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PROCEEDINGS OF THE FIFTH ANNUAL

NASA AND DEPARTMENT OF DEFENSE PRECISE TIME AND TIME INTERVAL (PTTI) PLANNING MEETING

DECEMBER 4-6, 1973

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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December 4-6, 1973

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U. S. Naval Electronic Systems Command
NASA Goddard Space Flight Center
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Prepared by
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

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CALL TO SESSION
Dr. William J. Klepczynski, NAVOBSY

WELCOME ADDRESS
Dr. John F. Clark, Director, GSFC

OPENING COMMENTS
Dr. K. Aa. Strand, Scientific Director, NAVOBSY

OPENING ADDRESS
Capt. Earl B. Fowler, Jr., NAVELEX

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

PROCEEDINGS OF THE FIFTH PRECISE TIME AND TIME INTERVAL PLANNING MEETING

FOREWORD

This volume contains the papers presented at the Fifth Annual Precise Time and Time Interval (PTTI) Planning Meeting. The meeting was sponsored jointly by NASA/Goddard Space Flight Center, the U. S. Naval Observatory, and the U. S. Naval Electronic Systems Command. The meeting was held December 4-6, 1973 at Goddard Space Flight Center.

The purposes of this meeting were to:

a. Disseminate, coordinate, and exchange practical information associated with precise time and frequency;

b. Review present and future requirements for PTTI; and

c. Acquaint systems engineers, technicians, and managers with precise time and frequency technology and its problems.

More than 300 people participated in the conference. Attendees came from various U. S. Government agencies, from private industry, and from several foreign countries and international laboratories. Twenty-eight papers were presented at the meeting, covering areas of navigation, communications, applications of interferometry, frequency and time standards and synchronization, and radio wave propagation.

Abstracts are presented for three papers given at the meeting for which no written paper was received. One paper, which was not presented at the meeting because the author was unable to attend, is contained herein.

It was readily apparent that the close communication and cooperation that was established between various Government agencies, private industry, and international laboratories at previous meetings has been maintained.

Many contributed to the success of the Meeting. On behalf of the Executive Committee of the Fifth PTTI Planning Meeting, I wish to acknowledge the Session Chairmen, speakers and authors, the members of the Technical Program Committee and Editoral Committee and the many others who gave freely of their time.

Copies of the Proceedings may be obtained by sending a request to:

S. C. Wardrip
Code 814
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Dr. William J. Klepczynski
General Chairman

INTRODUCTION

MR. WARDRIP: I am Clark Wardrip, from Goddard. I welcome you here this morning. I see many of you that were here last year, and I welcome you again.

In view of the fuel shortage and the cutback on air transportation, and the general restriction on government travel, I am gratified to see so many of you here this morning.

I think the attendance speaks well of the PTTI Planning meetings, and the importance that upper management places on these meetings.

As last year's chariman, it is my privilege and also a personal pleasure for me to introduce this year's chairman, Dr. William Klepczynski, of the U. S. Naval Observatory.

Bill has double-duty this morning. He is also chairman of Session I.

So, Bill, I would like to pass control of the meeting to you.

DR. KLEPCZYNSKI: Thank you, Clark.

CALL TO SESSION

William J. Klepczynski
U. S. Naval Observatory

DR. KLEPCZYNSKI: It is my great pleasure to call to session this Fifth Annual PTTI Planning Meeting. There are a few brief introductory remarks concerning this meeting which I would like to make.

The first concerns the organization of the papers on the program. For each of the three days of the meeting, the papers are grouped together according to the following general categories:

> The first day of the meeting is devoted to PTTI requirements, applications, and systems.
>
> The second day is concerned with time dissemination, clock calibration, and precision frequency sources.
>
> The third day is devoted to VLF transmissions for time synchronization, and PTTI requirements for communications.

I believe the technical program committee did an excellent job in selecting the papers on the program. However, if anyone feels that certain topics are not adequately covered, please contact any member of the executive committee during the course of the meeting, and make your preferences known. They will be taken into consideration for the next PTTI Planning Meeting.

One of the most important benefits of a meeting of this type is the gathering together of many knowledgeable and interested parties. Because of this, I urge all attendees to partake in the discussion periods, or engage in private discussions. If this is not done, then I am afraid that one of the benefits of such a gathering of expertise will be lost.

It is important to take note of the increased participation of representatives of foreign laboratories in this meeting. PTTI is one of those unique fields which not only brings together scientists and engineers of different fields of specialization, but also scientists and engineers of different countries.

Today, we have in our audience representatives of Australia, Canada, Germany, Italy, Taiwan, and the United Kingdom.

On the program tomorrow, we will have three internationally known scientists discussing the work done at their laboratories, Mr. Humphrey M. Smith of the Time Department of Royal Greenwich Observatory, Professor S. Leschiutta, Instituto Elettrotecnico Nazionale, the IEN, Torino, Italy, and Dr. E. Proverbio of the International Astronomical Latitude Station at Cagliari, Italy.

I am sure that we will all benefit from hearing first-hand the work being carried on at these facilities.

It is now with great pleasure that I now call upon Dr. John F. Clark, the Director of Goddard Space Flight Center, for our welcoming address.

WELCOME ADDRESS

John F. Clark, Director
Goddard Space Flight Center

DR. CLARK: Good morning, ladies and gentlemen. It is a real pleasure on behalf of the center to welcome you here.

I must confess, I haven't quite gotten over our date with the large planet last night. Many of us were out here until close to midnight. I think it was a disappointment only to those people who had hoped to be able to see enough real time rectified photography to be able to get out and just about crawl down into that Red Spot. Everything else about it was spectacular, as befits that giant lady.

Incidentally, I heard a new word this morning on the Today Show. John Wolfe, the project scientist at Ames was talking about what had been learned overnight, and he used the word "geochauvinism" to talk about the view that those of us who grew up about Earth have about another planet and what we should see as we come close to it.

It requires a lot of patience to get some of the rectified pictures. We saw the first one of those last night, taken about a week ago, and this morning they had another one which, unrectified, looked to the unaided eye as a somewhat distorted nome black and white television picture. This rectified picture had about twice as good a resolution as the best of the previous ground base photography.

So, I for one am looking forward to this with some excitement.

Many of you may know that Goddard is one of NASA's eight major field centers. NASA Headquarters is in Washington, D. C. Goddard has prime responsibilities in the areas of space science and applications, and in network mission and data operations.

It is particularly in these latter areas that we find our principal affinity with precise time and time interval measurements.

From early days, starting in 1958 when NASA was formed and this center came into being officially, Goddard people have been very active members of this time and frequency community, and I think our contribution to this field, as you will hear in some of the papers today, has been significant.

From Project Vanguard to the present, we have had close cooperation with DOD in many fields, particularly in the time and frequency area.

You folks have established a communication and mutual data exchange that has been beneficial to the entire scientific community, as is evidenced by this conference today.

In particular, Goddard has maintained very close cooperation with the Naval Research Laboratory, from whence many of our people migrated, and I must say in looking over the program I notice that your chairman of Session VI was a roommate of mine too many years ago when we both worked at NRL.

The assistance of the United States Naval Observatory in transporting time to some of our tracking stations in support of Apollo is very much worthy of mention, as is the use by NASA of the time broadcast and VLF transmissions from the stations of the National Bureau of Standards, and the Loran-C stations of the Coast Guard.

You may recall that up until a few years ago, radio station WWV was next door to Goddard. We certainly had no problem receiving time then. All we really had to do was hold up a finger.

We have all seen over the last decade accuracy requirements for time tightening: seconds, to milliseconds, to microseconds.

In the near future—almost the present—it looks even tighter, requiring fractional nanoseconds, both in laser geodesy and very long baseline interferometry.

Frequency stability requirements have advanced from a few parts in 10 to the 9th to parts in 10 to the 13th or better. I suspect only you can imagine what the more distant future requirements are going to look like.

We at Goddard look forward to continuing cooperation in this very interesting field, and therefore it is with pleasure, as your host, that I welcome you to this conference, and I look forward to participating as I am able.

Thanks very much.

DR. KLEPCZYNSKI: Now, for some opening comments from Dr. K. Aa. Strand, who is the Scientific Director of the Naval Observatory.

OPENING COMMENTS

K. Aa. Strand, Scientific Director
U.S. Naval Observatory

DR. STRAND: Good morning, ladies and gentlemen.

On behalf of the U.S. Naval Observatory it is my pleasure to extend a hearty welcome to the participants of the Fifth Annual PTTI Planning Meeting.

Since the Observatory's humble start as the Depot of Charts and Instruments in 1830 it has been continuously involved in the determination of time. Over the many intervening years the Observatory has achieved many firsts, both in astronomy as well as in time and time interval as such.

The Observatory has in this manner served not only the Navy, but also the Nation, for nearly 150 years, while at the same time contributing to many international undertakings in science.

Let me briefly mention a few contributions the Observatory had made in the field of time and frequency.

In 1845 the Observatory began its first time signals by dropping daily at noon a a time-ball from its roof.

In 1865 the Observatory commenced sending time signals to fire and police stations in Washington, and since 1877 to Western Union for nation-wide distribution. In 1904 the first operational radio time signals were transmitted by a Navy Radio Station with the time signals controlled by the Observatory.

In 1958 the Observatory established the duration of the atomic second in an experiment conducted jointly with the National Physical Laboratory, Teddington, England.

In 1962 the first high precision time transfer was accomplished between the Naval Observatory and the Royal Greenwich Observatory using the Telstar Satellite, a technique which has now become an essential link in the overall timing system. Finally, since 1960, the Observatory has used ensembles of clocks as the basis for an extremely precise and reliable atomic time scale. This atomic time and the principles of its operation have now become an important contributor to the international atomic time kept by the BIH.

When the Observatory began its time determinations, it was able to do so with an accuracy of 0.1 second, which corresponds to a frequency precision of one part in a million per day. Now our scale is stable to four parts in 10^{14} per day, an improvement of 25 million times.

It is now my pleasure to introduce to you Captain Earl B. Fowler, Deputy Commander, Material Acquisition Directorate, of the Naval Electronic Systems Command.

Captain Fowler is a graduate in mechanical engineering from Georgia Tech, and holds an electrical engineering degree from MIT. Since time does not permit me to describe his distinguished career in the Navy, I shall simply turn the rostrum over to Captain Fowler, who will speak on the Naval Electronic Systems Command's responsibility for PTTI within the Navy Department.

OPENING ADDRESS

Earl B. Fowler, Jr.
Naval Electronic Systems Command

CAPT. FOWLER: Thank you Dr. Strand.

It is my pleasure to be here this morning at Goddard after some years. A few years ago I was the project manager for the construction of the five ships for the support of the Apollo Program. I enjoyed that association with this organization.

It is my great pleasure to be here this morning representing Rear Admiral Raymond J. Snyder, United States Navy, Commander of the Naval Electronic Systems Command, one of the co-sponsors of this meeting.

I want to welcome each of you, especially our distinguished guests from Europe and the Orient.

Again this year, the Naval Observatory, the Naval Electronics Systems Command, and NASA Goddard Space Flight Center are co-sponsoring this event, which brings together many of the national and international agencies with responsibilities and interest in PTTI.

The Naval Electronic Systems Command is a worldwide organization, with headquarters here in Washington. It is a fast growing, dynamic command, supplying many of the electronics needs of the operating forces.

We were founded in 1966, and we are still a youthful organization. We do not enjoy the tradition and longevity of the 150 years that the Naval Observatory does, nor the contemporary exploration of unknown planets as our friends here at Goddard.

Originally, our responsibility was limited to shore electronics, remote sensors, special communications for submarines, navigation aids, and ocean surveillance.

But during our seven year history, we have expanded to include command controlled communications, reconnaissance, electronic warfare, special operations intelligence, and tactical electro-magnetic warfare, and we are still growing. We have about a billion dollar budget now.

The Naval Electronic Systems Command has been designated the Navy manager for PTTI, including planning, programming and budgeting for research development, procurement, and life cycle support.

In addition, the Naval Electronic Systems Command assists the Naval Observatory in its job of PTTI manager for the Department of Defense.

We are responsible for updating PTTI systems.

The presently accepted method for synchronizing clocks is through our portable clock service, which consists of teams carrying clocks to sites for calibration as required.

The cost in dollars and people necessary to provide this synchronization service is a problem.

To provide better precision at a lower cost, we, in cooperation with the U.S. Naval Observatory, and the Naval Research Laboratory, have developed a concept of time distribution utilizing long range transfer of PTTI via existing satellite systems, short range transfer via microwave lengths, and local transfer via hardware or optical systems.

The PTTI program has been progressing under this concept of operations, proving the feasibility of utilizing various methods of time transfer, so that ultimately a network of redundant paths will be available to users who can synchronize their clocks to a common source, normally the U.S. Naval Observatory Master Clock.

Navy application of precise time and time interval technology includes navigation and ship positioning, increasing the efficiency of point to point digital communications, and assuring that the crystal oscillators and synthesizers are precise.

The digital data rates of a given communications system under precise control can perhaps go up from 2,400 Baud to as high as 9,600 Baud, or better. However, the confidence of these rates directly depends on absolute accurate knowledge of the Baud-to-Baud time record.

International color television transmission can also profit from this knowledge. For example, in order to bring in real time color television at both ends, the oscillators and color separators must all be accurately synchronized.

Other potential uses of PTTI include effective collision avoidance systems for aircraft, more efficient use of radio frequency spectrum, further long line communications efficiency, and time correlation of distant geodetic and geologic astronomic events.

The overriding objective of the Naval Electronic Systems Command PTTI program is to disseminate PTTI utilizing wherever possible existing electromagnetic systems and to provide a common reference to most Department of Defense users, and above all, to effect standardization of time and frequency to the best of our ability.

The exchange of ideas and the dissemination of information at these PTTI meetings, which advance this objective, will certainly have some influence on decreasing proliferation of equipment and upcoming systems.

This way, we will encourage maximum use of existing capabilities, and this means cooperation with others.

I think I can underscore that last one, as I look to the future budgets, and what we are going to be able to do, and say that cooperation and maximum use of what we have is going to be the keynote.

I am sure that our NASA hosts are going to provide us with a very enjoyable and informative session, and I thank you very much and wish you the very best in your meetings to come.

DR. KLEPCZYNSKI: I thank our opening address speakers for the very informative insight into what goes on at the various installations.

At this time, we will start with Session I.

The first paper is entitled "Defense Mapping Agency Precise Time and Time Interval Requirements." The speaker was scheduled to be Rear Admiral Carnahan. However, he is recuperating from an operation and was not able to make it, but the Assistant Director for Plans and Requirements, Mr. O. W. Williams, will give his paper for him. You will also hear from him later on today.

SESSION I

Chairman: Dr. William J. Klepczynski
U.S. Naval Observatory

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DMA PRECISE TIME AND TIME INTERVAL REQUIREMENTS

R. H. Carnahan
Defense Mapping Agency

ABSTRACT

The Defense Mapping Agency, as well as its predecessors, has been a user of time for a number of years as part of the geodetic astronomy and satellite geodesy programs.

John Harrison's clock opened the door to the field use of time required in the determination of astronomic longitude. While current astronomic observing methods employ the same basic principles that were utilized 200 years ago, instrumentation used in the determination of astronomic positions has been greatly improved and epoch times are printed out rather than read from a clock face or interpolated from recorded clock ticks. The accuracy and particularly the stability of portable timing equipment used in the field for astronomic positioning has been greatly improved during the last 10 years.

Positioning by satellites using portable Geoceiver equipment has facilitated the rapid determination of geodetic positions on a uniform world system and has replaced positioning by astronomic methods in remote areas of the world. The high velocity of satellites being used for precise positioning has led to the requirement for more accurate time. Clock epochs to about 50 microseconds are now routine at satellite tracking stations with the goal being at least 10 microseconds. Although these accuracies are still less precise than the state of the art, they must be met with operational equipment and frequently under unusual field conditions. Crystal oscillators in the Geoceivers are stable in frequency to 8 parts in 10^{12} (short term) and 5 parts in 10^{10} (long term), and are among the better crystal standards.

Another geodetic system, the Very Long Base-Line Interferometer (VLBI) requires the synchronization of clocks at two or more observing stations to extremely high accuracy. The accuracy of the system depends largely on the accuracy of the synchronization. The use of Rubidium standards to replace the crystal standards will be tested in the near future at fixed satellite tracking stations for the purpose of improving satellite orbits. New satellite systems, such as those proposed in the Defense Positioning Program (DPP) will be able to use more precise timing for providing observational data required for the accomplishment of geodetic missions. Defense Mapping Agency timing requirements range from milliseconds to tenths of nanoseconds. These requirements will be discussed in detail.

INTRODUCTION

The Defense Mapping Agency was established in July 1972 by the Secretary of Defense. We are charged with providing the Unified and Specified Commands and Services with maps, charts, precise positions, gravity field data and other geodetic products. While DMA is a new agency, it is made up of elements of the former Army Topographic Command, the Naval Oceanographic Office and the Air Force Aeronautical Chart and Information Center, which have existed for some time. These are now known as our Topographic, Hydrographic and Aerospace Centers. Our small Headquarters is located on the Naval Observatory grounds.

One of man's earliest requirements for precise time was for navigation and positioning. The addition of the astronomical section of the Depot of Charts and Instruments in 1837 was a step in the direction of more precise time for greater accuracy for nagivation and charting. Although the U.S. Naval Observatory and the U. S. Hydrographic Office became separate entities in 1866, when the Depot of Charts and Instruments was reorganized, the need for time has made us more and more dependent upon the Naval Observatory throughout the years. This depedence shows up mainly in two areas of our work; time required for geodetic astronomy, and time required for satellite tracking.

GEODETIC ASTRONOMY

Since there is a direct relationship between longitude and time, determination of the local time at a specific point with respect to the time at the meridian of Greenwich will establish the longitude of the point. Present day time signals which are broadcast by several major observatories throughout the world have been synchronized and provide an excellent means of obtaining time with reference to the meridian of Greenwich. Time at the measurement point is determined by observing the meridian transit of stars using optical instruments and precise timing equipment.

The UTC (Universal Time Coordinated) time signal used to compute longitude must be corrected to UT1 (Universal Time Corrected For Polar Motion); in other words, the UT1-UTC corrections must be applied. This means that the local sidereal time of the observatory monitoring the radio signal which is received at the field station has been referenced to the identical pole or axis of rotation as the field station.

UT0 (Uncorrected Universal Time) as determined by stellar observations includes errors in the apparent positions of the stars observed, unknown refraction effects, observational errors, and a systematic error caused by the conventional longitude of the observatory not being exact, relative to the prime meridian. One millisecond of time represents approximately one half meter on the ground at the equator. Through the Bureau of International de L'Heure (BIH), the conventional longitudes of the time service stations are revised to minimize the errors introduced by inconsistent longitudes.

As a result of the longitude adjustments and the previous synchronization of the time services with the atomic frequency standards, conventional (high frequency) time signals and corrections thereof are based on the coordinated and synchronized system UTC (UT Coordinated). Published corrections are now available 30-60 days after the fact. It would, of course, be desirable to have these corrections available sooner, say, about 15 days. (Since the presentation we have been advised that the corrections are available in the desired time).

Until comparatively recent times, time for field astronomy was maintained with a mechanical chronometer which was compared about once an hour with a radio time signal. These comparisons were recorded in increments of two seconds on a chronograph along with the star transits over the observer's meridian and subsequently manually scaled (interpolated) and meaned. As the mechanical chronometers were replaced with crystal clocks, the times between radio clock comparisons were allowed to become less frequent. Finally, the increased accuracy, due to use of temperature controlled ovens, permitted longer periods between time comparisons.

Paper or magnetic tape recorders allowing direct input of star transit times into a computer have been considered for some time. This would eliminate the most time consuming (and I might add, the most monotonous) job in the determination of longitude; that is, the scaling of the time ticks from strip or oscillograph charts. As you know, field astronomic equipment must be portable. Very few sites, probably less than fifty percent, are "drive to" stations. Most stations are located on hill tops or in remote areas not accessible by road. The "backpacking" of generators or heavy batteries except for short distances is an extremely difficult task. We are still looking for a lightweight digital recorder system which can be used for direct entry into a computer.

Recently, DMA acquired several time position printer systems, Model SP-300, manufactured by Datametrics, a subsidiary of ITE Imperial Corporation of Wilmington, Massachusetts. One of these is shown with a Wild T-4 optical theodolite (Fig. 1). This system can be powered by disposable dry cell batteries. A sample of the "grocery tape" output of the system shows FK-4 star number, day of year, hours, minutes and seconds of observation (Fig. 2). About 60 astronomic stations have been observed to date with excellent results using this equipment.

