laser cooled and trapped atoms, such as Xe, will be possible. Use of squeezed light will allow sub-natural linewidths and sub shot noise limited signals to improve stability. Standards based on the emerging technology of Optical Parametric Oscillators (OPO)[12] will become available, and will make available stable references ranging in frequency from visible to RF.

Small and highly stable solid state standards based on new materials, high temperature superconductors, and optoelectronic circuits will become available. Some of these standards will be directly used in space, while others will be used in conjunction with other atomic standards to obtain ultra-high stability on board spacecraft.

Other stable frequency standards based on whispering gallery mode dielectric resonators and superconducting cavities will emerge in the future to extend the range of stability. Novel oscillators based on photonics will meet the needs of standards requiring improved local oscillators for their ultra-stable operation.

Based on these, predications for ultra-stable standards of the future are summarized in Figure 3. The figure depicts improved performance for standards that are based on existing technologies, and by necessity lacks information on other new technologies that will surely emerge within the next twenty-five years.

SUMMARY AND CONCLUSION

In this paper an attempt has been made to predict the future performance of government supported frequency standards for the next twenty-five years. These predictions were based on a number of considerations ranging from the needs of the future to the progress in certain key technologies which drive the frequency standards developments.

Despite these considered bases for the predictions made, it is important to also point to reasons why such predictions will prove to be highly inaccurate. To start with, there will undoubtedly be some new, and as yet unidentified, applications which will possibly guide the course of future development away from that considered here. New physics will certainly emerge and influence our present day knowledge of the fundamentals of ultra-stable frequency standards. Associated with the emergence of new physics is the birth of new technologies which will further influence advances. Advances in existing key technologies, such electronics, optics, and material sciences will also occur, and in an as yet undetermined manner influence the scope and the pace of future progress in the frequency standards technology.

Finally, all technologies, especially those such as frequency standards that enable so many other technical works depend greatly on societal priorities. Such priorities in turn determine the extent of their needs, and the size of the support that will become available to achieve technological progress. This single unknown of societal priorities in the next twenty-five years can by itself prove the predictions made here far off the actual mark.

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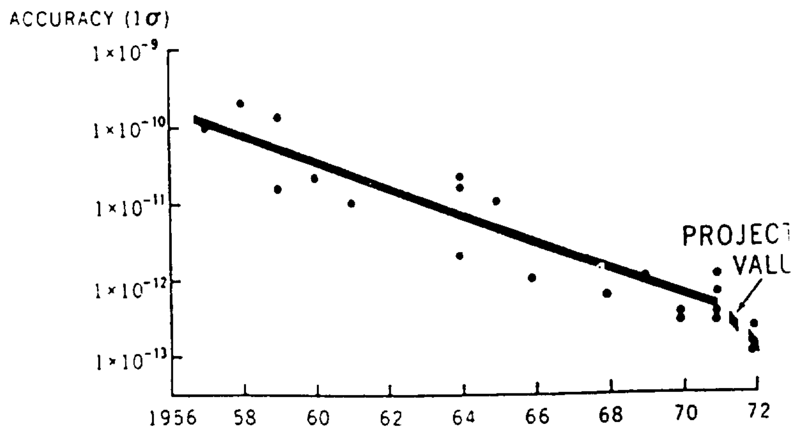

Figure 1. Accuracy Trends in Laboratory Cesium Standards, 1949-1971

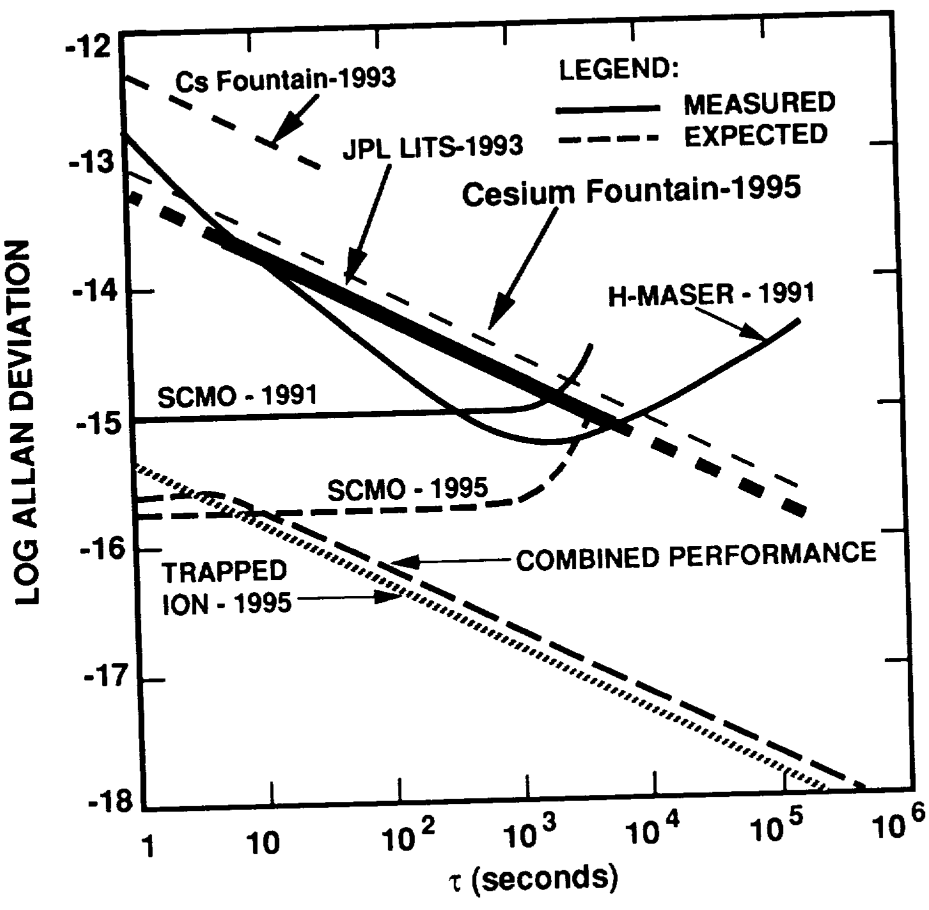

Figure 2. Performance of present day ultra-stable standards, and projected performance for the near term future.

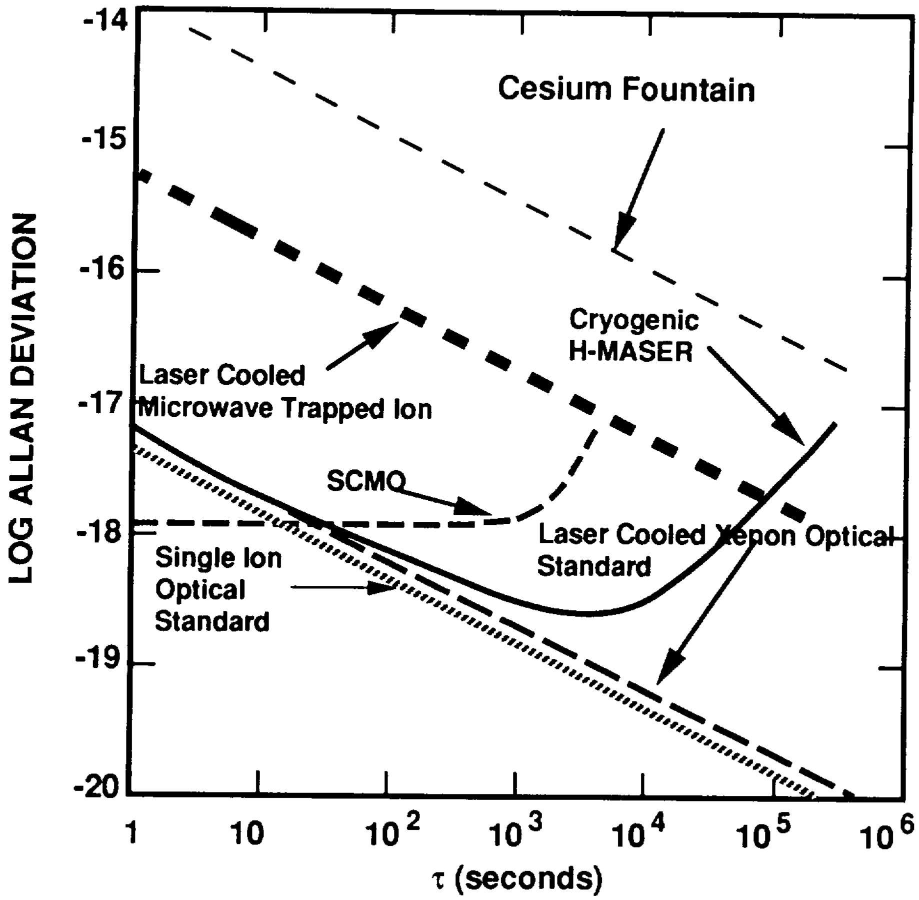

Figure 3. Projected stability of frequency standards in the next twenty-five years.

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FREQUENCY STANDARDS FROM INDUSTRY OVER THE NEXT TWENTY FIVE YEARS

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Abstract

Present and possible future performance for many of the existing and new commercial frequency standards is presented here. Recent progress in the gas cell atomic standards with regards to size and cost is significant and considerable improvement is expected. Cesium beam standards will benefit in stability and accuracy from optical pumping. Cooled hydrogen masers will offer extremely good stability. Advances in trapped ion and cesium fountain technologies make them good high performance candidates for the future. The quartz oscillator field is more mature and consequently performance improvements for the future are going to be less spectacular. Oscillators stabilized to GPS will have many applications. Recent performance of cooled microwave dielectric resonator oscillators is very good and they offer the promise of serving as flywheel oscillators for advanced performance atomic standards.

INTRODUCTION

Present and future performance for the well known atomic frequency standards is presented here. In addition, some of the newer standards that may well become commercial will be discussed. These include trapped ion and cesium fountain standards. Gas cell standards are decreasing in size and cost and will find many applications as a result. Quartz oscillators are also covered. They are fairly mature and have many direct applications as well as filling many of the needs for flywheel oscillators. Oscillators stabilized to GPS will have wide use and potentially could replace moderate–to–high–performance atomic standards in some applications. Cooled dielectric resonator oscillators, also discussed here, are promising candidates for flywheel oscillators for advanced atomic standards and may well have application in optical frequency standards.

GENERAL OVERVIEW

There has been a lot of progress recently in many areas of the frequency standard arena and the future prospects are quite promising. Telecom and datacom are becoming very important and are driving many aspects of the commercial frequency standard business. Crystal oscillators and gas cell standards stabilized to GPS will be widely used in moderately demanding applications.

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The main driving forces for the future include lower cost, smaller size, higher performance, and improved reliability. In particular, lower cost and smaller size are extremely important particularly in high usage applications and therefore continued progress in micro–miniaturization and increased integration of electronics is crucial. Better performance in both stability and accuracy will always be needed and considerable progress is being made here.

QUARTZ OSCILLATORS

Performance of present high quality quartz oscillators is limited by the resonator and environmental control of the resonator and associated critical circuitry. BVA crystals, made from an all quartz structure with electrodes spaced from the crystal surface, are the best resonators available today from the standpoint of frequency stability and drift. They are more expensive than conventional resonators with electrodes formed directly on the crystal. But, conventional resonators may have less sensitivity to vibration and shock.

Performances of several oscillators are show in Table 1. The ultra–precision 5 MHz BVA oscillator has the best overall performance. The 10 MHz BVA is next. The third oscillator uses a 10 MHz conventional SC cut resonator. The aging rate of the best oscillators is occasionally as low as $2x10^{-12}$ per day but more typical values are 1 to $5x10^{-12}$ per day. Occasionally flicker floor levels as low as $4x10^{-14}$ are seen. These results are mainly determined by the resonator as long as the circuitry is reasonably well designed.