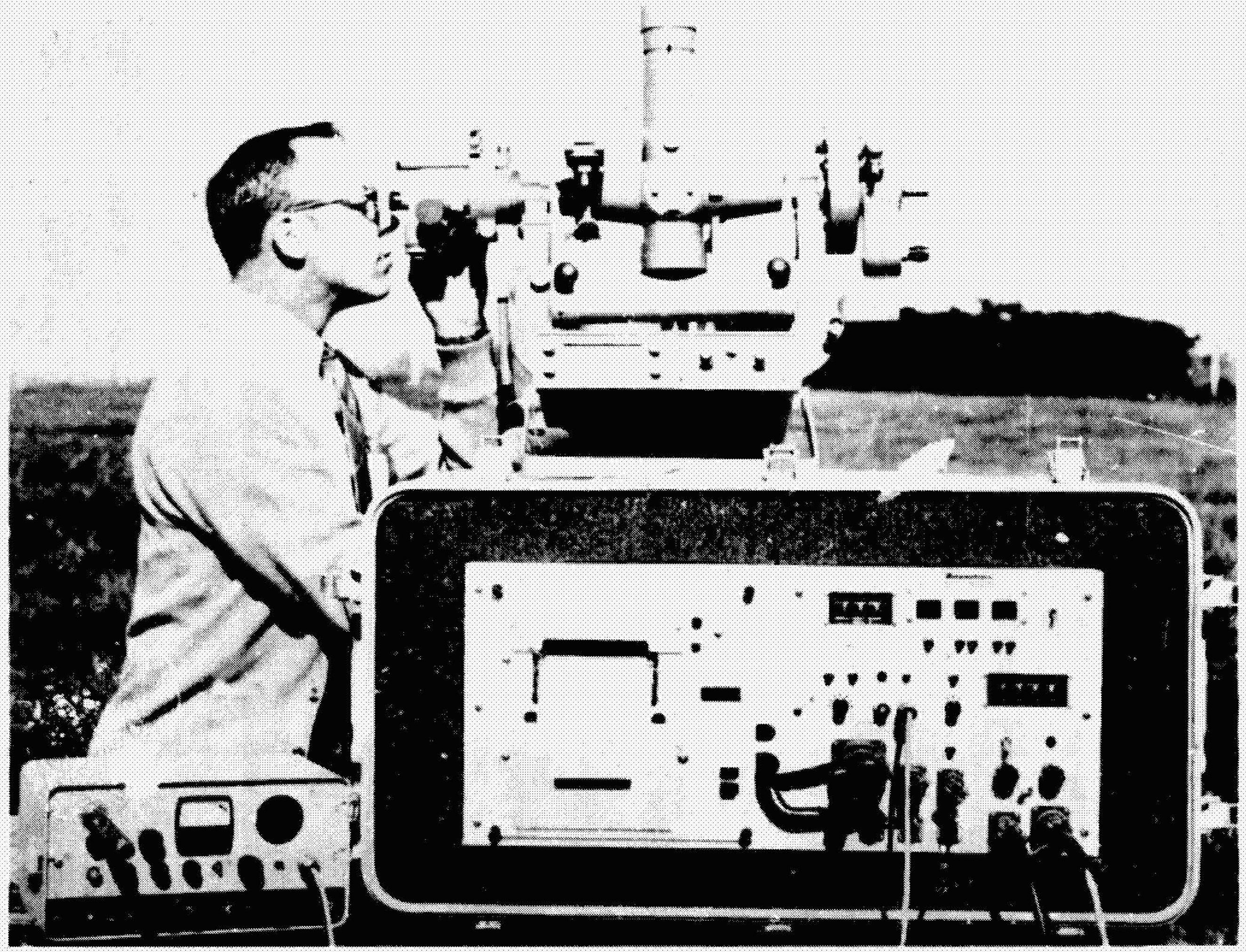

Figure 1

O-04
SETS 3,4,5,6
30JULY73 PM
F-4 #87018
K.D.ZELLERS

FK4 Star No.	Date (Day of year)	Hours	Minutes	Seconds
3610	212	06	25	44 .249
3610	212	06	25	42 .713
3610	212	06	25	41 .297
3610	212	06	25	39 .739
3610	212	06	25	38 .193
3610	212	06	25	36 .800
3610	212	06	25	35 .370
3610	212	06	25	32 .059
3610	212	06	25	30 .523
3610	212	06	25	28 .897
3610	212	06	25	27 .417
3610	212	06	25	25 .826
3610	212	06	25	24 .322
3610	212	06	25	22 .912
3610	212	06	25	21 .262
3610	212	06	25	19 .915
3610	212	06	25	16 .219
3610	212	06	25	15 .169
3610	212	06	25	13 .753
3610	212	06	25	12 .343
3610	212	06	25	10 .635
3610	212	06	25	09 .052
3610	212	06	25	07 .676
3610	212	06	25	05 .271
3610	212	06	25	04 .459
3610	212	06	25	01 .421
3610	212	06	24	59 .879
3610	212	06	24	58 .475
3610	212	06	24	56 .950
3610	212	06	24	55 .459
3610	212	06	24	53 .203

06 25 00

Figure 2

A major advantage of combining the DoD mapping, charting and geodesy functions under one single organization is that a larger base is available for the justification and development of new instrumentation. In an effort to reduce the possibility of error and to reduce the cost of astronomic positioning, an automated astronomic positioning system is being developed for DMA by the Control Data Corporation.

Electromagnetic distance measuring equipment used for trilateration or traversing measures the time required for a signal to make the round trip over the distance being measured. While the accuracy of measurements are limited by our knowledge of the speed of light, it is not the dominant error in these measurements.

SATELLITE GEODESY

DMA requires more precise time measurements for its satellite tracking programs. Satellites are tracked to determine an ephemeris which is used for positioning and in studies to improve our model of the earth's gravity field. Among other purposes, the model of the gravity field can be used to provide improved ephemerides. This bootstrap operation has been used primarily by the U. S. Navy, from whom the program was inherited, since 1960 and has resulted in the present gravity field model which includes harmonic terms through the twentieth order and degree, about 400 terms in all.

In addition to the Navy navigation satellites, other satellites, such as those launched by NASA, are used for gravity field improvements. The Timation III satellite, due to be launched next spring, will also be used. The GEOS-C satellite, scheduled to be launched next summer, will have an altimeter aboard which promises to provide deflections of the vertical over ocean areas and also an indication of the variation of the geoid. Other techniques, such as satellite-to-satellite tracking, are being examined to determine the least expensive system for improving the gravity field model and thus the shape of the geoid.

The DMA TRANET tracking network is managed by our Topographic Center and consists of 15 semi-permanent stations deployed worldwide and six stations available for mobile deployment. These ground stations track doppler satellites by recording the time of day when a preset number of doppler cycles have been received since the last data point. The measurements are dependent on a local clock synchronized with UTC from the Naval Observatory. The master tracking and control station at the Applied Physics Laboratory of The Johns Hopkins University is equipped with a cesium clock, which is tied to the Observatory by VLF, Loran, TV and portable clock transfers. When tracking the Navy navigation satellites, containing clocks maintained close to UTC, the time to receipt of the satellite's timing marks provides a means of calibrating the satellite clock against the Observatory's clock. The time signals from the same satellite, when received at the other stations, provide a means of calibrating the clocks at those stations. Redundancy is provided by tracking VLF time signals. At the present time, epoch is maintained at the tracking stations to an accuracy of about 50 microseconds. At the altitude of the NAVSATS, satellites move at the rate of seven meters per millisecond. The 50 microseconds, therefore, equates to 35 centimeters of satellite motion. Although this is well within the current observational accuracy, improvements are desired which will require timing accuracies of about 10 microseconds. Rubidium oscillators have been ordered for six of the semi-permanent stations, as a first step in achieving increased timing accuracy. Other changes are being considered at the same time to improve the overall observational accuracy. These include modification of a digitization technique, study of the third order ionospheric correction, and improving the phase lock loop. Quartz crystal oscillators are currently being used at the stations to drive the clocks as well as to measure the doppler shift. These oscillators have a stability of about one part in 10^{11} per day and slightly better than that over the period of a satellite pass.

As with astronomic observations, satellite observations must be corrected for the latitude shift due to the motion of the pole. A satellite making a dozen or so revolutions about the earth each day becomes a powerful tool for determing the position of the pole. The Naval Weapons Laboratory, Dahlgren, Virginia, reduces the data collected at the TRANET stations every other day to generate an ephemeris. These ephemerides can only be accurate if the polar motion is taken into account. Knowing the positions of the tracking stations, the position of the pole becomes a bias in the adjustment of the data, and must be applied as a correction. Comparison of the NWL polar motion values with the BIH and the IPMS (International Polar Motion Service) values shows as good agreement as between the BIH and the IPMS values themselves.

Although we are supplying the polar motion coordinates derived from doppler data to the Naval Observatory, the corrections applied to astronomic positions are derived by the BIH. Most astronomers are not ready to replace the traditional star observations with corrections derived from satellite data.

Positioning by satellite is also accomplished by using a geoceiver (Fig. 3) with the antenna unit located over the mark to be positioned. The geoceiver (geodetic receiver) is a miniaturized doppler tracking station weighing only about 45 kilograms. Designed by the Applied Physics Laboratory and Magnavox, geoceivers are operated by DMA Centers, as well as NAVOCEANO and others. The geoceiver clock is driven by a quartz crystal oscillator similar to the ones used at larger tracking stations. The clock is started from and synchronized with the NAVSAT time signals. The frequency of the oscillator and the clock drift can be

Figure 3

determined on site by hand calculations or as a part of the data reduction program. The stability of these oscillators is five parts in 10^{10} per day and eight parts in 10^{12} per minute. The time at the end of one doppler counting period and the start of the next is read out with a resolution of four microseconds. Positioning by geoceiver, when using the precise orbits computed by the Naval Weapons Laboratory is better than two meters in each coordinate axis. Approximately 35 usable passes are required to achieve this accuracy.

CONCLUSION

The knowledge of time epoch and the measurement of time interval have traditionally played an important role in the field of mapping, charting and geodesy. Current methods of astronomic positioning and satellite tracking will be replaced by new systems coming over the horizon. The present navigation satellites will be replaced with a new system of satellites, possibly those proposed under the NAVSTAR program (also referred to as the Defense Navigation Satellite System). We will be ready to make use of that system when it is available. Epoch accuracy will need to be about the same as the present accuracy. In the meantime, an order of magnitude improvement in the epoch accuracy of our tracking stations is anticipated which should approach the accuracy of the new system in the along track direction.

Much of the DMA survey work, particularly point positioning, depends upon time for its accomplishment. Nanosecond accuracy is not yet required, but the equipment for providing time and measuring time interval which is required, must operate under difficult field conditions. Cost, reliability and portability are of utmost importance. DMA is a production organization and must depend on the developers to provide the hardware needed to do the job with the accuracy and low cost demanded in these days of tight operating budgets.

In closing, I would like to acknowledge the fine assistance of Mr. Philip D. Kuldell of our Topographic Center in preparing this paper. I would also like to assure you as DMA's needs for increased precision and accuracy of time develop, we will appraise you of them.

QUESTION AND ANSWER PERIOD

DR. KLEPCZYNSKI:

Are there any questions from the audience? Yes.

MR. LIEBERMAN:

The new system that will replace the NAVSAT, will that be able to use geoceivers?

MR. WILLIAMS:

Yes.

MR. LIEBERMAN:

Is the new system GPS?

MR. WILLIAMS:

That is another name, yes. It is very hard to keep up with the bureaucratic name changes, I must admit.

DR. KLEPCZYNSKI:

I believe "GPS" stands for "Global Positioning System."

MR. WILLIAMS:

Right.

(Editor's Comment: Later during the week of the meeting, the System was renamed "NAV STAR".)

DR. KLEPCZYNSKI:

Are there any other questions?

(No response.)

DR. KLEPCZYNSKI:

Well, thank you very much. Maybe we can get a discussion going here for a few minutes with some audience participation.

Before the meeting started we were talking about writing requirements for PTTI system. This seems to be a very difficult thing to do. People require, or they say they need accurate time. Some people talk about accuracies of ten nanoseconds.

Apparently it becomes very hard to justify requirements in terms, which upper management finds easy to accept.

Now, I am wondering if anybody in the audience might be able to contribute some type of discussion as to some hard and proven techniques for justifying extreme accuracies in certain time systems?

Everybody knows all systems work better with more exact time, but it is difficult to formulate that in words which are easily understood, or can be proven. It sometimes gets to be a very difficult thing, and I don't know if anybody here has had experience with this.

Yes, Dr. Winkler.

DR. WINKLER:

Well, my experience is rather broad and general; there seems to be a subtheorem of the more general one that the more expensive a system is, the easier it would be approved. The subtheorem offered is: The fancier the clock, the better will be the system.

But I think, to be more on the serious side, in specifying requirements, and in justifying requirements, you have really two problems.

The first one is the acceptance of a common terminology; how do you specify a frequency, how do you specify time. or frequency and phase variations. In most specifications which you see there is a tremendous confusion. People like to talk in parts to the 10 to the something, when in fact they mean phase noise, and vice versa. We will later on have occasion to refer to some papers, some fundamental literature which exists regarding terminology, most notably, the IEEE Subcommittee work on Frequency Stability and its publication on characterization of frequency stability by Barns et al. I think this paper is one which may lead the way to a uniform specification of frequency stability.

Uniform specification language in time should be simpler. You simply state what your phase noise expressed in time is going to be.

But turning now to the second part of my concern, the credibility aspect, and to the justification which would be given in a language easily understood by the many levels of review and approval, I think you have again basically two aspects. One nanosecond propagation time of light corresponds to one foot; it is an extremely short interval of time. I will caution systems designers and systems proponents, to be very, very careful not to overstate the actual requirements, because it will be very expensive to implement timing systems with nanosecond time requirements.

In the discussion of a system, anyone, who talks about nanoseconds and so on, should better first study the various disturbances in the atmosphere, the various disturbances in signal propagation, through the electronic systems, etc., before specifications of requirements for clocks are firmed up.

Once you follow that common engineering syndrome of overspecifying, and of doing things more complicated than may actually be necessary, then you have already embarked on a path which leads to disaster, and you will end up with the typical problems of production, maintenance and cost. I remind you what an elephant is; an elephant is a "military specification" designed mouse.

(Laughter.)

And one should not use cesium clocks or hydrogen masers in a backpack unless absolutely required (if one can't get a time signal in time!).

(Applause.)

DR. KLEPCZYNSKI:

Do you have a comment over here?

MR. LIEBERMAN:

I think to turn the question around, rather than requirements, as Captain Fowler pointed out, perhaps we should look at what is available in precise time on existing systems, and try to make maximum use of what is available at comparatively reasonable costs.

We now have 1 microsecond around the world at the SATCOM stations. VLF, it was pointed out, could be used down to 10 microseconds and approximately 1 microsecond is available on some Loran C systems.

Try to build systems based upon this availability.

DR. KLEPCZYNSKI:

Very good. These are very interesting comments.

Are there any more?

TIME AND FREQUENCY REQUIREMENTS FOR RADIO INTERFEROMETRIC EARTH PHYSICS

J. B. Thomas
H. F. Fliegel
Jet Propulsion Laboratory

ABSTRACT

Two systems of VLBI (Very Long Baseline Interferometry) at J. P. L. are now applicable to earth physics: an intercontinental baseline system using antennas of the NASA Deep Space Network (DSN), now observing at one-month intervals to determine UTI for spacecraft navigation; and a shorter baseline system called ARIES (Astronomical Radio Interferometric Earth Surveying), to be used to measure crustal movement in California for earthquake hazards estimation. The DSN system is now regularly observing between Goldstone, California and Madrid, Spain, determining the Earth's integrated spin rate from fringe frequency measurements. This system will soon be improved by adding the capability to measure time delay and by extending the system to other stations of the DSN, making possible the determination of polar motion and of all three coordinates of the various intercontinental baselines. On the basis of experience with the existing DSN system, a careful study has been made to estimate the time and frequency requirements of both the improved intercontinental system and of ARIES. In this paper, such requirements for the two systems are compared and contrasted. The eventual requirements for the intercontinental system are a frequency stability of $\Delta f/f = 10^{-14}$ over an observing period of 24 hours, and a clock synchronization of 25 microseconds. The requirements on ARIES are less stringent in frequency, for reasons to be discussed in this paper. Over the shorter ARIES baselines, one must have a frequency stability of $\Delta f/f \; 3 \cdot 10^{-14}$ over 3 hours, and a clock synchronization of 25 microseconds to attain accuracy in each baseline coordinate of 3 cm, using an optimal observing strategy and bandwidth synthesis technique.

INTRODUCTION

A new system of Very Long Baseline Interferometry (VLBI) is being developed at the Jet Propulsion Laboratory (JPL) for earthquake hazards estimation. This system, called ARIES (Astronomical Radio Interferometric Earth Surveying), will be used to monitor crustal motion and regional uplift in such earthquake-prone areas a sourthern California and perhaps northern Mexico. The time and frequency requirements for ARIES are determined by two sets of parameters. First, one must specify the accuracy with which the crustal movement must be measured to give useful information concerning the earthquake mechanism, and then one must determine how many observations must be taken with what precision and over how long a period of time in order to attain such accuracy. This paper outlines the logic by which time and frequency requirements are calculated for the system, and presents the results.

An earthquake occurs when the accumulated stress build up in the solid crust of the earth, believed to be caused by underlying convective currents in the mantle, exceeds the elastic limit of the crust and is relieved by a sudden fracture. If two crustal blocks were to slide smoothly past one another, then they would yield freely to the force which moved them, so that no stress would accumulate and no earthquakes need occur. But such large blocks as we speak of here are far from rigid; rock considered on a scale of hundreds of kilometers is elastic and compressible. It is possible for such blocks to be sliding freely at one point of their contact and sticking elsewhere, while stress builds up in a complicated three dimensional pattern characteristic of any deformable solid. Then to measure the accumulated stress at any point, and so to estimate the likelihood and magnitude of future earthquakes, it is not sufficient to measure the relative motion of a few points only, or even the relative motion along the entire line of the fault, but measurements must be taken over whole areas tens of kilometers to either side of the line of contact, and integrated in a model of crustal stress and strain. To secure such measurements, a system must be devised which enables portable devices to be moved from benchmark to benchmark over wide expanses of mountain and desert. Compare Figure 1, which illustrates how two blocks may be expected to deform according to the elastic rebound model of the earthquake mechanism.

The reality of southern California geology is even more complicated than the simple theory outlined above would indicate. Consider Figure 2, which shows the major faults, or lines of fracture, in this region. The most important single fracture is the San Andreas Fault, which runs southeast-northwest from the Gulf of California to Point Arena about 160 kilometers north of San Francisco. The motion along the San Andreas Fault, in its immediate vicinity, ranges from 0 to 3 centimeters per year. Broadly speaking, this fault is the boundary between two interacting plates, or rigid sheets of rock into which the uppermost layer of the earth, the lithosphere, seems to be divided, plates which are sliding past one another along this line of fracture. However, the plate motion has torn the crust, not along one fault only, but along a whole system of parallel faults which divide southern California into numerous small blocks which are presumably all moving with respect to one another, at least as seen on a geological time scale (see Fig. 3). Furthermore, another system of faults exists in this region which runs almost due east-west, examplified by the Garlock Fault north of Goldstone, California, which is very difficult to account for theoretically.