Temperature sensitivities range from 0.2 to $40x10^{-12}$ per deg. C. Clearly the temperature results are quite variable depending on the design and construction of the oscillators.

The fact that very good aging and flicker performance can be obtained occasionally indicates that considerable improvement in resonators is possible but the processing and/or material is presently not well enough controlled.

Advances needed in quartz oscillators include: better material for the resonators perhaps accompanied by higher intrinsic Q; improved understanding and technology of the quartz–electrode interface; better oven designs and perhaps hermetic sealing to reduce environmental effects. Ultimately, the electronics will need improving. The multiple series resonator approach patented by Westinghouse can give better overall performance and may be used in the most critical applications.

Table 2. shows what might be expected in future ultra–precision oscillators.

GAS CELL DEVICES

Gas cell frequency standards work by passing a beam of pumping light through a gas cell containing vapor of the atoms being used (typically rubidium or cesium) with usually a buffer gas in an excited microwave cavity. The system is designed so that the intensity of the pumping light transmitted through the cell is a minimum when the microwave excitation frequency is at the atomic resonance.

The quantity of present rubidium standards sold is considerably larger than any of the other atomic frequency standards primarily due to cost and size. They are becoming an important element in telecom. Their performance is typically between quartz and cesium beam standards. Properly designed units can have considerably better shock and vibration performance than quartz. The same is true with regards to shifts due to change in orientation in the earth's g–field. Cost and size of these units is of prime importance and these are continually being reduced.

Most of the present units are optically pumped with an RF excited lamp. Typical performance is shown in Table 3. Using laser pumping can lead to smaller size and perhaps the performance shown in Table 4.

Using a laser for pumping the rubidium cell and designing the system for optimum performance rather than small size can give short term stability perhaps as good as $2\text{x}10^{-14}/\tau^{1/2}$ where τ is the averaging time. Very Low flicker floor may also be achieved. This type of device is a good candidate for a flywheel source for advanced very–high–stability atomic standards.

Work is presently being done on a laser pumped cesium gas cell device. This can be significantly smaller than rf lamp pumped rubidium devices because of the shorter wavelength of the cesium line (3.26 cm versus 4.39 cm for rubidium) and the small size of the laser compared to the rf excited lamp. The performance should be comparable to rubidium but the aging may be poorer due to the relatively high surface–area–to–volume– ratio in a small, elongated cell. A highly integrated set of electronics along with the small physics package could reduce the volume to 10 cm^3 or less and perhaps lead to lower cost if the manufacturing volume is large.

The already large market for gas cell devices has the potential to grow even larger if cost and size can be brought down. Laser pumping is important for size reduction and performance improvement and could reduce the cost compared to RF excited pumping lamps. Laser availability and price are crucial and depend on having large unit volume.

CESIUM BEAM STANDARDS

Cesium beam standards work by passing a beam of state selected cesiûm atoms through an excited microwave cavity. On exiting the cavity further state selection is used to select atoms that have made a microwave transition and eventually obtain a signal that is maximum when the microwave excitation frequency equals the resonance frequency of the atoms.

Cesium beam frequency standards are important where high accuracy and reproducibility, and negligible drift are needed. The present highest performance commercial unit has accuracy better than $1\text{x}10^{-12}$, drift much less than $1\text{x}10^{-15}$ per day, flicker floor less than $1\text{x}10^{-14}$, and short term stability better than $8\text{x}10^{-12}/\tau^{1/2}$. The high performance variety of cesium beam standards is moderately expensive.

Optical pumping of cesium beam devices using lasers to achieve state selection and atom detection is going on in a number of laboratories at the present time. The new laser pumped standard at NIST is now operational and is giving outstanding performance. Application to commercial standards will improve their accuracy by perhaps 3 to 5 and short term stability by more than 10. The latter comes about because of the much better utilization of the cesium in the beam. Improved short term stability is particularly important since that is the weakest performance area in present commercial cesium beam standards. Improving the short term stability by 10 reduces the time to make a measurement to a given precision by 100 – it would take 100 unimproved standards to get to the same precision in the same time! Accuracy improvement is due to several things. Rabi and Ramsey pulling are reduced and the C field homogeneity is better. These are due to the lack of deflection magnets in the optically pumped tube and the better symmetry achievable of the microwave transitions close to the main transition. In addition, better correction can be made for the frequency shifts due to cavity phase shift and relativity (the second order Doppler shift). Again, laser availability is crucial.

The market for lower cost, and consequently lower performance, cesium beam standards may grow due to continual increases in timing and synchronization requirements as communication rates go up.

HYDROGEN MASERS

Active hydrogen masers utilize the stimulated emission of hydrogen atoms in a cavity to produce an actual oscillation at the hydrogen hyperfine frequency in contrast to the passive standards we have discussed so far. They provide the best short term stability presently available from an atomic standard in the microwave range. Typical performance is about $1x10^{-13}/\tau$ for times shorter than about 20 seconds and $2.2x10^{-14}/\tau^{1/2}$ till the flicker floor or drift is reached. The best stability reached is typically somewhat better than $1x10^{-15}$. Active hydrogen masers are the standards of choice when extremely good short term stability is required such as in Very Long Baseline Interferometry, a form of radio astronomy. Drift rates of units without auto–tuning of the cavity are about $2x10^{-15}$ per day. Due to lack of precise knowledge of the wall shift, the accuracy is presently limited to about $1x10^{-12}$. Active hydrogen masers are relatively expensive and the market for them is not large at this time.

Passive hydrogen masers are similar to the gas cell devices and the cesium beam standards already discussed. Their short term stability is considerably poorer than an active maser but somewhat better than a high performance cesium. They have the same wall shift uncertainty as the active maser. Work has been done in the U.S. for some time on passive masers but no U.S. commercial units are on the market. However, commercial units are presently for sale by a Russian firm. The market is not large for these standards either.