A very important symptom of an impending earthquake may be provided by the phenomenon of dilatancy. When the rock in a tectonically active region is

RELATIVE PLATE MOTION

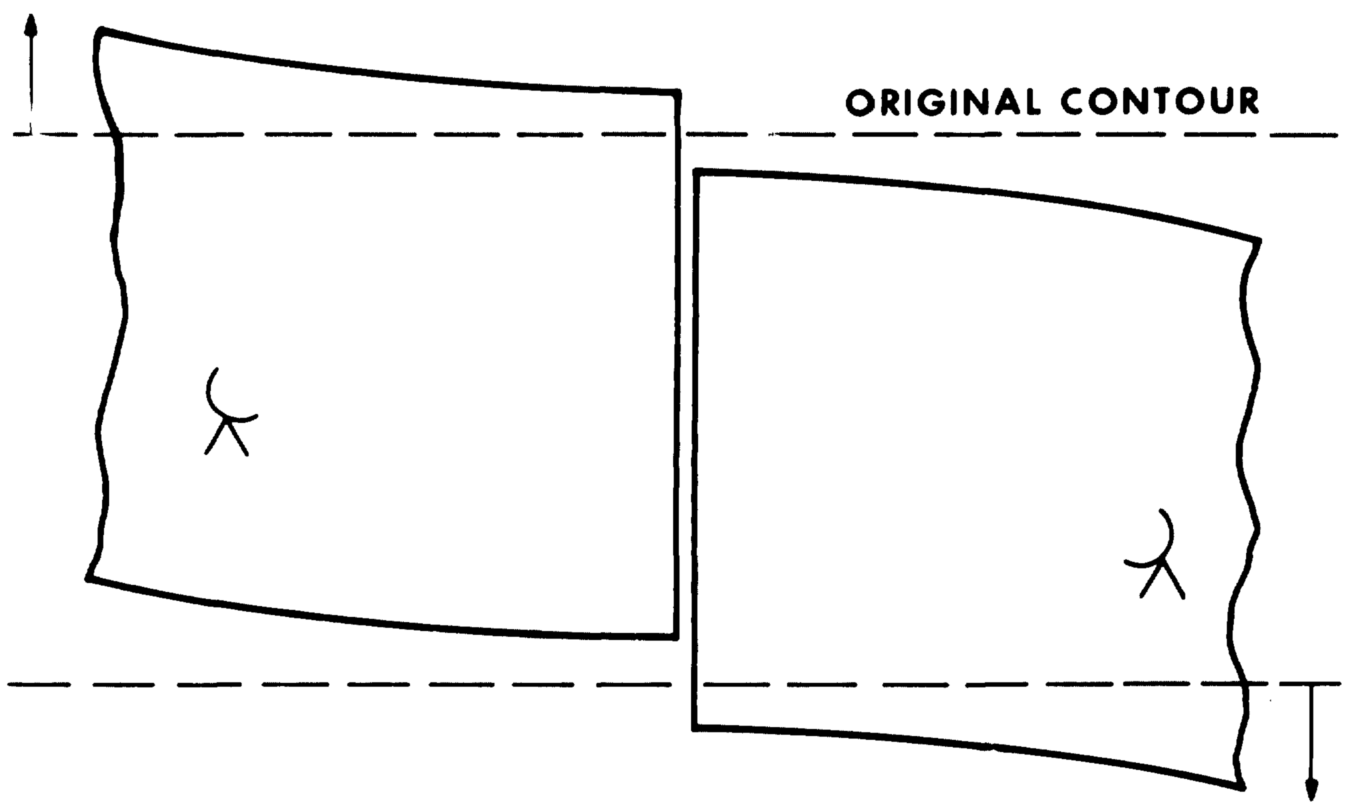

Figure 1. Schematic Diagram of Two Sideslipping Tectonic Plates Showing Deformation Due to Pressure and Fusion of Rock at the Boundary

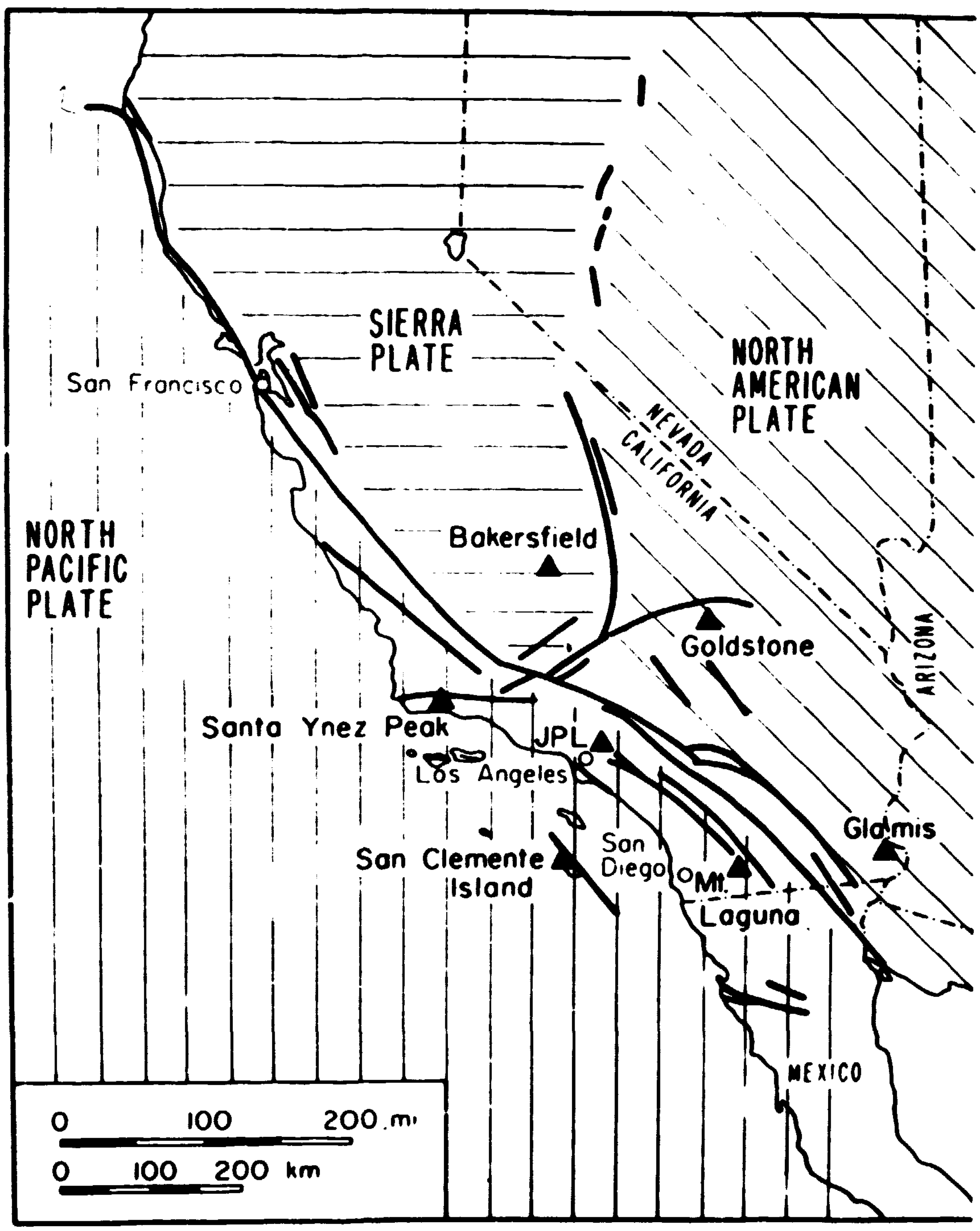

Figure 2. Simplified Fault Map of Southern California (Courtesy of Don L. Anderson, Seismological Laboratory, California Institute of Technology)

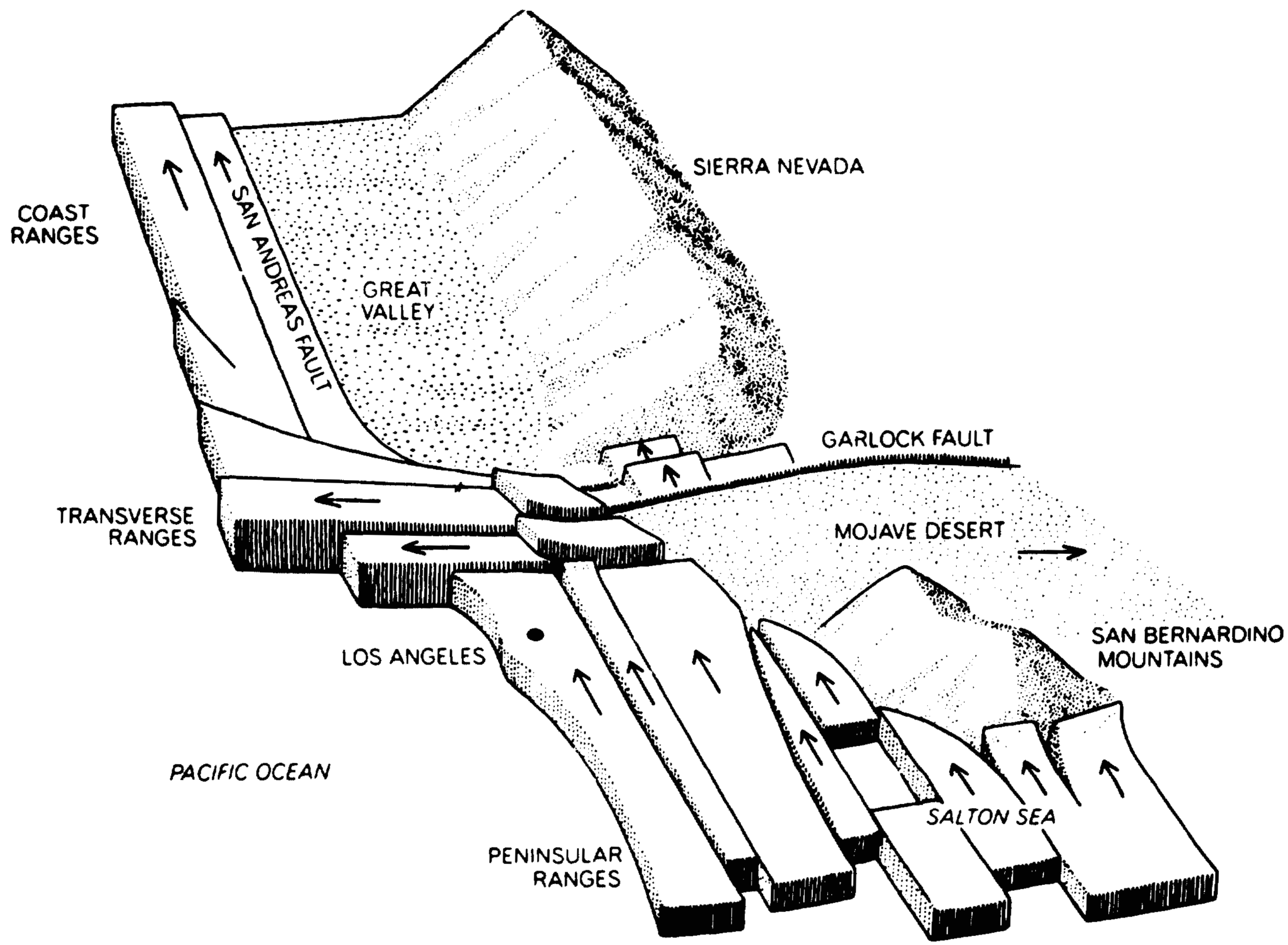

Figure 3. Schematic Diagram of Crustal Movements in Southern California (Courtesy of Don Anderson)

subjected to a sufficient shearing stress, it develops a fine pattern of cracks, which ultimately fill with groundwater. This microscopic cracking of the rock has two effects: the velocity of pressure waves (P-waves) thru the rock decreases; and the rock increases in volume, which may be expected to induce a small regional uplift in the months or years prior to the earthquake which ruptures the rock completely and thus relieves the strain.

These geological phenomena determine the capability which a geodetic technique should have in order to be useful for earthquake hazards estimation. It should be capable of locating points of reference in 3 dimensions, so that regional uplift as well as horizontal movement will be detected, to an accuracy of 3 centimeters or better, in a coordinate system which permits results to be reproduced or changes measured over several decades. The VLBI technique is capable of measuring baseline vectors in 3 dimensions and with respect to an extragalactic frame of reference. It seems likely that the necessary accuracy can be attained. We confine ourselves here to the question: what are the time and frequency requirements to attain 3 centimeter accuracy?

The basic principles of VLBI geodesy are illustrated in Figure 4. The basic observable is the delay between the times of arrival of an electromagnetic wave at two antennas. If $\vec{s}_i$ is the unit vector from the i th celestial source to either antenna, and if $\vec{B}$ is the vector baseline from one antenna to the other, and c is the speed of light in vacuo, then the time delay τ_i for the i th observation is given by the equation

$$\tau_i = \frac{\vec{B} \cdot \vec{s}_i}{c}, \qquad (1)$$

which can be rewritten in the form

$$c\tau_i = x_i X + y_i Y + z_i Z. \qquad (2)$$

where (X, Y, Z) are the baseline coordinates, and (x_i, y_i, z_i) are the coordinates of the i th source. If the baseline coordinates (X, Y, Z) are not to be functions of time, then one must express Equation 2 and the source coordinates (x_i, y_i, z_i) in a frame of reference rotating with the earth, allowing for the effects of the variation in the rotation of the earth and of polar motion. JPL now operates an intercontinental interferometer between Goldstone, California, and Madrid, Spain, which determines changes in UT1 at intervals of approximately one month. At present, the Goldstone-Madrid interferometer is able to measure only the rate of change of time delay, which is proportional to a quantity called fringe frequency, but the system will soon be improved by adding the capability to measure time delay and by extending the system to other stations of the NASA Deep Space Network, making possible the determination of polar motion and of

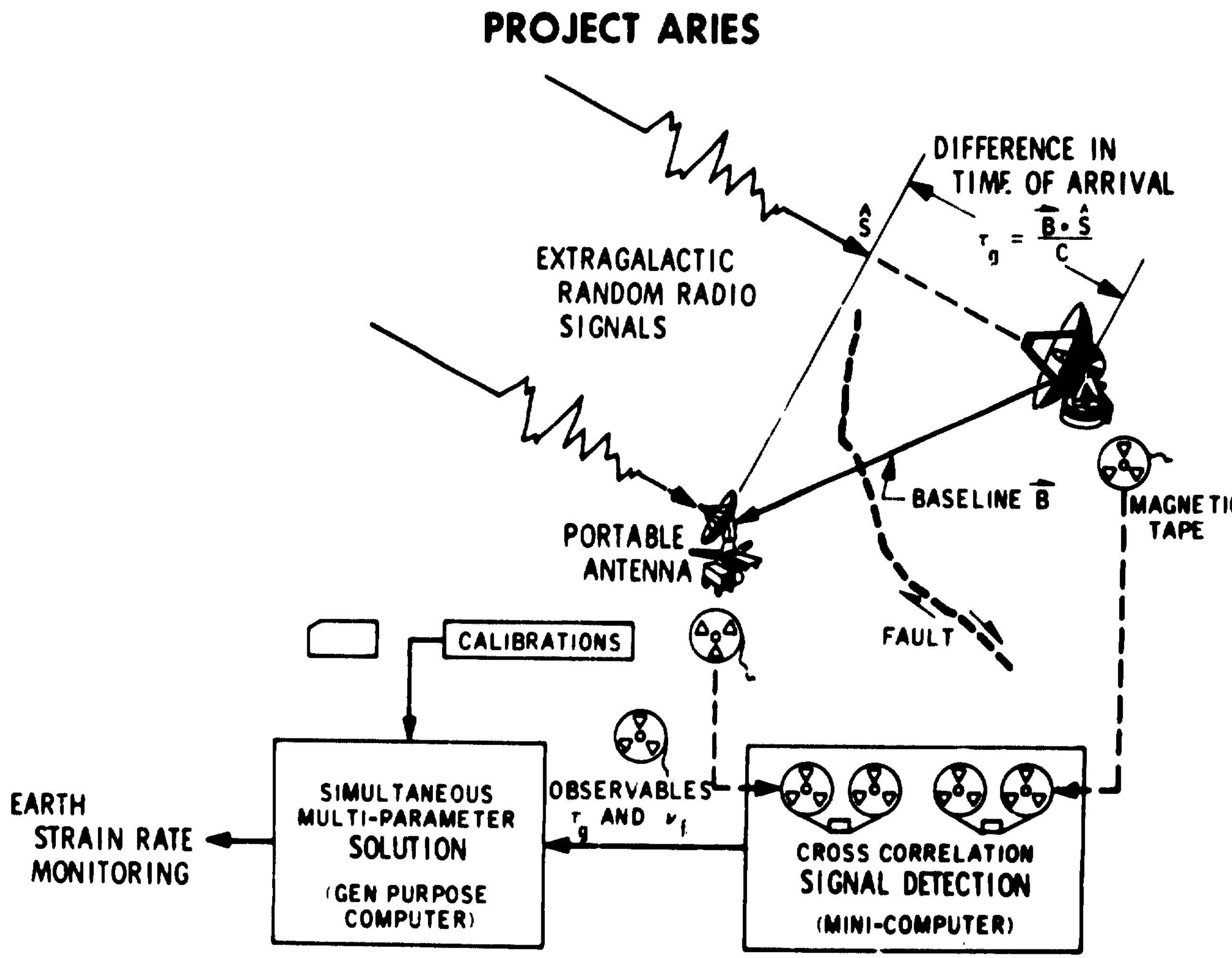

Figure 4. Sketch and Flow Diagram of a Working VLBI System for Earth Physics Using a Portable Antenna

all three coordinates of the various intercontinental baselines. It is planned to use the intercontinental interferometer at times not far removed from the dates of ARIES observations to determine UT1 and polar motion with high precision (~ 20 cm), and to determine a highly accurate catalog of celestial sources, so that the ARIES system, which will operate on relatively short baselines with a portable antenna, can input this information as known quantities. Thus, so far as the geometry is concerned, it will be possible to write Equation 2 above with only three unknowns, namely, ARIES baseline coordinates.

Apart from the geometry, it is possible and necessary to solve for two other parameters. In general, the two clocks at the two ARIES antennas will not be perfectly synchronized, and they will not have exactly the same rate. One may include the effects of clock offset and frequency offset by rewriting Equation 2 with two additional unknowns:

$$c\tau_i = x_i X + y_i Y + z_i Z + c \cdot \Delta T + cT \cdot (\Delta f/f). \qquad (3)$$

where ΔT and $(\Delta f/f)$ are the unknown clock offset and difference in clock rates, respectively, and T is time on a reference clock. Equation 3 is solvable with a minimum of five observations widely separated in azimuth. Notice that, in principle, VLBI can be used not only for geodesy but for clock synchronization in widely separated locations.

The basic mathematics, then, sets no requirement for clock synchronization, since one solves for clock offset. However, there *is* a practical requirement. As illustrated in Figure 4, the noise signal received from a celestial source is recorded at each antenna on magnetic tape, and the tapes are cross-correlated by matching the streams of binary digits, called bit streams, on the tapes. (The signal is received at whatever frequency the receivers are tuned, heterodyned to generate a sine-wave signal of frequency low enough to be recorded on video tape, and then re-heterodyned by a technique called "fringe stopping" to allow approximately for the difference in Doppler effect between the two antenna locations due to the rotation of the earth. The two resulting bit streams are then multiplied together.) It is necessary that the time-tags on the two tapes be reasonably accurate if excessive time is not to be wasted searching tapes in the cross-correlation process. Experience with the Goldstone-Madrid interferometer and the Mark II recorder of the National Radio Astronomy Observatory suggests an *a priori* requirement of 25 microseconds on clock synchronization. Once the cross-correlation is made, it is possible to deduce the clock offset with a precision of about 25 nanoseconds using an instantaneous recorded bandwidth of 2 megahertz on a single channel, or better using a technique called bandwidth synthesis.

Although one solves for frequency offset, Equation 3 presumes that the offset is a constant over the observing period. Since it is desired that Equation 3 be over-determined and well-conditioned, it requires about 3 hours = 10^4 seconds to observe a sufficient number of sources—say, 12 sources with about 10 minutes integration time on each, plus antenna moving time. A worst-case requirement for the frequency standards can be set by supposing that one neglects to include the term $cT \cdot (\Delta f/f)$ in Equation 3, and that the whole term is taken up in a single baseline parameter—say X. In that case, in order not to exceed 3 cm baseline errors, one would have

$$(\Delta f/f) = x/cT = 3\,\mathrm{cm}/(3 \cdot 10^{10}\,\mathrm{cm/sec}) \cdot 10^4\,\mathrm{sec} = 10^{-14}$$

Numerical simulations in which the effect of a constant frequency offset is included in the equations and in which sources are observed well distributed around the sky suggest that frequency variations of from $3 \cdot 10^{-14}$ to $8 \cdot 10^{-14}$ can be tolerated without exceeding a standard deviation of 3 cm in any baseline coordinate or in baseline length. We have adopted a value of $(\Delta f/f) = 3 \cdot 10^{-14}$ as a reasonable requirement for the ARIES system.

The requirement for the intercontinental interferometer is approximately $(\Delta f/f) = 10^{-14}$, and is more stringent than for ARIES chiefly because a longer observing period is needed for a good solution, about 10 hours.