Work has been going on in several places on cold (cryogenic) active hydrogen masers. They are expected to have extremely good short term stability, around $1x10-15/\tau$, and very good stability with ambient temperature. The required refrigeration is fairly complex and therefore these masers would be fairly expensive. They could be an excellent flywheel oscillator for some of the advanced standards.

There are concerns that the limited market for hydrogen masers and the shortage of government funding may hurt future maser R&D in the U.S.

TRAPPED ION STANDARD

Trapped ion standards use an RF quadrupole to trap quantities of one to many ions so that they can be interrogated for long periods of time leading to very narrow resonance lines. In the mercury 199 version, optical pumping using an rf excited lamp or a laser source is used for state preparation and observation of the resonance. Line widths well below 0.1 Hz at 40 GHz have been achieved. The biggest systematic frequency offset is due to the relativistic velocity effect (second order Doppler shift) caused by the induced motion of the ions in the RF field. This is minimized by using elongated clouds or virtually eliminated by using a line of single ions or a single ion.

Several trapped ion standards have been built using mercury 199 ions with an rf excited lamp for optical pumping. At least two groups are actively working in the field at present. Excellent short term stability, about $1x10^{-13}/\tau^{1/2}$, has been demonstrated with an rf lamp pumped, elongated mercury ion cloud trapped in a two–dimensional quadrupole trap.

Background gas can cause fairly large frequency shifts so cryogenic operation may be required for the ultimate in stability. Calculations indicate that a single trapped ion using laser cooling and cryogenic pumping to get rid of background gas could have offsets from the free ion resonance frequency as low as $1x10^{-17}$.

Trapped ion standards without either cryogenic cooling or laser optical pumping could be only somewhat more expensive than a high quality cesium standard. Adding laser pumping for mercury ions is very expensive at the present state of the art.

No units are available commercially at this time. A version using an rf lamp pumped elongated mercury 199 cloud and low pressure helium gas cooling could be made commercially and would have performance superior to high quality cesium beam standards at not too great a cost.

CESIUM FOUNTAIN

The cesium fountain is a passive standard that uses laser cooling and manipulation to toss a ball of extremely cold (microkelvin level), state selected cesium atoms upwards through an excited microwave cavity. They then fall back through the cavity under the influence of gravity and their state is determined to see if a transition has occurred. Transit times as long as a second are achieved leading to quite narrow lines with good signal–to–noise ratio. Several groups are presently working on these devices and progress is rapid.

Accuracy is expected to be $1x10^{-15}$ or better. The main limitation is a density dependent frequency shift due to spin exchange collisions. This shift can be quite large at the low temperatures and moderate densities used. Extrapolation to zero density can be done by a series of measurements and the accuracy value given above assumes this procedure has been carried out.

Frequency stability of $3x10^{-14}/\tau^{1/2}$ may be obtained with the signal–to–noise ratio already obtained.

Acceleration and orientation effects will be large with such slow atoms. This will make the fountain standard unsuitable for some applications.

No commercial units are presently available.

OSCILLATOR STABILIZED TO GPS

If an oscillator is stable enough it can be used with a GPS receiver and can average out the frequency variations (called Selective Availability) intentionally put on the GPS signals. If the oscillator is then locked to the average GPS frequency with a long time constant, excellent long term stability with respect to GPS can be achieved. Any high quality oscillator or standard can be used: quartz, rb cell, cs beam, hydrogen, etc.

Time uncertainty, rms, with respect to GPS of about 2 nsec can be achieved with high quality cesium and a good receiver. The uncertainty expected with a high quality quartz oscillator is perhaps 20 nsec.

This technique is relatively low–cost. It is not currently available commercially but could displace atomic standards in a number of applications when it does become available.

OSCILLATOR STABILIZED WITH COOLED SAPPHIRE RESONATOR

Cooled sapphire has extremely low dielectric losses at microwave frequencies and consequently a sapphire microwave dielectric resonator can have very high Q (in excess of 10^7 at X–band has been measured). Several groups are working on oscillators stabilized by such resonators and are achieving excellent results in the X–band region with temperatures 77 Kelvin and below.

The spectral purity achieved at X–band is about -50 dBc in a 1 Hz bw at 1 Hz. The noise floor is about 162 dBc and is reached at about 3 kHz. These, particularly the noise floor, are better than can be achieved with a high quality 10 MHz quartz oscillator multiplied in frequency to X-band. This stability at X-band has only been exceeded by an oscillator stabilized by a superconducting niobium cavity. A source with this kind of spectral purity is needed for high performance Doppler radars. It would also be useful as a high performance flywheel for advanced microwave and optical atomic standards.

Careful design and construction is necessary to avoid modulation by acoustic noise and vibration.

No units are available commercially at this time.

OPTICAL FREQUENCY STANDARDS

Optical atomic frequency standards have the potential for very high accuracy and stability. Stabilized helium–neon lasers at 633 nm using the Lamb dip and other techniques have been sold for more than 25 years. Their reproducibility and accuracy is around $1x10^{-7}$. Much better performance was obtained with lasers stabilized to iodine absorption lines. Methane stabilized lasers in the near infrared appeared with reproducibility of a few parts in 10^{12}. A great deal of work on methane was done in the U.S. at what was then NBS (now NIST) and also in the USSR. A number of portable methane standards were built and used in the USSR.

Very good candidates exist among atoms and ions with very narrow optical spectral lines. The mercury ion is a good example. Accuracy of standards built using these lines is predicted to be considerably better than 1×10^{-15}.

While these standards are excellent in the optical range, it is still very difficult, complicated, and expensive to connect their frequency with the rf/microwave region. Work is being done in this interesting and challenging area in several locations and there are some promising ideas that may ultimately lead to a practical solution to the connection problem.

SUMMARY

Continued improvement will be made in performance, size, cost, and reliability in many of the existing standards. Inexpensive, small gas cell devices will have a large market. Telecom and datacom are rapidly growing fields and their synchronization requirements are getting tighter. These are strong driving forces for the frequency standard market. GPS stabilized oscillators will be widely used.