An attempt to compare the simple theory outlined above with experimental data illustrates both general similarities and striking differences. Two interferometry experiments were conducted on two separate days over a short (16 km) baseline, using a 24 kHz instantaneous recorded bandwidth, between the Mars (64 meter) and Echo (26 meter) antennas at the Goldstone DSN complex, as part of a series of tests of the ARIES technique. On the first day (18 October 1972), both stations were equipped with hydrogen masers; on the second (21 November 1972), one of the hydrogen masers was replaced by a rubidium oscillator. Each experiment consisted of 7 hours of observation, over which a single solution was made for ΔT and for $\Delta f/f$ via Equation 3. Residuals were formed of the observed fringe frequencies and time delays minus those calculated from the solution, and are displayed in Figures 5 and 6. The fringe frequency jitter for the rubidium-equipped station is about 0.5 millihertz, corresponding to $\Delta f/f \doteq 2 \cdot 10^{-13}$, since all observations were at S-band (~ 2.3 gigahertz). This figure equals or exceeds the expected performance of the rubidium oscillator. On the other hand, the jitter for the hydrogen maser equipped station is 0.12 millihertz, corresponding to $\Delta f/f = 5 \cdot 10^{-14}$, which fails to meet the expected short-term stability of the hydrogen maser by about a factor of 5. However, in this case, the observed fringe frequency reflects other sources of error, not only oscillator instability; and we suggest that the dominant error source is produced by the ionosphere. Also, in the case of the time delay residuals, the dominant error

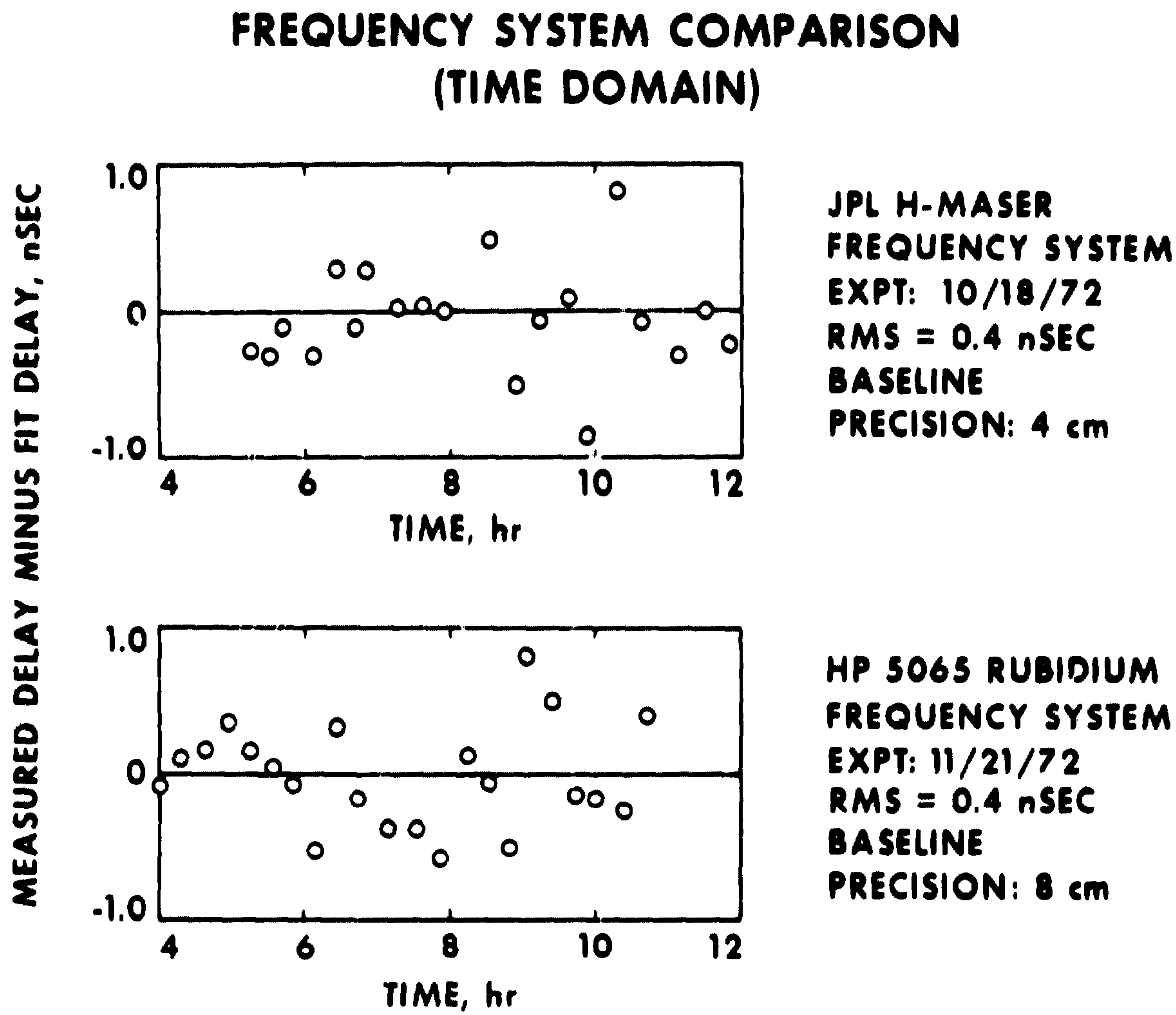

Figure 5. Residuals in Time for Two Experiments, One Using Hydrogen Masers, and the Other, a Rubidium Oscillator

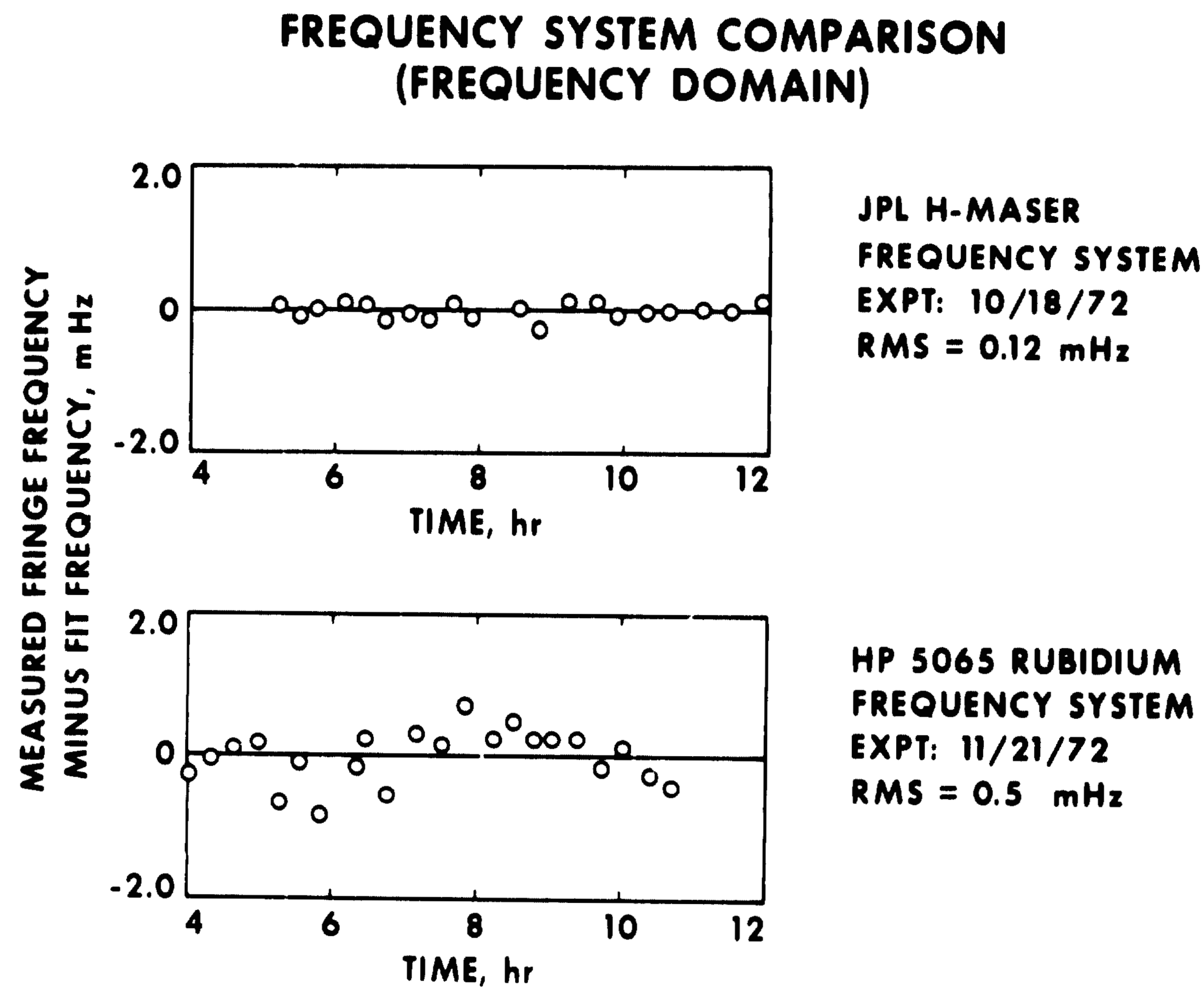

Figure 6. Residuals in Frequency (Same Experiments as Figure 5)

source was not the frequency standard, but rather the system noise (Fig. 5). Although the stability of the hydrogen maser exceeds that of the rubidium by about a factor of 20, accuracy of the solution for baseline coordinates increases only by a factor of 2, from 8 centimeters to 4 centimeters in baseline length, and the scatter of the delay residuals hardly improves at all. Nevertheless, the accuracy of the H-maser equipped stations is close to that required for geophysical purposes. Future improvements to ARIES will include local calibrations for water vapor in the troposphere and for charged particle content in the ionosphere, and use of a wider recording bandwidth.

ARIES has two advantages which the intercontinental system does not enjoy:

1. Since UT1, polar motion, and source locations will be input into ARIES as data, the list of parameters to be solved for is shorter, and the number of necessary observations smaller.

2. Since ARIES will operate on fairly short baselines, a much larger area of the celestial sphere will be mutually visible to both antennas, and a source list may be chosen much better distributed over the celestial sphere to optimize the solution for the unknowns.

SUMMARY

A simple theory of the time and frequency requirements for VLBI geodesy suggests that, with current equipment, a frequency stability of $3 \cdot 10^{-14}$ and synchronization requirement of 25 microseconds will permit the determination of baseline coordinates to about 3 centimeter precision with 3 hours observing. Once a solution is obtained, the VLBI technique itself would permit clock offsets to be calculated with an accuracy of 25 nanoseconds at widely separated sites, or potentially to about 1 nanosecond using a bandwidth synthesis technique. Actual demonstrations showed that a baseline accuracy of 4 centimeters was attained with a prototype system over a 16 km baseline utilizing H-maser frequency standards.

QUESTION AND ANSWER PERIOD

DR. KLEPCZYNSKI:

Are there any questions or comments? Yes Dr. Johnston from NRL.

DR. JOHNSTON:

I would like to make a comment on the new H. P. cesium standard.

In cooperation with the Naval Observatory, on a recent very long baseline experiment, we attempted to use two cesium standards, one at each station. We did have some small problems with time synchronization, but we failed to get fringes with the cesium standards, which could possibly indicate short term stability on the order of one second, maybe as low as a part in tenth to the tenth, which is very poor.

If anyone has any further comments on that, I would like to hear them.

DR. KLEPCZYNSKI:

Yes.

I have a separate question.

DR. KLEPCZYNSKI:

Before we go to this question, are there any comments on the last one? Yes.

DR. TOM CLARK:

We have used one of the H. P. Cesium standards at Goldstone in an experiment, oh, several months ago, when the hydrogen maser at Goldstone was not in the best of health, and although we had fringes at 7.8 and 15 gigahertz, the phase stability is probably worse on short terms, 10 seconds or so, than even a rubidium standard. Is there a possibility that some internal loop time constants can be changed in the cesium standards to assist us?

I know that Clark Wardrip here at Goddard has run considerable tests on the stability of the cesium. Perhaps you would want to talk to him about that, too.

DR. KLEPCZYNSKI:

Is there a comment over here?

DR. HELWIG:

At the National Bureau of Standards, we have some results with a Hewlett-Packard Super Tube and I think it performs according to specs, and that is all I can say. I think a part in 10 to the 11th is at least an order of magnitude for a one second averaging time.

So this would be my comment, if you use the Super Tube just as a black box, and you assume that specs of H. P. are correct, I think you are in good shape. If you expect more than the specs say, you may not get it.

DR. KLEPCZYNSKI:

A comment from Dr. Winkler.

DR. WINKLER:

We will hear much more about it by Mr. Percival, who will report tomorrow on experiments which we have done in the observatory with 11 units.

There is one point in regard to Dr. Helwig's comment with which I completely agree. It is that I think one has to remember that the characteristics of the sigma, tau plot of the cesium standards are vastly different from that of a hydrogen maser, and of that of a rubidium standard.

These are three different kinds of animals. The cesium standard, in general, will follow a one over square root of tau performance, beginning from the time constant of the servo loop, which is in the order of a second to a minute or slightly shorter than a minute down to, and that is a point of some contention, to the flicker level.

It is here where the standards, according to our experience, seem to be better than the specifications. It is how far they will go down to long integration periods which determines their main quality for time keeping.

In the short time range, if you want to compare them with a rubidium standard for periods of 100 seconds or so, they will be slightly inferior, but again I completely agree with Dr. Helwig, there seems to be something wrong with that one standard referred to before which, incidentally, had completely stopped on its way from the observatory, and which has not performed according to what it should be.

But more about it tomorrow.

DR. KLEPCZYNSKI:

Dr. Helwig again.

DR. HELWIG:

As an example, we have reliable data on a comparison of one rubidium standard against our primary standard, we get 8 parts in 10 to the 12th one second, and it averages down as the square of tau, reaching a flicker level of about 2 parts in 10 to the 14th.

DR. KLEPCZYNSKI:

There was another comment over here? Yes.

When you ask a question, please identify yourself by name and place, so that people will get to be familiar with everybody in the audience.

DR. REINHARDT:

Dr. Reinhardt, from Harvard.

If you were to use an artificial signal source, let's say on a satellite, what performance could you get using hydrogen masers, and do you need that kind of performance? Would you benefit from that kind of performance?

DR. FLIEGEL:

I imagine that we could. We have no experience using artificial sources for the AIRES project, of course. We had to use natural sources, for obvious reasons, because we want our observations finally to be reduced to an inertial system, which the extra galactic framework provides us, or some kind of a fixed body reference.

I am certainly not ruling out the idea of using artificial sources, but we haven't used them up to now.

DR. REINHARDT:

What kind of performance did you get, signal to noise?

DR. FLIEGEL:

Incredibly good, but I couldn't put the number up.

DR. REINHARDT:

Could you use that kind of accuracy?

DR. FLIEGEL:

I may have misled you on one respect. We are not really limited by the signal to noise ratio of the faint sources, because there are enough brighter sources to use to really control the solution.

So, yes, I imagine the solution would be somewhat better, but not an order of magnitude better, and we are not primarily limited by the sources. It only appeared so because of the way that slide was displayed.

QUESTION:

I was just going to suggest that you look into using artificial sources, because these sources are all time variable, since they are very small extragalactic sources and they have only been studied for the last -- well, they weren't known 15 years ago, and the characteristics of these sources are still under study, so that perhaps using artificial satellites you would have a very good signal to noise which may improve your solution somewhat.

DR. FLIEGEL:

Yes, that is a good point. We are sticking with the quasars and the Seyfert galaxies primarily because we hope that we will not have the same problems as people who work, for example, with water vapor sources.

We hope, for example, that the proper motion will turn out to be zero, but we will have to keep an eye on it.

QUESTION:

Can I just comment about the use of artificial satellites. We have used them and got results from them, but I think in connection with the particular project you are talking about that you do have to be concerned with the satellite orbit itself, as well as the librational motion of the satellite. This introduces many new parameters into the solution, and just from the point of view of the post processing analysis, as we call it, the analytical framework is going to be very much more complicated.

The fact, for instance, that the satellite is at a finite distance from the stations, and you don't have the vectors from each station parallel to each other, specifically to the accuracy that you are talking about, is also going to have to be taken into account. It is a rather messy analytical problem.

DR. FLIEGEL:

I quite thoroughly agree. We would only use artificial sources as a last resort for that very reason, and they would have to be distant space probes, interplanetary probes, I think rather than earth satellites. But we can talk about this.

DR. KLEPCZYNSKI:

I am going to stop the discussion on this so we can move on to our next paper, but before I do that I want to thank Dr. Fliegel for a very interesting presentation.

N75 11278

TIME, GEODESY, AND ASTROMETRY: RESULTS FROM RADIO INTERFEROMETRY

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ABSTRACT

The results from a total of a dozen transcontinental and intercontinental VLBI experiments will be discussed. Particular emphasis will be placed on: (1) the inferred behavior of the frequency standards, usually hydrogen masers, on time scales from 10 to 10^5 seconds; (2) the estimated celestial positions of the observed radio sources; (3) the determinations of the vector baselines; and (4) the inferred values of polar motion and UT.1.

INTRODUCTION

By now VLBI is all but a household word. Although lofty promises held out of centimeter accuracy geodesy and millisecond-of-arc accuracy astrometry have not yet been fulfilled, we have made much progress in the last two years. We present here the most recent results obtained by our group. To be precise, our group is a shifting amalgam of people and organizations who join together to do a particular experiment; to list all the individuals and their affiliations would nearly take up all the allotted space. Suffice it to say that, together with our colleagues at MIT and at the Haystack Observatory,* we have played the major role in organization, equipment development, and data processing with invaluable contributions by representatives from the University of Maryland, the National Oceanic and Atmospheric Administration (NOAA), the Jet Propulsion Laboratory (JPL), and the Onsala Space Observatory in Sweden.

EXPERIMENTS

Our results come from a number of experiments, all conducted at a radio frequency of about 8 GHz:

1. Goldstone (210') - Haystack (120')
   - April 1972-March 1973; nine separate ($\lesssim$1 day) experiments

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*C. C. Counselman, H. F. Hinteregger, S. M. Kent, C. A. Knight, D. S. Robertson, A. E. E. Rogers, and A. R. Whitney.

2. Goldstone - Haystack - NOAA (85', Alaska)
   - May-June 1972; two separate (0.5-1 day) experiments

3. Haystack - Onsala (84', Sweden)
   - April-May 1973; two separate ($\lesssim$2 day) experiments

4. Haystack - Westford (60') - NRAO (two 85', West Virginia)
   - January-October 1972; two ($\lesssim$2 week) experiments.

The types of results include vector baselines, clock epoch and rate synchronizations, polar motion, UT.1 variations, and astrometric positions of radio sources. We omit for brevity the results we have obtained—using exactly the same body of data—on the structure and variability of extragalactic radio sources. We also omit the results from Goddard's extensive VLBI program at meter wavelengths, and mention only briefly our tests of the theory of general relativity.

The capability for the determination of all three components of each baseline vector, as well as for the accurate determination of the declination of sources near the equator, is dependent on our group's development and use of a wideband synthesis technique that allows us to measure unambiguously the actual difference in arrival times at the sites of the signal from the extraterrestrial source being observed. As we shall see, our uncertainty in these measurements is at the sub-nanosecond level on each individual determination.

BASELINE RESULTS

In Table 1, we show the baseline results from all nine of the separate Goldstone-Haystack experiments. Note that the baseline-length determinations are consistent to within about 25 cm. The two baseline-orientation parameters show consistency only to within one to two meters.

In Figure 1, we show a "sample" of the post-fit residuals for observation of two sources from the August 1972 experiment. For reasons that we do not yet fully understand, this experiment yielded post-fit residuals with the smallest systematic trends.

In these baseline determinations—each was carried out separately and involved only the delay and delay-rate data taken during the course of that individual experiment—we solved for the following parameters: the zenith electrical path length of the atmosphere at each site; the clock epoch and rate offsets; the three components of the baseline; and all of the coordinates for the 7 to 11 sources

Table 1

Preliminary Coordinates from Nine Experiments to Determine the Goldstone-Haystack Baseline*

Date	Length (m)	Hour Angle† (hr x 10^6)	Declination† (deg x 10^5)
April 14-15, 1972	3,899,998.51 ±0.22	7,051,413.6 ±0.3	-914,473.4 ±1.8
May 9-10, 1972**	7.61 ±0.76	4.6 ±2.8	87.1 ±5.2
May 29-30, 1972	8.64 ±0.33	5.4 ±0.8	83.0 ±1.4
June 3-6, 1972	8.60 ±0.45	3.7 ±1.1	82.8 ±2.2
June 27-28, 1972	8.56 ±0.28	2.1 ±0.7	77.8 ±1.4
August 29-30, 1972	8.77 ±0.09	5.9 ±0.3	81.6 ±0.6
November 7, 1972	8.99 ±0.15	5.5 ±0.4	82.1 ±1.1
February 4-5, 1973	8.83 ±0.10	3.7 ±0.4	81.6 ±0.4
March 30-31, 1973	8.99 ±0.11	6.1 ±0.3	84.7 ±0.5
Weighted Average ± weighted rms spread of solutions about the weighted mean	3,899,998.75 ±0.23	7,051,414.8 ±1.3	-914,481.8 ±2.8

*The reference point at both Haystack and Goldstone is the intersection of the azimuth and elevation axes of the antenna. The baseline vector points from Haystack to Goldstone. The hour angle is measured from the Haystack meridian, defined by the International Latitude Service mean pole of 1900-05; the declination is measured from the plane that passes through Haystack and is parallel to the equator defined by this mean pole. The uncertainties shown are the formal standard errors, based on a value of unity for the weighted rms of the post-fit residuals. The coordinates describing the baseline direction are clearly being affected by systematic errors (see text).

**In this experiment, for another purpose, half of the time was utilized for special observations of two source pairs, thus accounting for the relatively large errors.

†Note that 10^{-6} hr $\simeq 1.0$ m and 10^{-5} deg $\simeq 0.68$ m for this baseline.

observed in a given experiment, save the right ascension of 3C273 which was set in accord with the results of Hazard et al. (Nature Physical Science, 233, 89, 1971) from lunar occultation data and optical photographs. Since the VLBI observations of extragalactic radio sources are extremely insensitive to the earth's orbital motion, we must choose an arbitrary origin for right ascension. The choice of the value of Hazard et al. for 3C273 should provide us with a good "tie" to the FK4 system, to which conventional astrometric results are referenced.

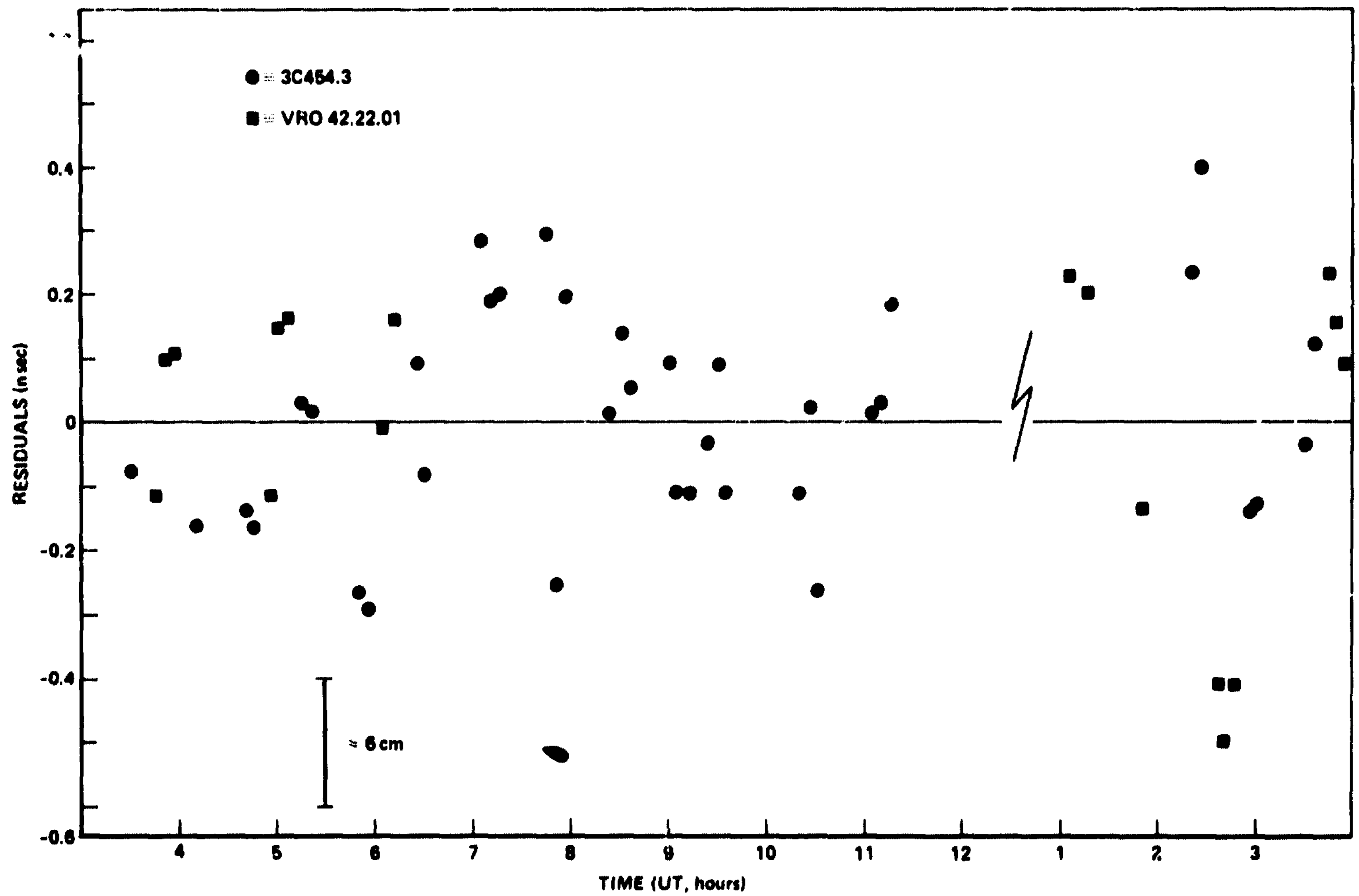

Figure 1. Postfit residuals from Observations of the Extragalactic Radio Sources VRO 42.22.01 and 3C454.3 during the Goldstone-Haystack VLBI Experiment of 29-30 August 1972

The results for the antennas in Alaska and Sweden are much poorer than the "Coldstack" results, primarily due to reduced sensitivity. Both of these sites use only ~85'-diameter telescopes which have surfaces designed for operation at frequencies much lower than 8 GHz and we have had to content ourselves with 10 to 20% antenna efficiencies. The receiver in Alaska was also poorer, with a system temperature of about 300°K instead of the 25-60°K we have on the other telescopes. Thus, we find that the baseline-length determinations here have uncertainties of about 2 m instead of the ~25 cm uncertainty for the Goldstack baseline.

One interesting fact is that the antenna in Alaska has an X-Y mount, with two horizontal non-intersecting axes. We modelled the offset between these axes and solved for it from the relevant VLBI data to provide a good independent check of our results. (This procedure is almost equivalent to moving the dish a known amount and seeing how well the offset can be determined.) Our result was 6.3 ±0.9 m for the distance between the axes, as compared with the true value—scaled from the original telescope plans—of 7.23 meters.

CLOCK SYNCHRONIZATION

In Table 2, we present the epoch and rate offsets determined for the Goldstack experiments. Here again, the errors are formal standard errors based on scaling the weighted rms of the post-fit residuals to unity. The rather large rate offsets are due to the fact that the hydrogen-maser standard at Goldstone was set "off-frequency" during most of 1972. The epoch errors reflect difficulties in a priori synchronization at Goldstone, where Loran-C is unavailable. Haystack and the other stations routinely synchronize clocks with Loran-C to within 1 to 3 μsec.

POLAR MOTION AND UT.1

The Goldstack data, being the most accurate, are best suited for estimates of polar motion and variations in UT.1. (Note, however, that a single baseline is sensitive to only one component of polar motion.) To estimate these quantities, we used the August 1972 experiment as a reference since it yielded data with the smallest systematic trends. We combined all the data—actually in two separate runs, each containing the August 1972 data and those from four other experiments—and estimated parameters corresponding to the polar motion and UT.1 differences between each of the experiments and the August 1972 experiment.

Table 2

Clock Synchronization for Goldstone-Haystack Experiments*

Date	Epoch Offset (μsec)	Rate Offset (psec/sec)
April 14-15, 1972	-5.009 ±0.002	10.88 ±0.03
May 9-10, 1972	-13.040 ±0.002	12.18 ±0.01
May 29-30, 1972	-3.008 ±0.002	13.20 ±0.01
June 6-7, 1972	-28.211 ±0.006	13.64 ±0.04
June 27, 1972	-7.717 ±0.003	13.04 ±0.03
August 29-30, 1972	-15.320 ±0.001	14.140 ±0.001
November 7, 1972	-2.088 ±0.001	-3.640 ±0.001
February 4-5, 1973	-6.813 ±0.003	-8.611 ±0.06
March 30-31, 1973	4.398 ±0.001	-1.070 ±0.001

*Results are given in sense of Goldstone value minus Haystack value and are referred to start time of first observation of experiment.

The results presented in Table 3 are still quite preliminary and undoubtedly are affected by systematic errors. From the comparison shown between the BIH and USNO values for these quantities and ours, we see that the polar-motion differences are nowhere worse than the equivalent of about 5 meters, and that the UT.1 estimates differ very systematically. But, at this point-in-time—to use an overused cliché—we would emphasize that our results may not be the most accurate, although we expect them to be in the not-too-distant future.

SOURCE POSITIONS AND ASTROMETRY

In each of these experiments we simultaneously estimated source coordinates. Our averaged results, with errors based on consistency between independent sets of data—and considered to be conservative—are shown in Table 4. We have compared our results with other determinations of high accuracy, including VLBI results obtained at JPL and short-baseline phase-stable interferometer results obtained in England and the U.S. We find quite reasonable agreement. The accuracy of radio techniques has now surpassed that available to our "optical" colleagues.

Table 3

Preliminary Polar Motion and UT.1 Variations from Goldstone-Haystack Experiments

Date	Universal Time (UT.1)*		X-Component of Polar Motion
	USNO-VLBI (msec)	BIH-VLBI (msec)	BIH-VLBI (m)
14-15 April 1972	10.7	1.1 ±0.8	2.2 ±0.3
9-10 May	7.7	-3.2 ±1.2	-1.6 ±0.6
29-30 May	3.6	-4.9 ±0.8	-1.2 ±0.3
6-7 June	5.5	-1.6 ±1.3	-2.0 ±0.5
27 June	-4.9	-10.1 ±4.8	-4.4 ±1.5
29-30 August	—	—	—
7 November	2.2	-1.5 ±0.8	0.3 ±0.2
4-5 February 1973	6.3	0.4 ±0.8	0.6 ±0.2
30-31 March	3.2	-6.4 ±0.6	1.8 ±0.2

*Note that for 29 August 1972, BIH-USNO = 11.4 msec.

We have also gathered a large amount of data, which is still being analyzed, from our so-called four-element interferometers. As mentioned in EXPERIMENTS Section, we have employed for these experiments the 120'-diameter Haystack and 60'-diameter Westford telescopes in Massachusetts and two of the 85'-diameter telescopes at the National Radio Astronomy Observatory in West Virginia. One antenna at each end observes source "A" while the other observes source "B". Since the antennas at each end are interconnected with a phase-stable-link—typically buried coaxial cable—we may regard them as having identical local oscillators. Although the local-oscillator phase between the two ends is not known, the difference in phase from the fringes for the two sources is independent of the local oscillator phase. Use of this difference permits, in principle, a very accurate determiuation of the difference in positions of the two sources. There is only one major problem: The atmospheric contribution to the phase is different for the two sources and hence does not cancel out unless the sources are quite close on the sky. Unfortunately, we can not yet present source-position results from these experiments.

We have also attempted an experiment of this four-antenna type to measure the gravitational deflection of the signals from the quasar 3C279 as it is occulted by the sun—this measurement has become our annual Oktoberfest. In this case we used as a second source the quasar 3C273 which is only 10° away on the sky. The

Table 4

Source Coordinates from VLBI Observations*

Source	Right Ascension, α (1950.0)			Declination, δ (1950.0)		
	hr	min	sec	deg	min	sec
3C84	03	16	29.539	41	19	51.75
3C120	04	30	31.586 ±0.005	05	14	59.2 ±0.1
OJ287	08	51	57.232 ±0.005	20	17	58.45 ±0.1
4C39.25	09	23	55.296 ±0.004	39	15	23.73 ±0.04
3C273B	12	26	33.246**	02	19	43.2 ±0.1
3C279	12	53	35.831 ±0.004	−05	31	08.0 ±0.1
OQ208	14	04	45.626	28	41	29.4
3C345	16	41	17.634 ±0.004	39	54	11.00 ±0.07
PKS2134+00	21	34	05.222 ±0.005	00	28	25.2
VRO42.22.01	22	00	39.394 ±0.007	42	02	08.3 ±0.1
CTA102	22	30	07.82	11	28	22.8
3C454.3	22	51	29.530 ±0.009	15	52	54.24 ±0.03

*Coordinate determinations for which no uncertainties are quoted were based on only a single set of observations or had formal errors greater than 0″.1; the errors in these coordinates are probably no more, and in some cases considerably less, than 0″.5.

**Reference right ascension (Hazard et al., 1971); see text.

data were taken in September and October 1972. Although it is now a year later, the data are still being analyzed. It should be noted that the magnitude of the bending predicted by general relativity is 1.75"/R, where R is the distance of closest approach of the ray path to the sun, measured in solar radii. Our data were obtained at R $\gtrsim$ 20, implying a maximum deflection of 0.1". In Figure 2, we show the difference in fringe phases, with diurnal variation removed, for one day's observations. Note that 2π in phase (equivalent to one "fringe") equals 0″.01. The major problem is to insure that the phase has no 2π "jumps" even where our highly-motivated, but lowly-paid, graduate-student tape hangers goofed and tapes were missed. The figure illustrates the ease with which we can bridge such gaps.

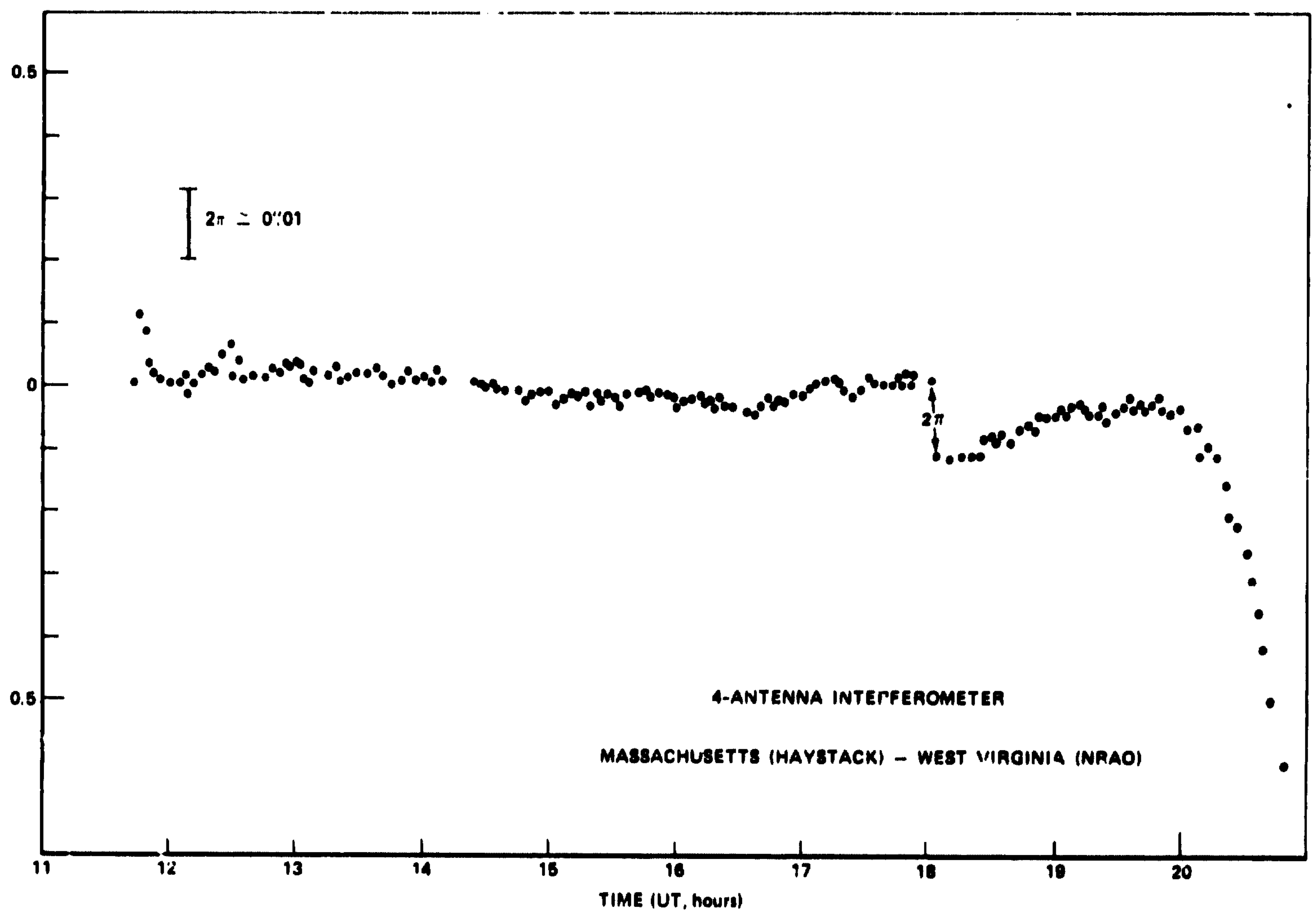

Figure 2. Fringe-Phase Differences: 3C279-3C273, 19 October 1972

THE FUTURE

We feel there are several obstacles to be overcome to achieve the significantly higher accuracy we require: instrumental calibration, which has been mostly lacking to date; calibration of the neutral atmosphere, which is currently modelled theoretically with a single parameter per day per site; and calibration of the ionosphere, less important at our 8 GHz frequency than at the $\simeq$2 GHz frequencies employed by others, but important for the achievement of centimeter-level accuracies.

At present we use only a simple solid-earth-tide model "grafted" onto the standard precession and nutation effects to represent the effects of the earth's deformation. Our next theoretical effort will involve development of a more accurate model for the earth's rotation, building, for example, on the work of McClure (GSFC Report, X-592-73-259, September 1973). We have also begun design studies on a system that will permit a 30-50 MHz bandwidth signal to be recorded instead of the currently available 360 kHz or 2 MHz. And we always seem to need more masers than are available in the world. In this connection, we wish to thank H. Peters, C. Wardrip and D. Kauffmann of GSFC, R. Sydnor of JPL, and R. Vessot of SAO for their continuing advancement of this field and for their frequent assistance in getting masers to obscure places around the world.

In conclusion, we feel pleased to have helped to bring VLBI to its current state of development and hope to continue this development and thereby to raise VLBI to its rightful place as the best measurement tool yet invented for clock synchronization, geodesy, and astrometry.

QUESTION AND ANSWER PERIOD

DR. CLARK:

Any questions?

DR. WINKLER:

Your comment about the clock synchronization on the West Coast prompts me to repeat something which we had announced last year, that there is now a Loran chain operational on the West Coast, with which one can make time synchronization experiments. I would like to encourage anyone who has requirements or interest to contact Mr. Lavanceau at the observatory.

DR. CLARK:

I appreciate your continued efforts in that area, too.

My comment was perhaps slightly wordy in that the Loran capability was not available at Goldstone during the time of those measurements.

Because of VLBI and delays in processing things, we always reported past history, in the past being typically two years back, and we speak of it as if it was now.

DR. BLACK:

Harold Black, APL.

I notice you solve for the zenith distance at each site. I would surmise that those are individually rather poorly determined, but that the differential zenith height is well determined. Is my surmise correct?

DR. CLARK:

Yes, the zenith thickness of the atmosphere amounts to a couple of meters of path length thickness. Well, it is no more than a couple of meters in thickness. When we are only doing geodesy in the couple of meter level, it is not that critical.

We do find that we are able to come up with fairly good bits for the neutral atmosphere. We wish we were able to calibrate it. We have some ideas in mind on how to calibrate it, but we just haven't gotten there yet.

Remember that these stations are quite widely separated, and typically just because of the fact that the Earth is curved and not flat, we are observing at rather different zenith distances. We are observing on the East Coast through the humidity and smog, and on the West Coast through their nice, dry climate.

There is absolutely no correlation between the atmosphere in California and the atmosphere in Massachusetts.

So, the differential atmosphere is really just as poorly determined as the individual site atmosphere.

QUESTION:

My comment is -- well, it is really a question. What do you feel is going to be the fundamental limitation on VLBI positions? It looks to me as though the atmosphere is finally going to close in on us, and stop us at about a part in 10 to the 15th or so. So is there a future need for better frequency standards in VLBI? The best standards today were used on the two antenna experiment, does one need that good a frequency standard?

DR. CLARK:

Well, there are a couple of types of experiments to do source positions, which could use far better frequency standards. Ones which would essentially remove the atmospheric bias very easily.