In the higher performance area a number of things are happening. Optically pumped commercial cesium beam standards will offer considerable improvement in stability and accuracy. Trapped mercury ion devices have very good potential. Good flywheel oscillators will always be needed and their performance requirements are severe for the advanced atomic standards coming along. Very high performance standards such as the cesium fountain and single ion devices are in active development and may be commercialized in the future. Optical standards have great promise but the problem of connection to the rf/microwave range needs to be solved. Very high performance standards will always be needed but their market is not large.

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Parameter	5 MHz ultra-prec.	10 MHz ultra-prec.	10 Mhz prec.	UNITS
aging	2 to 50	5 to 50	<100	10^{-12}/day
g sensitivity	1	0.5	<10	10^{-10}/g
flicker floor	0.4 to 2	1 to 3	10	10^{-13}
temperature sens.	2 to 5	<50	<400	10^{-13}/°C
spec. purity: 1 Hz	-130	-120	-105	dBc in 1 Hz bw
100 KHz	-160	-155	-162	dBc in 1 Hz bw

Table 1

Performance of several present high quality quartz oscillators

Parameter	ultra-precision.	UNITS
aging	1 to 5	10^{-12}/day
g sensitivity	<1	10^{-10}/g
flicker floor	0.1 to 0.5	10^{-13}
temperature sens.	<1	10^{-13}/°C
spec. purity: 1 Hz	-145	dBc in 1 Hz bw
100 KHz	-165	dBc in 1 Hz bw

Table 2

Possible performance of future ultra-precision quartz oscillators

Parameter	compact rb. (lamp)	UNITS
aging	1 to 2	10^{-11}/mo.
g sensitivity	<1	10^{-10}/g
flicker floor	3 to 5	10^{-13}
temperature sens.	<6 (but non-linear)	10^{-12}/°C
spec. purity: 1 Hz 10 KHz	-80 -145	dBc in 1 Hz bw dBc in 1 Hz bw
short term stability	3 3	10^{-12} (1 sec.) 10^{-13} (100 sec)
volume	16 260	in^3 cm^3

Table 3
Performance of present compact lamp pumped rb gas cell standards

Parameter	compact rb. (laser)	UNITS
aging	1 to 2	10^{-11}/mo.
g sensitivity	<2	10^{-11}/g
flicker floor	1	10^{-13}
short term stability	1 1	10^{-12} (1 sec.) 10^{-13} (100 sec)
volume	6 100	in^3 cm^3

Table 4
Possible performance of future compact laser pumped rb gas cell standards

QUESTIONS AND ANSWERS

Dr. Klepcynski, USNO: One of the areas where I feel that there really needs to be development or something to be done now and in the immediate near future is with the development of basic laboratory cesiums. Because right now, we only have effectively two in operation. NIST's seven will come on line shortly. And everybody a few days ago and this morning was talking about having UTC as good as possible. But UTC is steered to these devices. And is anything being done in the way of trying to get more of these devices on line to help with the recommendations, the paths to steer UTC to the primary cesium laboratories?

Dr. Cutler: Well as far as additional work in laboratories is concerned, certainly the French are working on an optically-pumped standard. And they are also doing some work on cesium fountains. So I think you are going to see considerable improvement on the laboratory cesium standards that will be contributing to the time scale in the near future.

The other thing, as Claudine Thomas has mentioned, is that the active hydrogen masers with the cavity auto–tuning systems are very good contributors to the time scale at the present time.

Dr. Winkler, USNO: I found this paper extremely interesting and stimulating. And I am sure that there is a great deal of reality which will develop in what you have said. But I am reminded that if one really wants to look into the future, one must not believe the experts too much because we remember what Edison had to say about the future of AC as a power, or others – Ramsey has been mentioned. There is really a problem. And the reason why that is so is because the experts see the problems and difficulties. And they may suddenly disappear because of some opening of technology. There are breaks. Because with the established technology, there is inevitably a point of diminishing returns. I think we are seeing that or have been seeing that with cesium. That is the answer to your observation that the absolute laboratory standards have not reached a part in ten to sixteenth or seventeenth, as could have been predicted by the first slide.

So there is a point of diminishing returns. And therefore, opening must come from entirely different technologies. And that means also entirely different technologies concerning the radio frequency or high frequency circuits which they are using. I think the good old RG–58 and the BNC connector and all that will be out of the window. In fact, they are going out now already. You can see that.

There is also going to be a fantastic degree of simplication. Any maturing of a technology is marked by a drastic simplication of everything. If we compared the devices, for instance, computers, today with their ancestors of comparable capability, it is drastic. The volume is a fraction and the cost is a fraction.

But in everything, I was surprised by one omission. I have not heard anyone predicting that the Mössbauer effect will be used. I am surprised by that.

Dr. Cutler: Well I would like to make a comment there. The ability to use stimulated emission there is extremely low because of the large energy separation. It is pretty much going to be spontaneous emission. So it really is very narrow band noise. However you are right, it is very narrow bend.

Dr. Maleki, JPL: Actually in a roundabout way, the idea of the Mössbauer effect was mentioned in a sense that one can go ahead and have a single ion in the matrix, similar to the notion of the Mössbauer effect, the difference, of course, being the transition – in one case being a nuclear transition, and therefore a very, very high frequency. The reason it wasn't mentioned is that for the past ten or 15 years, if one extrapolates again and sees how well have we done in just tying the terahertzes to GHzes. And we have done very poorly. In fact, I claim that we haven't done it except in very cumbersome laboratory chains. So one extrapolates from this on how are we going to do terrahertzes to I don't know what six orders magnitude higher would be, and that is the difficulty. But you are absolutely right. I didn't mention them because I don't see how to overcome that difficulty.