If you could merely count the total number of fringes during a day, even if you missed by a couple of fringes because the atmosphere today was different from the atmosphere of yesterday, merely counting the total number of fringes during the day would give us a very good position.

Now, that would require stability of a fraction of the fringe per day, which is down in parts to 10 to the 16th or 17th level, which is certainly past the state of our frequency standards.

As of right now, we are on the hairy edge between whether it is the frequency standards that are dominating our determination, or the atmosphere.

We need to calibrate the atmosphere better, and at that point we will be exploiting the frequency standards even more fully.

Parts in 10 to the 14th, or so, for the same reasons that were mentioned in the previous talk, are adequate for most of the determinations, but it is sure nice to have a part in 10 to the 15th, if you can get it.

MR. RYAN:

Jim Ryan, Goddard.

It sounds like you have solved for just about every parameter that could give you problems. I am wondering, typically, how many parameters are you solving for, and what feeling of confidence do you have that you have been able to eliminate the correlations?

DR. CLARK:

In all cases, it is less than the number of data points. That is my first look, and it is never any more than we absolutely have to have. It varies from experiment to experiment, depending on how many transient glitches occurred in clocks, how bad the atmosphere was, do we need to parameterize it on a sub day basis, things of that form.

A typical number is, oh, perhaps 30 or 40 parameters for 150 observations, something in that order, for a given day.

We do keep careful track of the correlations between these terms in our post processing program and this is one of the things that bothers us, and one of the reasons why we have been very conservative in some of our claims on error bars.

We do have the ability in our program to apply a priori covariance matrices to the data, so that we can essentially change the weighting in these different parameters, too. But we very seldom use that.

MR. MERRION:

My name is Art Merrion. I am from the Defense Mapping Agency.

I have a question -- perhaps I am asking the wrong person.

I can see when you finish your work, you are going to have a result, just the same as, say, for instance, Dr. Weber did at the University of Maryland. He had a result.

But after he finished and published and so forth, then they started experiments in other parts of the world.

Are you or anybody else performing a similar type experiment over the PLATE movement, similar to what you are doing between the Pacific and the North

American PLATE movement? Is there something like this going on right now somewhere else in the world?

DR. CLARK:

Well, we have the one which is going across the Atlantic right now, a continuing program using the telescope at Onsala, Sweden.

I believe, that later on, you will hear the other VLBI group at Goddard report on one of their proposed programs, which will involve just this type of measurement.

We are always on the lookout for new stations, and we, just philosophically and historically, are a very low budget group that have just joined together because we find the problem scientifically interesting.

As a result, we are particularly constrained to use those telescopes that already exist, that we can beg, borrow or steal observing time on. Hence these results use existing telescopes. We don't move telescopes around. We are striving for the best sensitivity, in order to give all of these programs simultaneously.

So, we have concentrated on a relatively small set of baselines to develop the techniques.

Really, I think what you should hear, the main summary point that I would like to make, what we are trying to do is to get the techniques developed so that VLBI can be turned into this operational tool at the centimeter level. And I feel that it can be in the future.

DR. KLEPCZYNSKI:

Thank you very much.

SESSION II

Chairman: A. R. Chi
Goddard Space Flight Center

N75 11279

APPLICATIONS OF RADIO INTERFEROMETRY TO NAVIGATION

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ABSTRACT

Radio astronomy experiments have demonstrated the feasibility of making precise position measurements using interferometry techniques. The application of this method to navigation and marine geodesy is discussed, and comparisons are made with existing navigation systems. The very long baseline technique, with a master station, can use either an artificial satellite or natural sources as position references; a high-speed data link is required. A completely ship-borne system is shown to be feasible, at the cost of poorer sensitivity for natural sources. A comparison of doppler, delay and phase-track modes of operating a very long baseline configuration is made, as that between instantaneous measurements and those where a source can be tracked from horizon to transit. Geometric limitations in latitude and longitude coverage are discussed. 'he characteristics of natural radio sources, their flux, distribution on the sky, and apparent size are shown to provide a limit on position measurement precision. The atmosphere and frequency standard used both contribute to position measurment uncertainty by affecting interferometric phase.

INTRODUCTION

The Navy, as well as civilian mariners, have been looking for the ideal navigation system for centuries. Recent developments in radio frequency navigation techniques, together with inertial navigation, have made navigation much more reliable, but a study of future possible techniques is still of considerable interest. One such technique is radio interferometry. The radio interferometer technique combines radio signals from two antennas spaced a distance apart to obtain the angular resolution of an antenna whose diameter equals this distance. In principle the radio interferometer is similar to the Michaelson interferometer used at optical wavelengths with both signals being combined coherently (with phase preserved) to produce an interference pattern. However, while the earth's atmosphere limits optical coherent interferometers to baselines of a few meters because of atmospheric phase degradation, this effect is much less serious at radio wavelengths, and baselines of thousands of kilometers have been used. Radio interferometers have determined positions of radio-emitting galaxies more precisely than can be done by optical means, and have measured the distance between fixed antennas with a precision of centimeters. The attractive characterictics of radio interferometry for a navigation system include, besides its high inherent precision, a possible savings on the cost and complexity of a satellite navigation system, and an all-weather capability.

The radio interferometer technique was developed several years ago by radio astronomers as a means to overcome the inherently poor angular resolution available from a radio-astronomy antenna. Figure 1 shows the basic principle of operation. A radio interferometer consists of two antennas spaced a distance apart, pointing at the same radio emission source, which may be either natural or artificial. The two incoming radio signals are amplified separately, and then brought toghether and correlated. The maximum correlation occurs when the signal from one antenna is delayed an amount equal to the excess travel time along a line from the radio source to the other antenna; the source must be smaller than the resolution of the interferometer. Thus, the interferometer measures, for a source at a distance much greater than the baseline, the dot product of the baseline and the source position vector. Early interferometers had the two antennas located close enough together so that the two signals, a[illegible] one oscillator needed to beat to base band, could be communicated by means of cables. This limited interferometer baselines to several kilometers. To overcome this, independent master oscillators were used at each station and the signals brought together by means of microwave link or high-speed tape recording. This technique is known as the Very Long Baseline Interferometer, or VLBI, technique, and has enabled antennas placed on opposite sides of the earth to form a successful interferometer. The longest baseline used so far is that between Westford, Massachusetts, U.S.A. and Semeiz, U.S.S.R. (near Yalta), a distance of about 8000 kilometers.

As mentioned in the preceding paragraph, the principle of interferometer operation is straightforward. When applied to a navigation system, however, there are many possible choices to be made. Figure 2 shows some of these. Either natural or artificial (artificial satellite) illuminating sources can be used. The two most suitable classes of natural sources are the quasars, which have a broad spectrum, and the water-vapor sources, which emit narrow band radiation near 1.35 centimeter wavelength. The natural sources are in general weaker than an artificial source, and are variable in signal intensity, but of course spare us the cost of an artificial satellite. The basic operating configuration can be either the VLBI one, with a shore-located master station, or a shipboard configuration, using two antennas on the bow and stern of a ship. If an artificial signal source is used, a "one-station" interferometer configuration is also possible, with the satellite generating the signal reference. The basic observable in all interferometers is relative phase. However, in VLBI measurements, the oscillator stability is usually too poor to measure phase directly, and either delay or relative doppler rate is measured. An instantaneous measurement of one radio source always gives a line of position on the earth's surface. There are several ways to obtain the two intersecting lines of position needed to determine ship position. This includes observing two radio sources, observing both delay and doppler from one source, observing one source at different positions on the sky, or, for the shipboard interferometer, rotating the ship. Rotating the ship adds no information for a VLBI system. The same is true for simultaneous use of more than one master station.

Although land-based interferometry is now done on a routine basis, there are several practical problems to be solved in implementing a shipboard, real-time system. Figure 3 shows in symbolic form a block diagram of a possible system, using natural sources and the VLBI concept. Note that both ship and master station require two antennas, one at each station pointed at the same natural radio source, and one each pointed at the data link satellite. Since both antennas on the ship must be kept pointed accurately, they must be mounted on an inertial platform. Second, random phase excursions must be kept to less than 1/4 of the observing wavelength (or about one centimeter) over the integration interval of several seconds. This may be done using a three-axis accelerometer as input to a phase-compensating network. Finally, the correlation peak shows up as one point in a plane in which one dimension is time delay, and the other is differential doppler. The width in both planes is affected by the ship's position uncertainty, the frequency-standard's accuracy, and ship's velocity uncertainty. A special-purpose, real-time computer is required to do this search.

The configuration diagram for the shipboard system is shown in Figure 4. The requirement for phase stability is easier to meet than for the VLBI system, since only differential acceleration must be measured, but the ship's heading must be accurately known, since this system measures angles. In addition, there is a problem obtaining sufficient signal from natural sources with two antennas small enough to be easily mounted on board ships. Figure 5 illustrates this. Two one-meter antennas can produce a usable signal for water-vapor sources in about two minutes integration, but at least 10-meter antennas would be required for a quasar system. This is not a problem for artificial sources.

Artificial satellites may be used with interferometers in various ways; in some ways, this is an extension of techniques already in use. For example, coherent doppler tracking of a space probe corresponds closely to the interferometer phase-track concept. One important use of interferometer techniques developed by radio astronomers is to point out the feasibility of measuring the range, as well as range-rate, to a target to within one carrier cycle, by the use of wide-band modulation techniques. With a precise clock on board the satellite, the range to the satellite can be measured without a real-time master station, making a "one-station" interferometer. A system with less dependence on the satellite orbit results if the satellite is observed simultaneously with a master station, and triangulation is used. The range can be tracked during a satellite pass, thus enabling determination of both coordinates of mobile station position.

Use of a shipboard interferometer with an aritifcial satellite enables determination of one angular co-ordinate at the same time its range is measured, thus enabling instantaneous position determination.

Although exact observation geometry is often complex, Figure 6 shown approximate precision that can be obtained for various modes if a favorable geometry is assumed (a signal-to-noise ratio of 10 is assumed for all sources). All measurments in the bottom half of the graph are limited by atmospheric constraints to a precision of about three meters. From this graph the inherent high precision of radio interferometer measurements may be appreciated.

Thus the concept of radio interferometric navigation may add to the complement of techniques already available for navigation. Its high inherent precision makes it especially suitable for high-accuracy applications. Although some practical problems remain to be solved for a shipboard configuration, these are believed to be easily masterable if the system is pursued.