Dr. Cutler: I would like to make one response to Dr. Winkler's comment on simplification. Indeed things, as time goes on, get smaller, more reliable and so forth. But I don't believe they really get simpler. In fact, if you look at the computers of today and the frequency standards of today as compared to what we had 20 years ago, they are much more complex in their circuitry and so forth. But they appear on the surface to be simpler because the level of integration of the electronics is much greater and you can do so much more. And as a result, you get the ability to have higher performance, higher reliability and smaller size, even though they are more complex.

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The Future of Time and Frequency Dissemination

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Abstract

I will try to extrapolate the changes in the dissemination of time and frequency information that have taken place during the last 25 years to predict the future developments both in the methods of disseminating time and frequency and in the kinds of customers we will be asked to serve. Two important developments are likely to play pivotal roles in driving the evolution of dissemination. The first is the commercial availability of very high quality clocks – devices whose performance may eventually rival that of the current generation of primary frequency standards. The widespread use of these devices may blur the traditional distinction between client and server, and may replace it with a more symmetrical interchange of data among peers. The second is the increasing demand for digital time and frequency information driven by the increasing sophistication of everything from traffic lights to electric power meters. The needs of these individual users may not tax the state of the art of primary frequency standards in principle, but their large numbers and wide geographical distribution present a technological challenge that is difficult to meet at a reasonable price using existing methods.

Some of these problems may be solved (or at least addressed) using developments in communications and consumer electronics such as the increasing use of fiber–optic telephone circuits and the increasing bandwidth and sophistication of the cable network used to transmit television pictures. To be useful, these advances in hardware must stimulate parallel advances in software algorithms and methods. These advances are more difficult to predict with great confidence, but the developments of the last few years will be examined to provide some indications of the future.

Introduction

In 1964, the 1–day stability of what was then a state–of–the–art cesium clock was about 20 ns. It was very difficult for a user far from a timing laboratory to receive a signal that maintained this stability, and people who were serious about time usually used portable clocks to transfer it. It took a number of years for dissemination methods to improve to the point where portable clock trips were no longer necessary – the last trip from NIST to the BIH at the Paris Observatory was in the middle 1970s. State–of–the–art clocks today are about 100 times better than those of 30 years ago, and dissemination must improve accordingly. This is not a trivial undertaking; transit times, which may be tens of milliseconds or longer must be measurable and stable to a fraction of a nanosecond. The parameters that affect the transit time must also be understood well enough so that this level of stability can be achieved over long periods of time, which is perhaps even more difficult.

In addition, two other trends will also have great impact on the dissemination process. The first is the availability in the commercial market–place of devices which are at least as accurate as the primary standards of a generation ago. Sites equipped with this hardware cannot really be considered potential users of most of the services currently provided by a national timing laboratory – they are closer to peers, and their hardware may be more efficiently used by implementing two–way data exchanges rather than by the one–way time transmissions and the client–server relationships that have been the norm up to now. The second is the increasing demand for moderately accurate time in various digital formats. These uses do not tax the state of the art from the point of view of accuracy, but satisfying the sheer volume of the requests and their great diversity requires some careful planning. Both of these trends are likely to continue for the foreseeable future, and meeting them is likely to be a significant challenge during the next 25 years.

The High–End Dissemination Problem

The transit time of a signal between a timing laboratory and a moderately distant user is larger than the fluctuations of the signal produced by the frequency standard itself, so that the full accuracy of the clock can only be realized at a distant site if the transit time of the signal to the user is measured and the fluctuations about its mean value are well–characterized. Three techniques can be used to estimate the magnitude of this delay and to correct for it; the principles underlying all of them have been around for many years, although the details of the implementations have evolved with time.

1. Two–Way Methods

These methods use signals that travel in both directions along the path between the clock and the user and they estimate the one–way delay as one–half of the round–trip travel time. They obviously depend on the reciprocity of the path; while reciprocity is a simple concept, it is difficult to realize in practice. The basic problem is simple: if the hardware is inherently bi–directional, the message protocol is often half–duplex – the messages in the two directions traverse the path at different times and the fluctuations of the path delay in time may limit the reciprocity. If, on the other hand, the channel is full–duplex so that messages can travel in both directions simultaneously, then at least some of the hardware is inherently uni–directional so that the reciprocity will be limited by the imbalances between the send and receive channel end–point hardware even if the intervening path (through the atmosphere, for example) is highly reciprocal. Examples of both types of system are easy to find. Computer networks, for example use bi–directional hardware, but the channel is used in a half–duplex manner – the messages in the two directions are sent at different times, and the reciprocity will be limited by short–term fluctuations in the load on the network and especially at the switching points. Two–way time transfer using communications satellites, on the other hand, is a full–duplex method which exacts the expected price: different hardware is used for the two directions and the reciprocity is likely to be compromised unless the two channels are very carefully balanced.

2. Common–View Methods

These methods use one–way signals that travel along two different paths at almost the same time to two separated receivers. Unlike a two–way method which depends on the equality of the transit times in both directions on the same path, a common view method depends on the equality (or at least the stability) of the transit times in one direction along two different paths. Near–equality of the physical lengths of the two paths is obviously desirable since paths of different lengths can only be imperfectly compensated for by extrapolation – if the signals arrive at the end–points simultaneously they must have left the source at different times, whereas if they left the source at the same time they will not arrive at the end–points simultaneously. One of the advantages of this method is that the active cooperation of the transmitter is not required – it may not even "know" that it is part of a measurement. Signals from television stations, from LORAN stations and from GPS satellites have been used for common–view dissemination, and there have even been proposals to use the 60 Hz power system in this way.

3. Dispersion–Based Corrections

These methods estimate the correction to the transit time due to the refractivity of the transmission medium by measuring its dispersion – the dependence of the transit time on signal frequency. The system sends the data using several different frequencies simultaneously. The power of the technique depends on the fact that the time delay introduced by the medium can often be expressed as the product of a known function of the signal frequency and a known function of some path parameter (such as column density). If this is the case, the medium–dependent portion of the distance and dispersion equations are the same, so that a measurement of the dispersion can be used to correct the transit time itself. This method is not universally applicable since not all paths are dispersive, and some dispersive media cannot be characterized by a separable dispersion equation. Given the dependence on path parameters that we have assumed above, the fractional error in the determination of the transit time will be equal to the fractional error in the dispersion. The dispersion is usually much smaller than the transit time itself so that its measurement accuracy must be correspondingly higher. The error budget of the dispersion estimate often dominates the error budget of the entire measurement as a result.

All of these methods are currently used in disseminating time and frequency, and some systems use more than one method simultaneously. The GPS system, for example, is often used in common view mode, and its dual–frequency signal structure is designed to facilitate an estimate of the ionospheric refractivity using the observed dispersion between the L1 and L2 signals. The tropospheric refractivity, on the other hand, usually cannot be estimated from the dispersion. The effect is very small to begin with and is not completely separable because of the presence of a term due to tropospheric water vapor. Various methods have been used to estimate the tropospheric refractivity including balloon measurements and water–vapor radiometers, but none has proven completely successful. Corrections for the tropospheric index of refraction are already widely used in geodetic measurements using GPS, and they are likely to be necessary in time–transfer in the future.

Many of the current high–end users are more interested in frequency than in time, and the ideal dissemination system for them would be one whose fluctuations could be characterized as white phase noise at all averaging times. The uncertainty in the frequency transmitted by such a system can be made as small as desired by increasing the averaging time until some other process (such as the performance of the clock itself) becomes important. No currently operating system satisfies this condition, and developing such a system will be one of the goals of the near–term future. Although it may be possible to improve the characteristics of the transmission media, further decreases in the uncertainty of the transit time may only be realized with more sophisticated averaging schemes, perhaps including extensive post–processing.

One of the difficulties in improving time dissemination is that many of the systems that are currently used for this purpose were in fact originally designed for some other function which was not very sensitive to the propagation delay itself or to fluctuations in the delay about some average value. A system that can meet the increasingly stringent requirements of the next 25 years may have to be designed as a time–transfer system from the start rather than as a piggy–back on a system designed for some other purpose.

At least in the short term, dissemination will probably depend on the two–way and common–view methods. Both of them are inherently symmetrical and do not single out either participant as client or server. Any system based on these methods is able to support the peer concept that is likely to be the optimum way of interacting with customers with very high–quality clock hardware. Common–view GPS would seem to have an initial advantage in terms of the number of sites that can participate in a simultaneous measurement campaign, but this advantage may not be fully realized in practice because of the intentional degradations of the GPS signal. A two–way system using communications satellites is less likely than a common–view GPS system to be limited by fluctuations in the atmospheric component of the transit delay, but this advantage may be lost due to time–varying asymmetries in the hardware.

The Low–End Dissemination Problem

The fundamental problem of high–end dissemination is finding a way of preserving the inherent accuracy of the clock hardware during the transmission of the information to the user. This issue is usually not so important to the low–end user. The more significant issues are often cost, reliability, ease of use and possibly legal traceability. The accuracy of the signal transmitted by WWV, for example, is adequate for many users, but receiving the signal reliably often requires an outside antenna, and extracting the time in a digital format requires something more than a bottom–of–the–line receiver. A telephone time service like the NIST Automated Computer Time Service may be easier than WWV to install and more reliable to operate, but each use requires a telephone call to the server. A user with many systems to synchronize may be faced with appreciable telephone costs, and a significant investment in server hardware will be required to provide an adequate level of service. A single ACTS server can handle perhaps 1500 calls/day; more than 500 servers would be needed if only 1% of the estimated 80 million domestic PC users used ACTS only once per day. Similar scaling arguments apply to almost any publicly–available service which attempts to estimate the transit time of the signal along the path to the users. (The cost of running a radio service like WWV obviously does not depend on the number of users, but the path delay can only be estimated using tables of the average propagation characteristics at any site.)

The load on the servers could be reduced with better client oscillators that required less–frequent synchronization and more sophisticated use of the calibration data when they are acquired. The NIST Internet Time Service is a first attempt in this direction – it has demonstrated performance accuracies substantially better than one second using less than one calibration message per day. A single stratum–1 server can handle at least 20 000 requests per day so that the required server hardware increases much more slowly with heavy use than would be true for an ACTS–type system. Although ACTS can deliver time signals more accurately than the internet, the difference is not important in many applications.

Both ACTS and the internet time service are based on the two–way principles outlined above; the ACTS system is more accurate because its signals travel over a dedicated telephone circuit that is more easily characterized. Several internet methods are based on a combination of two–way and common view in an attempt to compensate for the relatively poor characteristics of the internet. Improvements here are quite likely, both in the speed of the network itself and in the sophistication of the software at each client node.

None of the currently available dissemination systems addresses the issue of authentication – the need for some users to be able to obtain a time–stamp that can provide legal proof of its authenticity. A simple example is the need to prove that a document describing the disclosure of an invention actually existed on a certain date. This requirement is currently satisfied for conventional documents by obtaining the stamp or the signature of a disinterested third party like a notary or a post–office, but there is no correspondingly simple method for authenticating the time–stamps on documents that are in digital format such as computer files.

A related issue to authenticity is the need for anti–spoofing – a method of allowing a client to verify that a time message originated from a genuine time server. It is unfortunate that the probability of fraud will increase as time–stamping becomes more important and as the certified data become more precious, but this is likely to be true, and some means of authenticating time transmissions may be required in the future. Several proposals have been advanced for adding authenticating digital signatures to messages transmitted over wide–area computer networks, and various public–key encryption systems such as the method currently used for GPS transmissions have been proposed for authenticating messages sent by other means, but none of these methods is generally available or particularly easy to use. It is quite possible that simplicity and robustness will continue to be conflicting goals, and there may be no alternative to systems that are complex and somewhat awkward to use as a result.