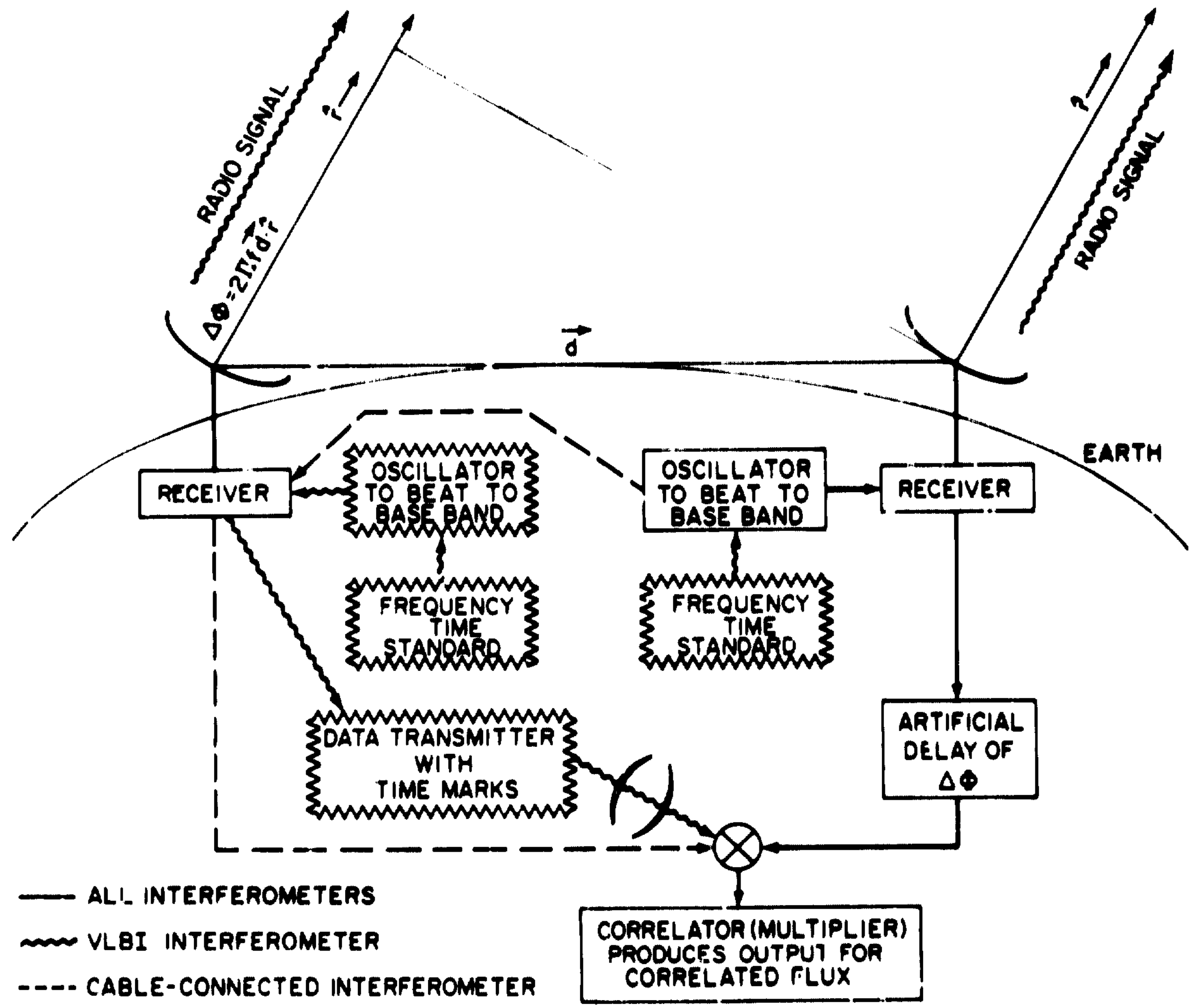

Figure 1. Basic Interferometer Configurations

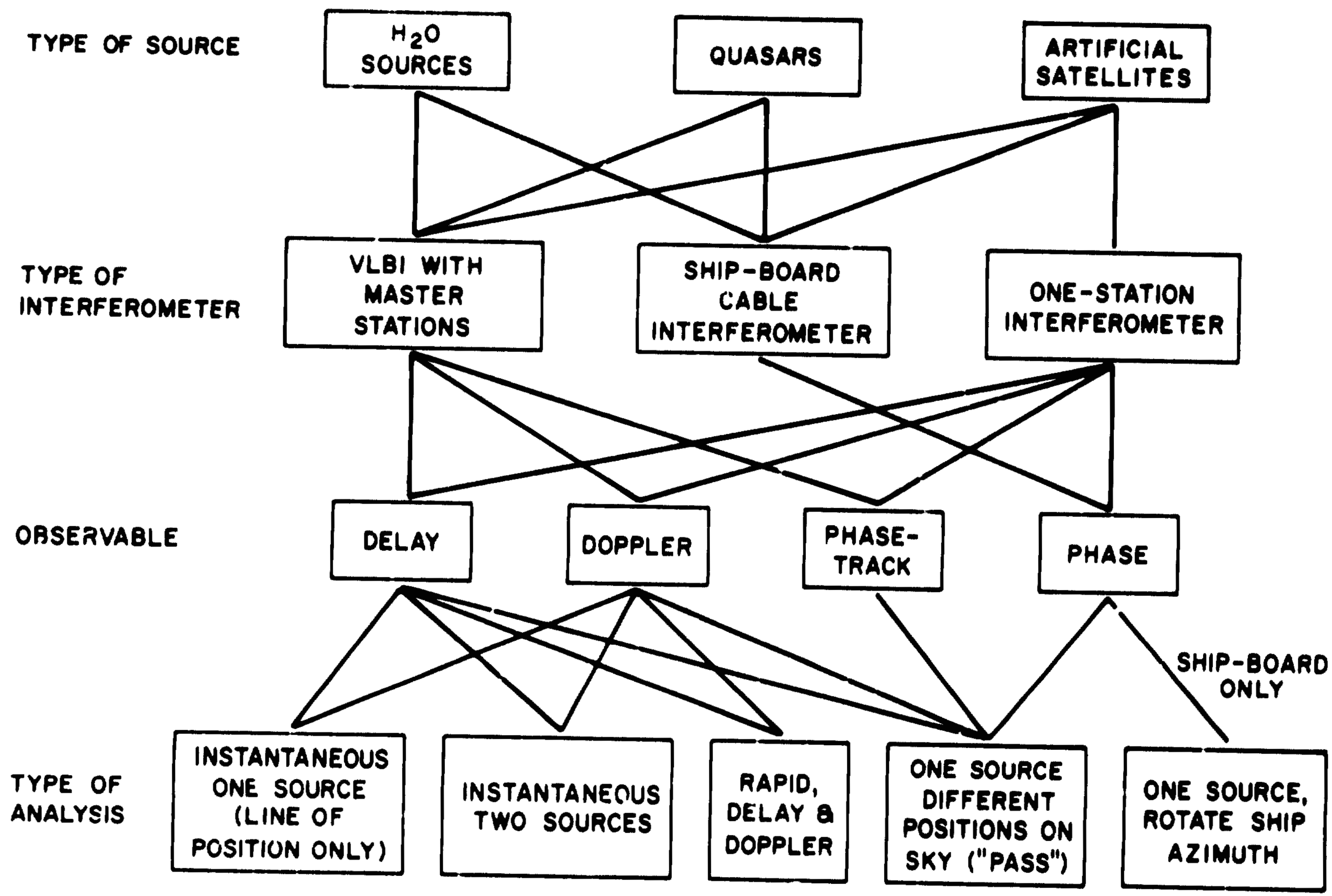

Figure 2. Interferometer Navigation System Operating Modes

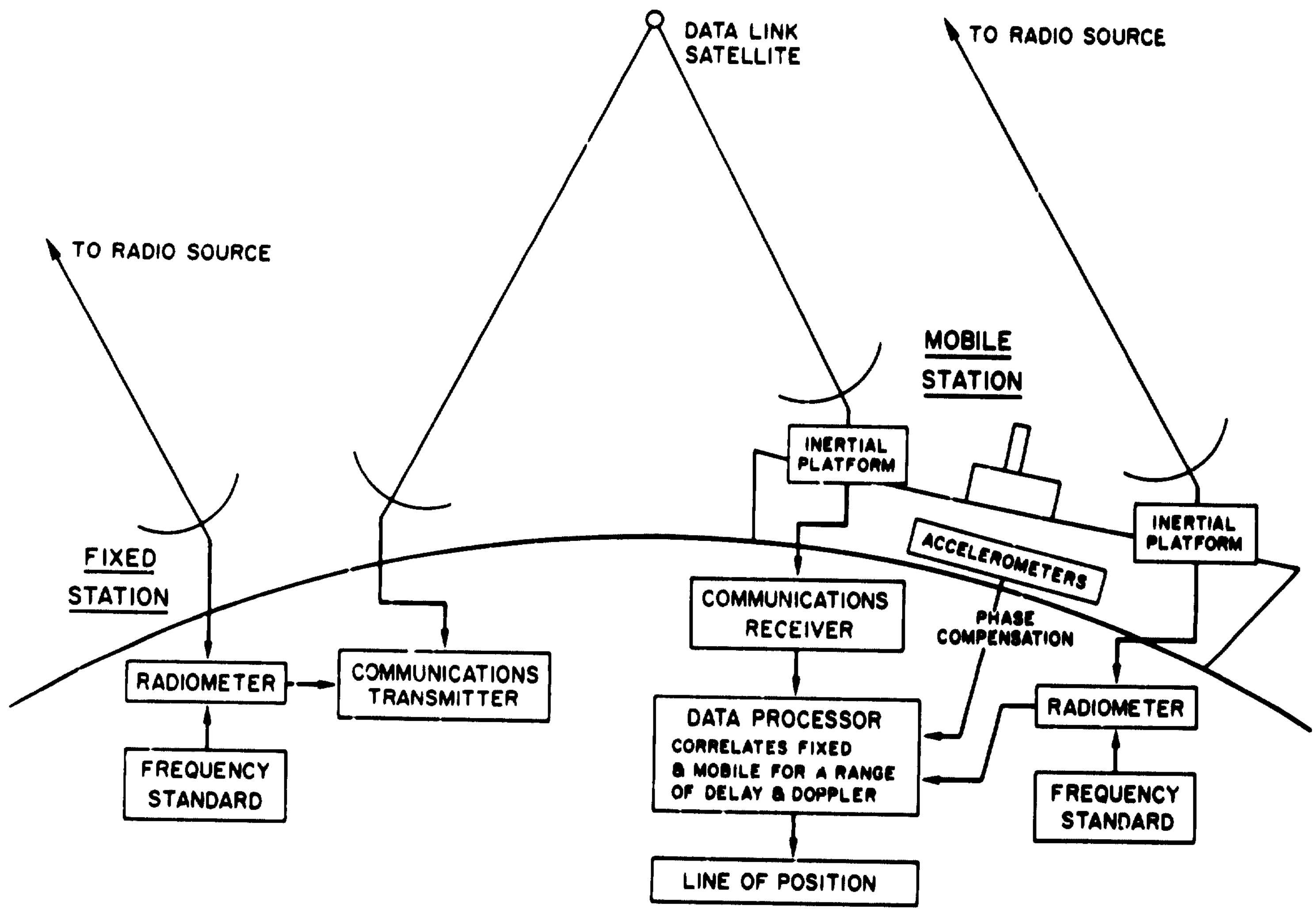

Figure 3. Very Long Baseline Interferometer Navigation System

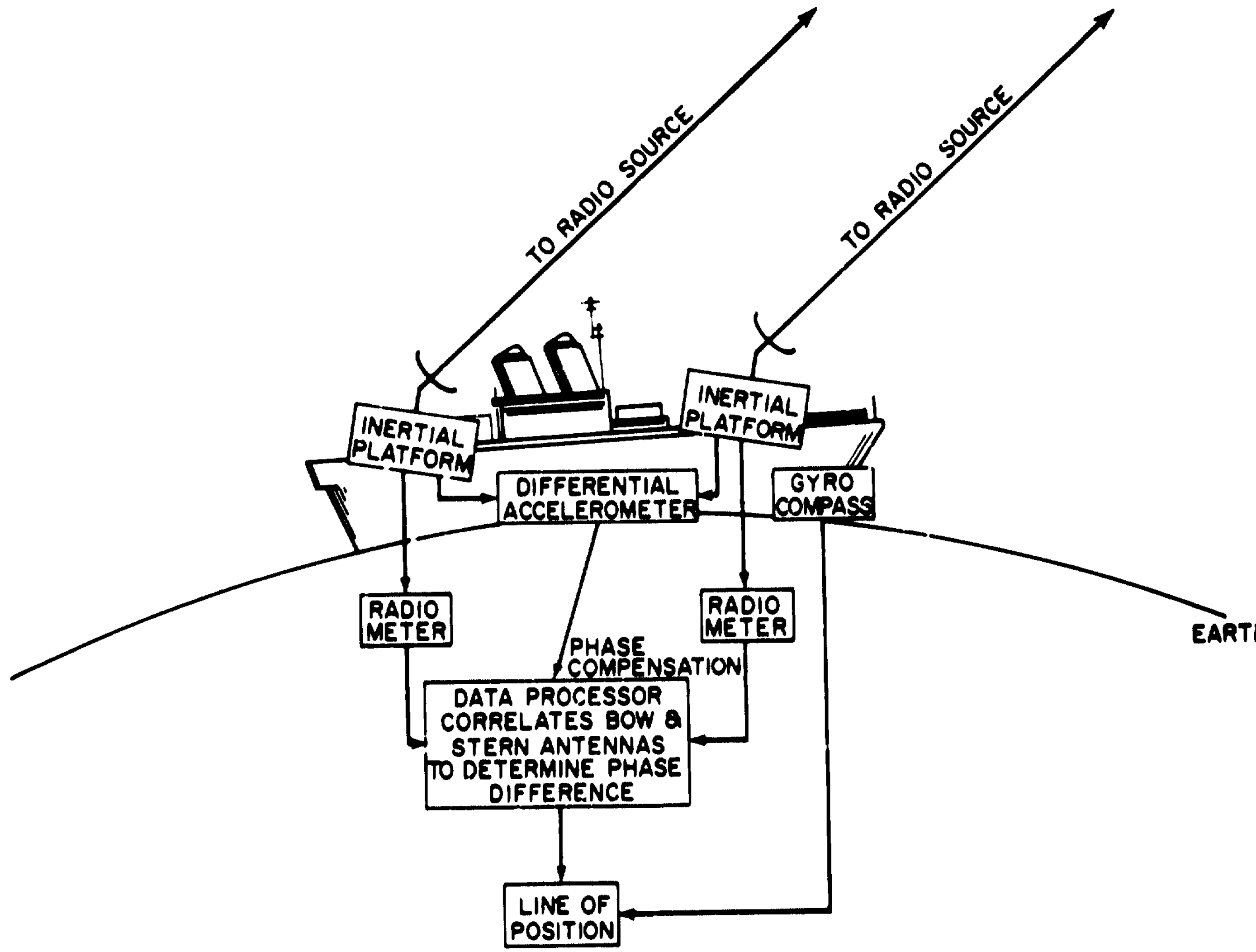

Figure 4. Shipboard Interferometer Navigation System

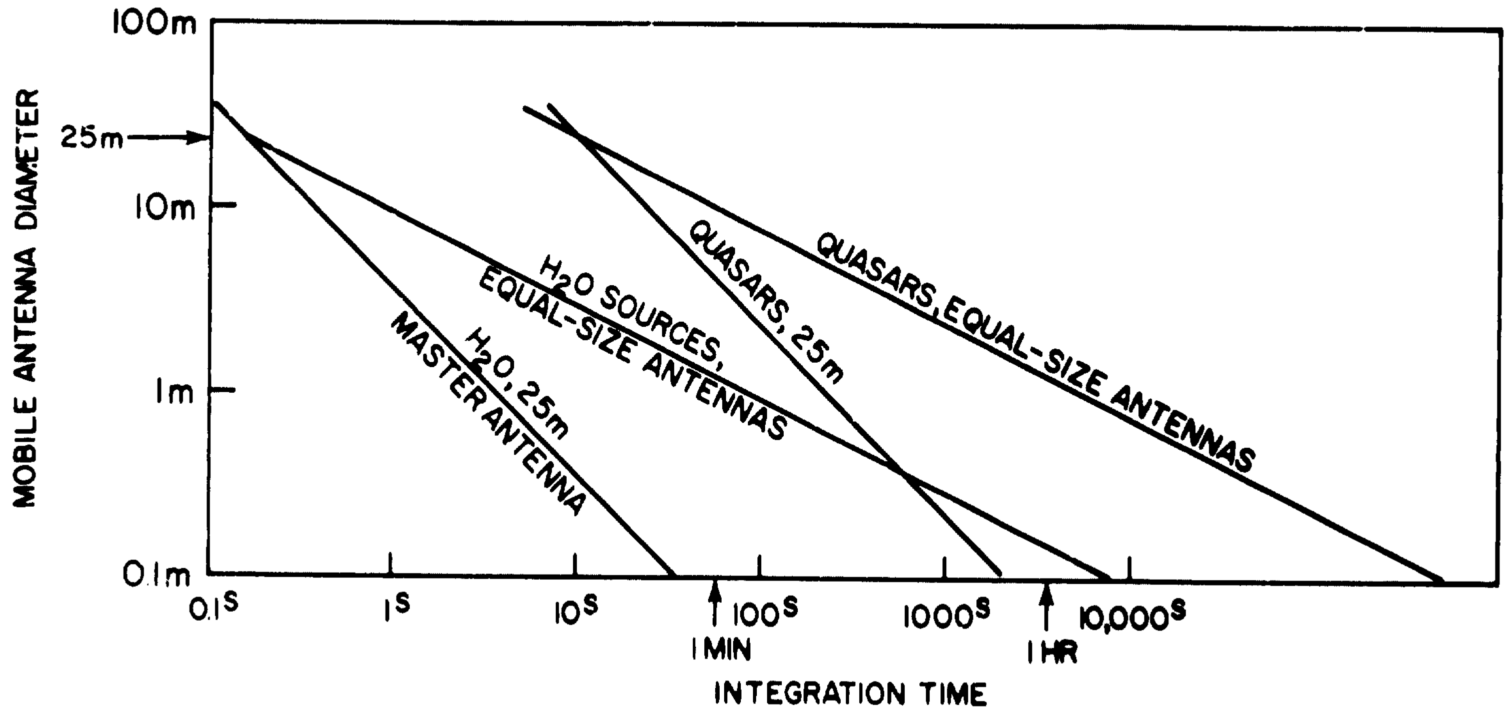

Figure 5. Required Integration Time for a Signal-to-Noise Ratio of 10 for Natural Radio Sources

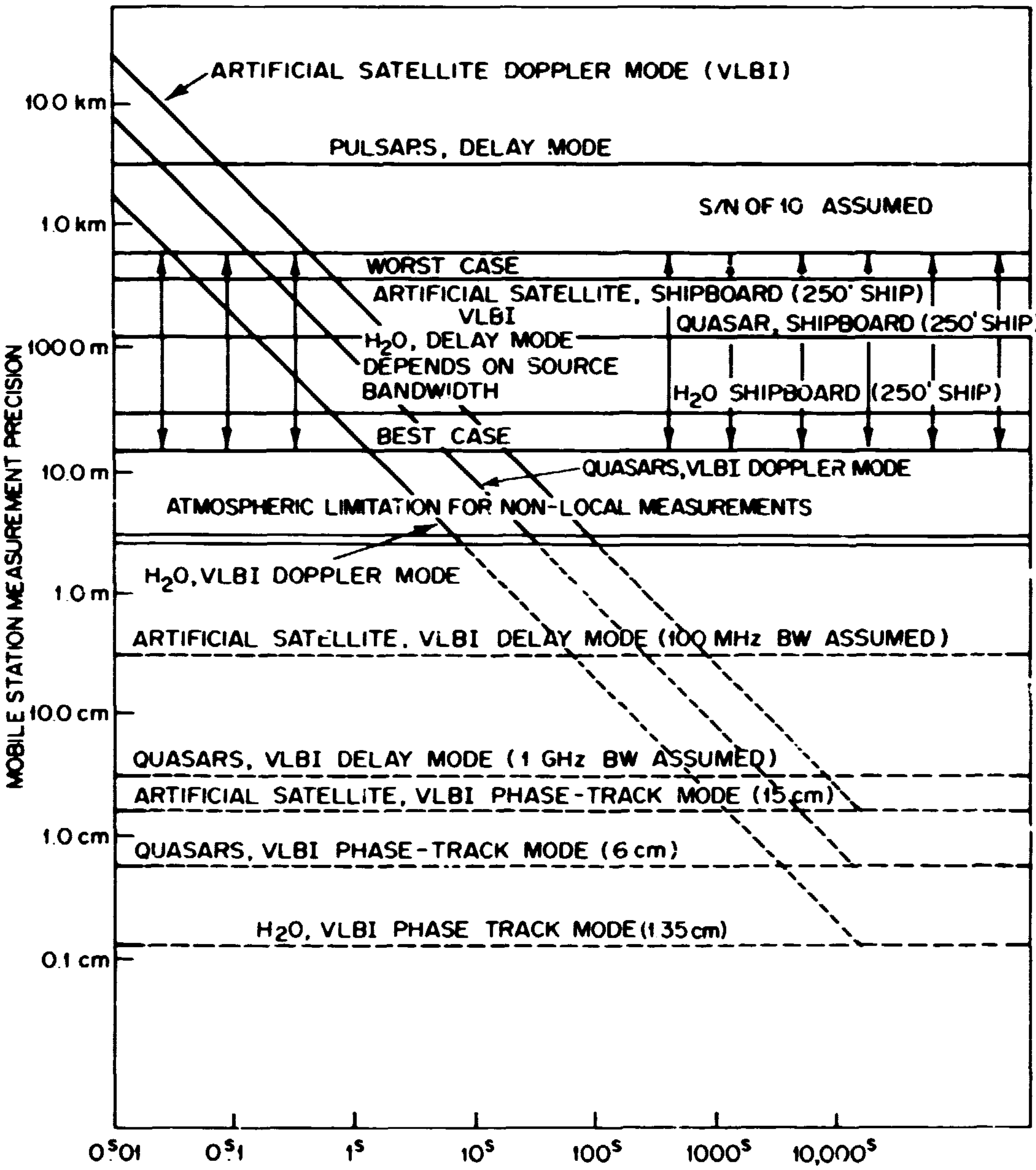

Figure 6. Inherent precision for a signal-to-noise ratio of 10 for various interferometric navigation systems. S-band operation is assumed for artificial satellites, and X-band for the quasar system.

QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

MR. BLACK:

Harold Black, of Johns Hopkins APL. I misunderstood what you intended to say, when you said that a doppler system didn't work on the Equator.

DR. KNOWLES:

A doppler system will not determine latitude for you on the Equator.

MR. BLACK:

That is not correct. The Navy Navigation Satellite System, which is a doppler system, works beautifully on the Equator. It gives both components of position.

Now, you have to qualify your statement somehow.

DR. KNOWLES:

Yes, you are right, I am sorry. I should have qualified it, that applies to natural sources that travel from east to west. It doesn't apply to artificial satellites, which can get an inclination in there.

MR. BLACK:

Thank you.

MR. SWANSON:

Eric Swanson, NELC. I would like to make a comment. The whole use of VLBI for navigation, as you quite properly pointed out, requires a very wide down link. Given that the inherent function of navigation actually demands a very slight band width – it can be argued the real need is zero on transmission – you are now talking of a method that will impact the spectrum by some megacycles or worse.

Could you comment on that?

DR. KNOWLES:

Yes. It is a disadvantage of it, but I am not clear as to the statement that the real need for band width on a navigation system is zero.

And particularly, on the other point that on a satellite system there is definitely a finite band width in there.

This is, by the way, one thing which I didn't mention on the VLBI technique. When you use it on artificial satellite techniques it is really more an extension of other satellite techniques. If its essential contribution is trying to tell you to use a transmitter with a wide band width coding on it, so that you can get a lock in on the absolute phases of the transmission, the problem is that you could get by with a zero band width if you were not at all concerned about ambiguity problems. In particular, on the water vapor sources, we can get very accurate position measurements with the narrow band width, and you could let that go to infinitely narrow and still get position.

The reason you need the band width is to provide you with longer waves as well as shorter ones, to let you zero in on your position.

I am not clear that that is the answer to your question. I will just leave that up for thought.

MR. CHI:

Thank you very much.

The next paper, No. 6, which has been withdrawn, and in place of it is a paper under the title of "Application of Radio Interferometry to Clock Synchronization," by Dr. William Hurd, of Jet Propulsion Laboratory.

N75 11280

DEMONSTRATION OF INTERCONTINENTAL DSN CLOCK SYNCHRONIZATION BY VLBI

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ABSTRACT

The prototype system for Deep Space Network (DSN) clock synchronization by VLBI has been demonstrated to operate successfully over intercontinental baselines in a series of experiments between Deep Space Stations at Madrid, Spain, and Goldstone, California. As predicted by analysis and short baseline demonstration, the system achieves reliable synchronization between 26 m and 64 m antenna stations with 17 and 37 K nominal system temperatures using under one million bits of data from each station. Semi-real-time operation is feasible since this small amount of data can be transmitted to JPL and processed within minutes. The system resolution is 50 to 400 ns, depending on the amount of data processed and the source intensity. The accuracy is believed to be comparable to the resolution, although it could be independently confirmed to only about 5 μs using LORAN C.

INTRODUCTION

The prototype for a semi-real-time system for DSN clock synchronization by radio interferometry was first demonstrated on a short baseline in August 1972.[1,2] A series of three experiments has now been conducted between Madrid, Spain and Goldstone, California, to demonstrate that the system performs as expected on intercontinental baselines. The series of experiments had three primary classes of objectives, all of which were achieved:

1. To confirm that the system achieves the predicted resolution with the predicted amount of data; this implies that there are radio sources available which act as strong enough point sources over the long baseline.

2. To check the system accuracy by demonstrating consistent results at different times of day and with different radio sources and, by direct comparison with other clock synchronization systems, to within the accuracy of these systems.

3. To gain experience in operating VLBI systems so as to uncover potential problem areas and facilitate the design of a higher-accuracy, operational clock synchronization system.

Using one 64 m and one 26 m antenna, several sources were available which were strong enough to achieve resolutions of from 200 to 400 ns with about 1 million bits of data and 50 to 100 ns with several million bits. We believe that the system accuracy is consistent with these resolutions. However, the absolute accuracy could be confirmed only to the approximate 5-10 μs accuracy of LORAN C.

DESCRIPTION OF EXPERIMENTS

The three experiments were conducted on April 12, April 30, and June 11, 1973. On the first of these days, two 26 m antenna stations were used, DSS 12 at Goldstone and DSS 62 at Madrid. The last two experiments used the 64 m antenna at DSS 14, Goldstone together with DSS 62. To maximize the use of station time and to obtain a rough check on the accuracy, the last two experiments were run simultaneously with another VLBI experiment (conducted by J. Faneslow of JPL). The purpose of this other experiment was to measure the platform parameters, the source positions, and UT1. The two independent experiments agreed in their estimates of clock offset to within about 10 μs, the approximate accuracy of the platform parameter experiment.

The data were acquired and processed in the same manner as for the first clock synchronization demonstration.[1,2,3] Coherent bursts of about 0.31 Mbits of usable data, as limited by the computer memory size, were taken at 10 second intervals and recorded onto magnetic tape. Since the sampling rate was 0.5 Mbps, the burst length was only about 0.62 second, but the burst frequency was limited by the 200 bpi magnetic tape density. Each full tape of data consisted of 72 bursts. However, some tapes contained less data due to tape failures. In the joint experiments, the source schedule of the platform parameter experiment was followed, which sometimes allowed only 2 or 3 minutes between sources. When only one tape unit was operational, the number of bursts of data on each tape was reduced due to the time required to change tapes. Other short tapes were caused by tape errors.

The tapes were mailed to JPL for processing. The maximum likelihood estimator function[3] was calculated for each burst of data, and then the function values were accumulated in a nonoptimal manner over enough successive bursts of data to achieve an adequate estimator signal-to-noise ratio. The accumulation was nonoptimal only because fringe phase coherence was not maintained between bursts. This resulted in little degradation for strong input signal-to-noise cases, when only 2 or 4 bursts were required, but in significant degradation for weak sources and when both stations had 26 m antennas. The system was not designed to operate in these situations because too much data is required for satisfactory operation.

RESULTS

Estimates of clock offset were obtained for two tapes of data on April 12, using two 26 m antennas, and for ten and five tapes of data on April 30 and June 11, respectively, using one 26 m and one 64 m antenna. The nominal system temperatures were 17 K at the 64 m station and 37 K at the 26 m stations. Successful estimates were not obtained for all pairs of tapes on any day. On the first day, this was because the signal-to-noise ratios were too low on all but the strongest source. On the two days using the 64 m antenna, the failures are believed to be due mainly to tape failures. This is discussed further in the next section.

The clock offset estimates are presented in Table 1, together with estimates of the resolution obtained and of the amount of data required for reliable measurement. The first three columns identify the case by date, time (GMT), and radio source name. The fourth column indicates the number of subcases into which the data were divided, and the fifth column indicates the number of coherent bursts of 0.31 Mbits of data that were combined noncoherently in each subcase. The sixth column is the average estimate of clock offset for the case, in microseconds, with positive values indicating that the clock at DSS 62 is early. The seventh and eighth columns are the estimated resolutions for one subcase and for the entire case in nanoseconds. For cases with more than one subcase, the resolution for one subcase is taken as the sample standard deviation, and the overall resolution is this standard deviation divided by the square root of the number of subcases. For the four cases having such a low signal-to-noise ratio that there was only one subcase, the estimated resolutions were obtained from the value of the estimator function. These estimates are quite unreliable. The final column in Table 1 is the estimated amount of data required to obtain reliable estimates for that source, on that day, and with the system parameters used. It is the amount of data required for an estimator signal-to-noise ratio of 10 and a resulting resolution of 366 ns.