Conclusions

The continuing improvement in the stability and accuracy of frequency standards must be accompanied by corresponding improvements in the means used to disseminate time and frequency data to users if these standards are to be widely usable. Several dissemination methods currently exist, but none is likely to be completely adequate either from the point of view of adequate stability and accuracy to satisfy high–end users or from its ability to be scaled up to serve an increasing number of users with moderate requirements who are more interested in ease of use and low cost. Several different techniques are likely to be required to serve these very disparate demands, although they are all likely to be based on the general principles we have discussed. The increasing demand for automated time–stamp systems and the increasing value of time–critical data make various forms of cheating or even fraud more lucrative, and some form of authentication of time transmissions may eventually be required. Existing authentication techniques tend to be cumbersome and inefficient, and finding a simpler method that maintains adequate security may become a high priority task in the next few years.

QUESTIONS AND ANSWERS

Dr. Cutler, Hewlett–Packard Labs: I would just like to comment on the very last thing that you talked about, anti–spoofing. There are some people at AT&T labs that have already developed a system of authentication that is very neat and very clever for time stamping using hashing techniques.

J. Levine: I have a similar proposal along the same line which is similar to the proposal. NTP, the Network Time Protocol that I spoke about this morning, has a DES incription mode connected to it. So people are beginning to think about it. But it is just a beginning. It is going to become a real problem in a few years.

Dr. Winkler, USNO: I have two comments. First, your interesting story about Ramsey, I was not aware of that. What that means really is the decision, if it would have been a decision of the BIPM or the CIPM to define the second; if it would have been done in respect to universal time seconds during these years when Ramsey estimated the correct frequency of cesium, we would be all right today, because that has not changed very much. We would still be offset 300 parts in ten to the tenth from ephemeris time. The problem is they selected ephemeris time in order to provide the continuity with the decision of the general conference of 1956 to adopt ephemeris time. And I think the reason why we have these leap seconds really goes back to the fact that we have pushed for a change too rapidly. We have done that before we really understood the implications of what was going to be done.

J. Levine, NIST: I would say that you are right, but it is also true – I mean, I was only a graduate student in 1965, and I spoke only when I was spoken to; and I wasn't really in the time and frequency community. But it was also true that there were two different communities because we haven't spoken at all about the spectropscopy and frequency community. And they were pulling in a very different direction.

Dr. Winkler: You are right. There was this difference of languages and everything, philosophy and everything, after that. But let me go to the second point, which I think is more of immediately practical importance and that is the point which you made about the problems of access and costs. I think the worldwide availability of GPS will eliminate them. There is simply no problem. You have a passive reception of – 10 billion people can do that if they want to. And it doesn't cost them anything because to receive all you have to provide the little receiver which will in five years be within a wristwatch; and everybody will have time within 10 ns at minimal cost. So I really think the problem which you have construed here as being a danger is going to go away.

And the last point which I would have to make is the problem of the legal time reference in the

United States. And we have to state that by law; the responsibility of NIST is to provide the standard of frequency, the standard of time to seconds. The responsibility of the Observatory is to provide the time reference.

J. Levine: Sorry, you misunderstood the essence of my point. The essence of my point was not that NIST had a unique responsibility; it's that some downstream user had to be able to have –

Dr. Winkler: I agree with that, and that is a problem. But the problem is very similar to what you have in navigation. If an accident happens in the high seas and the question comes up, "Has there been sufficient care in navigation or has there been a lack of care? Has the access to the navigation system been so that prudence has been exercised or not?" And that also immediately applies to any other technical information. And if anyone, just without making any checks, accepts the next time reference from the next church tower and makes critical decisions, this is not sufficient prudence and not sufficient care; and it will not stand up in court. So I refer to the legal practices which govern questions of accidents at sea and the use of navigational information; because exactly the same situation exists here in such expressions as when you have to make decisions on time or have to be certified on certain moments and so on.

Ralph Partridge, Los Alamos National Lab: You were commenting about the escalating costs of having to supply a million telephone calls today and saying that it has to be done in a reasonable way. And of course, Gernot's point is well made with the wristwatch GPS receiver and so forth; except those things need antennas and the antennas have to be outdoors. So it may not be as universally usable as he was hoping perhaps. But if you can have a system as it expands does so exponentially rather than linearly, you come out ahead. And so if you simply have the time disseminated locally at each central office, each one can serve 10,000 telephones, that can get it from the next higher level; and now your system increases exponentially and the cost goes as the logarithm in the number of servers.

J. Levine: I agree with you. That brings up the issue of traceability. You then have to be sure that all of these folks are doing the right thing. I agree with you 100 percent.

Ron Beard, Naval Research Lab: I just wanted to make the point that time is already money, because one of the bigger users of the computer networks in data exchange that is currently ongoing is commodities and monetary exchange. I think it is highly important that they know exactly when these transactions take place. And as they are going through these networks, the timing of them, when they are actually associated with the various buyers is already a critical point. So I think we are already in that state. We just may not appreciate many of the implications yet.

Dr. Winkler: I think this is an extremely important point. You are absolutely right. And the most critical one is the confusion which is possible during a leap second, when it is introduced. And it may be the most powerful argument to revise the rules which govern the insertion of leap seconds and the coordination of universal time. It is really something which we will have to consider.

But let me say another thing here. And that is there is always going to be a minimum interval of time within which actions must be considered as simultaneous. And they will have to deal with the ability of the human mind to do different things, or to distinguish two different things. Where time can be measured electronically, of course there is no question. But when you talk about actions and certification and decisions I think we are not talking about microseconds.

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—Recent developments in rubidium, cesium, and hydrogen-based frequency standards, and in cryogenic and trapped-ion technology.
—International and transnational applications of Precise Time and Time Interval technology with emphasis on satellite laser tracking networks, GLONASS timing, intercomparison of national time scales and international telecommunications.
—Applications of Precise Time and Time Interval technology to the telecommunications, power distribution, platform positioning, and geophysical survey industries.
—Applications of PTTI technology to evolving military communications and navigation systems.
—Dissemination of precise time and frequency by means of GPS, GLONASS, MILSTAR, LORAN, and synchronous communications satellites.

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