Data Requirements for Reliable Results

Of primary importance is that reliable results were obtained with four radio sources with one million or fewer bits of data when using the 64 m antenna. These sources are 4C39.25, OJ287, DA193, and NRAQ190. The flux densities were not estimated directly from the data, because this requires considerable additional computer time. However, from the estimator signal-to-noise ratios and

Table 1

Clock Offset Estimates, Estimated Resolution, and Data Required for Reliable Performance

Date, 1973	Time, GMT	Source	Number of subcases	Number of bursts per subcase	Estimated clock offset, μs	Resolutions for one subcase, ns	Resolution for entire case, ns	Minimum data required, Mbits
4/12	2152	4C39.25	4	36	134.63	345	172 (2 tapes)	10
4/30	1756	NRAQ190	15	4	125.77	340	90	1.1
	1812	3C84	8	8	125.17	510	180	5
	1845	DW0224 + 67	8	8	124.41	470	170	4
	1906	NRAQ190	6	8	125.59	220	90	0.9
	2118	3C371	1	38	122.7	400*	400*	14
	2203	4C39.25	8	4	125.49	190	70	0.4
	2242	QL553	1	72	126.6	370*	370*	22
	2300	QJ287	23	2	125.56	240	50	0.3
5/1	0007	3C371	1	54	123.3	220*	220*	6
	0022	4C39.25	9	4	125.24	150	50	0.2
6/11	1726	DA193	16	4	203.16	220	60	0.5
	1848	OI363	8	8	203.39	470	170	4
	1905	DA193	16	4	202.71	190	50	0.4
	1923	4C39.25	16	4	203.25	210	50	0.4
	1941	3C371	1	71	200.8	1000*	1000*	50

*For these cases the signal-to-noise ratio is so low that the estimates of resolution and data required may have large errors.

the nominal system temperatures, we estimate the correlated flux densities for these sources to range from 1 to 2 f.u. There are enough radio sources of this strength that clock synchronization is attainable at any time of day between DSS 14 and Spain or Australia. Similar performance will be achievable between Spain and South Africa when DSS 63, a 64 m station, is operational in Spain.

Resolution and Consistency

The results for the ten cases of April 30 are shown as a function of time in Figure 1. The straight line has a slope equal to the rate of change in the clocks, −0.6 μs/day, as predicted by the fringe rate data taken in the platform parameter VLBI experiment on that day. The error bars shown are the estimated resolutions. At best, the accuracy would be the resolution plus a degradation of up to about 100 ns due to propagation and geometrical effects. This should be added in a mean square sense. (There is also a constant error due to time delays in the stations, which would not show up in the results.)

Overall, all of the clock offset estimates fall as close to the straight line as expected except for the case for DW0224+67 and the two cases for 3C371. Although these sources are quite weak, especially 3C371, there appears to be some significant error for these cases. The cause for this error has not yet been satisfactorily explained. However, one likely cause is that the time delay predictions were in error due to the high declinations of the sources, +67 deg, for

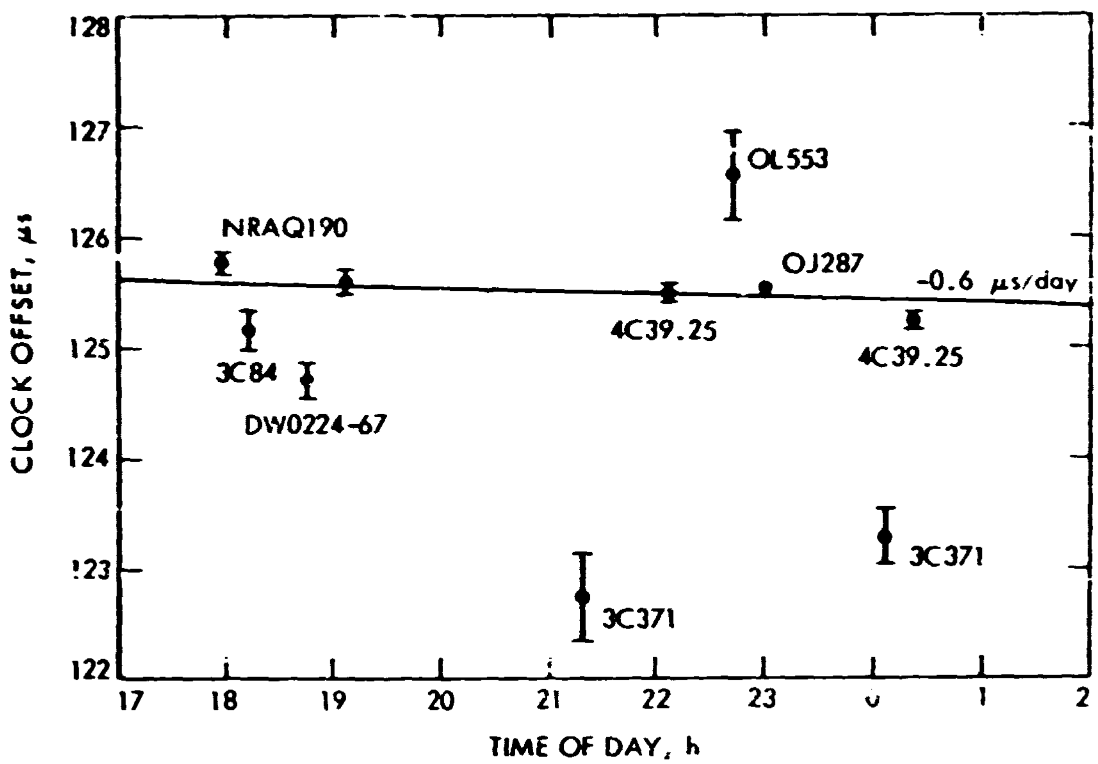

Figure 1. Clock Offset Estimates for April 30, 1973, with 1σ Resolutions

DW0224+67 and +69 deg. for 3C371. The highest declinations for the other sources are +56 deg. for OL553 and +41 deg. for 3C84. Furthermore, the geometry was so unusual for 3C371 that the received frequency was higher for DSS 62 than for DSS 14, just the opposite from the usual case, because the antennas were pointed on the opposite from usual sides of due north. This can happen only with high declination sources.

Comparison to LORAN C and Platform Experiment

The clock offset estimates obtained in these experiments agree with estimates made on each day using LORAN C, to within the approximate 5-10 µs accuracy that could be expected. For the last two days, the results also agree with the VLBI platform parameter experiment, to the accuracy of that experiment. There was, however, a constant 200 µs offset with respect to LORAN C. This was determined to arise because some of the 1 second period reference signals at DSS 62 occurred 200 µs early because of reference to the wrong edge of a 200 µs duration pulse.

The comparisons to LORAN C and the platform experiment are shown in Table 2. The first column identifies the experiment date. The second column is the

Table 2

Comparison of Clock Offset Estimates

Date, 1973	LORAN C uncorrected DSS 62 to LORAN C, μs	LORAN C corrections DSS 12/14 to LORAN C, μs	LORAN C offset estimate DSS 62 to DSS 12/14, μs	VLBI platform parameter estimate, μs	Offset estimate of this experiment, μs
4/12	-62	+1	-61	–	-65
4/30	-74	+7	-67	84	-74
6/11	+3	-4	-1	-9	+3

difference between the DSS 62 and the LORAN C Mediterranean chain clock. The nominal accuracy is about 2μs, but ambiguities often cause errors in 10μs increments. The third column is the sum of all known corrections from the LORAN C Mediterranean clock to the DSS 12 or 14 clock, that is LORAN C to the U.S. Naval Observatory (USNO), USNO to the National Bureau of Standards (NBS), NBS to the Goldstone master clock and the Goldstone clock to DSS 12 or 14. Each of these legs introduces some error, typically on the order of 1μs. The fourth column is the estimate of clock offset between the stations obtained from LORAN C. The last two columns are the offsets obtained by the VLBI platform parameter experiment and by this experiment, corrected for the known 200μs error at DSS 62.

The clock offsets measured in this experiment agree with LORAN C to within an average of 5μs and to the VLBI platform experiment to an average of 11μs. These results are consistent with the accuracies of LORAN C and the platform experiment.

PROBLEMS, CAUSES, AND SOLUTIONS

The two major problems in the series of experiments were that results were not obtained for any day until the data from the last experiment were processed and that good results were not obtained at all for a number of cases for which the signal-to-noise ratio should have been adequate. A number of possible causes for lack of results were studied while an unsuccessful attempt was being made to process the data. These investigations will influence the design of the final operational system.

The delay in achieving results was caused primarily by the 200μs error in the predicted clock offset. This area of clock offset was not searched until after the large offset error was discovered by the VLBI platform parameter experimenters. Even then, there was a delay in obtaining good results due to a discrepancy between the software and the hardware which was caused by a system modification made after the short baseline experiments. One of the ramifications of this [illegible] was overlooked. Aside from leading to a more complete analysis of the system, this processing problem will have no effect on the future system.

Search Range and Variable Bandwidths

The 200μs offset error will have an effect on the future system. It pointedly illustrates that large errors can occur, even when the system is supposedly calibrated with LORAN C. It also illustrates the problems which could occur if synchronization is lost and the best available timing information available is by radio broadcast, with errors on the order of milliseconds. An operational system should be capable of efficiently searching as wide a region of clock offsets as possible. This is best accomplished by enabling data acquisition with a number of selectable bandwidths and sampling rates. Lower bandwidths and sampling rates enable wider searches because the wide region encompasses fewer samples. Programmable digital filtering would be the most flexible and economical method for achieving this.

Local Oscillator Frequency Adjustment

One possible cause for bad data was that the third (10 MHz) local oscillator (LO) was offset at the Goldstone station in order to compensate for the fringe rate or doppler frequency difference. This LO was manually adjusted for each case, and it is possible that the frequency synthesizer was improperly set for some cases. This problem can be avoided by accounting for the fringe rate entirely in the data processing. There would be some cost in computer time.

Synchronization of Samples to Station Clock

Another possible trouble area is in synchronization of the samples to the station clocks. In these experiments, the hardware was resynchronized to the frequency and timing system (FTS) 1 pps and 1 MHz signals at the beginning of each burst of data, i.e., every 10 seconds. It would probably be more reliable to synchronize the system to the station clock only once for any experiment. Since the resolution of the present FTS is only on the order of 0.1 to 1.0μs, a higher-resolution clock will be required in any case for the more accurate clock synchronization system. This high-resolution clock could either be a part of the clock synchronization hardware or be in the form of a new timing system.

CONCLUSION

The prototype VLBI clock synchronization system has been demonstrated to operate as predicted over transcontinental baselines. Resolutions of 50-400 ns were achieved, and the accuracy is believed to be approximately the same. A wideband system is being designed which will achieve a resolution of 1-10 ns, depending on the available receiver bandwidth. The accuracy of this system will be limited by atmospheric and geometric effects and by errors in calibrating time delays in the stations rather than by the system bandwidth and resolution.

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QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

DR. WINKLER:

What clocks have you used between the two stations for which you showed us before the last slide, the second to the last slide?

DR. HURD:

Well, all the experiments used rubidium. I think there might have been a maser at one station, but there was at least one rubidium in the system. That is the advantage to this type of system; since we are taking the data over such a short period of time, the oscillators ability isn't a problem.

DR. WINKLER:

May we see the second to the last slide again, because I have several questions on that.

(Slide.)

DR. WINKLER:

There is something on that slide which, I think, even if you have two very poor rubidium standards is simply incomprehensible.

DR. HURD:

Well, to fill this buffer in the existing system takes six tenths of a second — it is a 320 kilobit buffer being filled at a 500 kilobit rate.

DR. WINKLER:

Yes.

DR. HURD:

So, to —

DR. WINKLER:

But my question aims at clarification of the meaning of the error bars which you have here which evidently must be connected with your estimate of internal precision of each individual synchronization experiment. Evidently there must be very much larger external errors.

There simply is no clock which would jump around four, five or six microseconds between one and two hour intervals. Even the worst crystal would do much better than that.

So, you must have considerable external errors, which are completely ignored here.

DR. HURD:

Well, as I tried to point out, I haven't explained why the few larger error results occurred. These were weaker sources; they were in peculiar positions in the sky; and we didn't calibrate the atmosphere. The atmosphere couldn't cause that much error, though.

DR. WINKLER:

What sense do the error bars make then? If you put error bars on which appear to have absolutely no significance whatsoever --

DR. HURD:

Oh, the error bars represent the errors due to statistical errors and due to receiver noise.

The error bars are the observed standard deviations of the errors for that source. In other words, they are how consistent the measurements were for that particular source. For example, for the first point on the curve, I believe that one tape of data was divided into 18 cases. Each case was an accumulation of four of these batches of data. So that we had for each batch of data roughly one million bits of data for each of 18 cases. The error bars represent the standard deviation of the estimate for those 18 cases. In other words, it is how well we would have done, you know, if the system had been perfectly calibrated.

MR. CHI:

The error bars enumerate the number of data points?

DR. HURD:

Well, no. If you gather statistical data and you want to make an estimate of it as to how accurate you are estimating some parameters, you divide it up into several batches, and compute the sigma, the standard deviation of these batches, and then you divide that sigma by the square root of the total number of batches to get the standard deviation on the entire amount of data, and that represents the error just due to receiver noise, not due to atmospherics, not due to anomalies in the clock changing during the time. Well, you can see, even with the worst cases, there are not very many signals from the line, four or five sigma.

DR. WINKLER:

Yes, but what you seem to claim is that your clock essentially has shifted by several microseconds every few hours.

DR. HURD:

No, I am claiming that that measurement was a bad measurement. I am claiming that it was a poor measurement, it is a bad result. I am not just showing the good results.

MR. CHI:

There is a question, Dr. Reder.

DR. REDER:

Isn't there really a misunderstanding between the two of you? Are these measurements taken on the same day?

DR. HURD:

Yes.

DR. REDER:

They are taken on the same day?

DR. WINKLER:

Yes.

DR. REDER:

Then I will be included in the misunderstanding.

DR. HURD:

These are results on the same day, and they don't all agree. The results for the stronger sources do agree, as well as we expected. The results from some weaker sources have unexplained large errors.

DR. CLARK:

Tom Clark, NASA-Goddard. I have two questions or comments.

I would first of all be curious in making these clock calculations which you had here. You obviously have made some assumptions as to the positions of the sources, and the length of the baseline. That is, those factors included in the geometry.

It would be interesting to know what assumptions were made in that case.

Second of all, for the much wider band width system which you described, there is one effect which you didn't indicate how it would be taken out, about which I am curious. This is differential phase response over the pass band, which is going to cause an instrumental delay dispersion.

Do you plan some sort of instrumental phase calibration to be taken with this data?

DR. HURD:

I feel that since I am using the full continuous band width, phase stability requirements on the system will be less critical.

On the second point of view, to answer your question as to how good I expect this to be; the projections are for a total system stability, from and including the front end maser and the receiver system, which is supposed to be stable to 10 centimeters, over a 12 hour period or so, with certain assumptions on how much the temperature can change and things like that.

So, at the 10 nanosecond level, I think that the system stability will not play an important role here. I think that atmospherics will be dominating. I think that how good you do with the system depends on what you do with the atmosphere.

To get 10 nanoseconds, I think you would agree that we can probably a priori model the atmosphere that well, especially at S band.

DR. CLARK:

The question I was asking, however, had to do with the differential phase response over the pass band. You are going to just have to rely on the networks themselves calibrating that out for you.

DR. HURD:

The entire differential group delay is 10 centimeters, it can vary 10 centimeters over a day.

DR. CLARK:

No, I am talking about at one instant of time, over the pass band, the group delay which you are measuring, the time delay number you are measuring is essentially rate of phase change over the pass band. Now, from that, that number has to be subtracted from the instrumental phase response, and I was asking --

DR. HURD:

I don't even measure the phase.

DR. CLARK:

Well, that still has to be defined. This is a group delay, and group delay is $\Delta\phi/\Delta\omega$, so the instrumental phase response, the dispersion of the filters in the pass band are an important factor to you.

DR. HURD:

The tentative spec on the system is 10 centimeters for eight hours total change. That is, change in the total delay through the system.

Clearly, the differential delay at the two edges of the pass band is going to be much better than the total delay in the whole system.

DR. FLIEGEL:

Henry Fliegel, JPL.

I believe the question was that if you want to measure the absolute difference between two clocks at two different stations, that you have to calibrate the different phase delays and different channels that you are using.

DR. HURD:

I am not using different channels.

DR. FLIEGEL:

Or across the one channel that you are using then, if it is broad banded.

DR. HURD:

By utilizing the entire continuous band width, what you are buying, in a loose sense, is the average change in the group delay as a function of frequency, rather than being particularly concerned with the differential phase delay at two edge bands, and I think it is clearly easier to average this thing out.

DR. FLIEGEL:

Let's get together over coffee. I think that there is an issue here that we are not getting across.

DR. HURD:

That is not my area of expertise, in any case.

MR. KAUFMANN:

I have a question in regard to this system relative to moon bounce. Is it more economical, what kind of savings do you envision, and is the performance greater, and if so, how much better?

DR. HURD:

Well, performance is cetainly much greater. The moon bounce system accuracy is 10 to 20 microseconds.

The major cost of the moon bounce system is in maintaining the system. There is over a million dollars worth of equipment involved in the system, and if you make reasonable estimates as to what your average long term maintenance figures are going to be for this amount of equipment, it turns out to be quite a lot of money. The cost is considerably more than the amount of money which is now budgeted for maintaining that system, which is 40 thousand a year.

I mentioned to Bill that a VLBI system would cost in the neighborhood of a couple hundred thousand to build. This includes three data acquisition systems for a reliable digital system.

MR. CHI:

Thank you, Bill.

N75 11281

THE AUTOMATED ASTRONOMIC POSITIONING SYSTEM (AAPS)

O. W. Williams
Defense Mapping Agency

ABSTRACT

The Control Data Corporation, Minneapolis, Minnesota, under contract to Air Force Cambridge Research Laboratories, L. G. Hanscom Field, Bedford, Massachusetts, has recently delivered two prototype systems of The Automated Astronomic Positioning System (AAPS) to DMA. The AAPS was developed to automate and expedite the determination of astronomic positions (latitude and longitude). This equipment is capable of defining astronomic positions to an accuracy of $\sigma = 0\overset{''}{.}3$ in each component within a two hour span of stellar observations which are acquired automatically. The basic concept acquires observations by timing stellar images as they cross a series of slits, comparing these observations to a stored star catalogue, and automatically deducing position and accuracy by least squares using pre-set convergence criteria. An exhaustive DMA operational test program has been initiated to evaluate the capabilities of the AAPS in a variety of environments (both climatic and positional). Status of the operational test is discussed and participation is invited.

BACKGROUND THEORY AND TECHNICAL DESCRIPTION

The idea of automating astronomic position determination has been actively pursued for at least two decades. To date, however, no one has come up with a portable field instrument. Current first order observing instruments such as the Wild T-4 and Kern DKM 3AX do not readily lend themselves to automation without serious redesign and the probability of performance degradation.

Following a series of feasibility studies supported by Air Force Cambridge Research Laboratories (AFCRL), the Air Force directed AFCRL to initiate development and design studies in 1970 for an Automatic Astronomic Positioning System (AAPS). As a result, a development and fabrication contract for two (2) prototype AAPS is awarded to Control Data Corporation.

The current instrument represents a radical departure from past astronomic positioning instruments. It is based on the timing of the transits of star images past slits in a focal surface reticle. While developed independently during the 1960's at Control Data Corporation, such a detection technique had been pioneered in the 20's and 30's by Pavlov (1946) in Russia. He employed such measurements in the accurate determination of time at a fixed observatory. Since

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then, Liang Tseng-Yung (1963), Moreau (1966), and Abby (1969) have separately experimented with field versions, usually theodolites with photoelectric attachments. At the present time, Hog in Germany is developing an interesting meridian transit instrument based on the same principle.

The present instrument system is the first which combines a truly automatic field instrument with a portable computer. The AAPS was designed with the following specifications in mind:

a. The portable-field equipment should not exceed 45 kilograms in total weight. Any individual portion of the system should not exceed 25 kilograms.

b. The system should provide an astronomic position within a two hour observing and computing period.

c. The accuracy of astronomic latitude and longitude should be within ± 0.3 arc sec, one sigma, at 45° latitude.

d. The system should contain its own internal battery capable of supplying power for ten hours of continuous operation.

The AAPS was conceived to be a totally automated system. This quantum jump in relation to present systems was deemed necessary to provide greater efficiency in operations and to eliminate operator mistakes and errors caused by the "personal equation". In addition, increased data rate and on-site data reduction holds out the promise of rapid, reliable, and accurate site surveys.

The theory involved in the AAPS is based on a star detection concept (Fig. 1) where the transit of a star passes through a lens, whose optical axis is vertically oriented, onto the slits of a reticle. This star transit is detected photoelectronically as its image passes across the slits of the reticle.

The constraint for one such transit is shown in Figure 2. A spherical triangle equation is used in the AAPS computation both to (1) predict transit times for an assumed position in order to identify actual transits, and (2) to solve for the true position from the identified and measured transits.

For the purpose of prediction, the equation is rewritten as shown here. This equation is then solved using the negative portion of the quadratic equation.

The transit time for the given slit and star is determined by Equation 3 (Fig. 3).

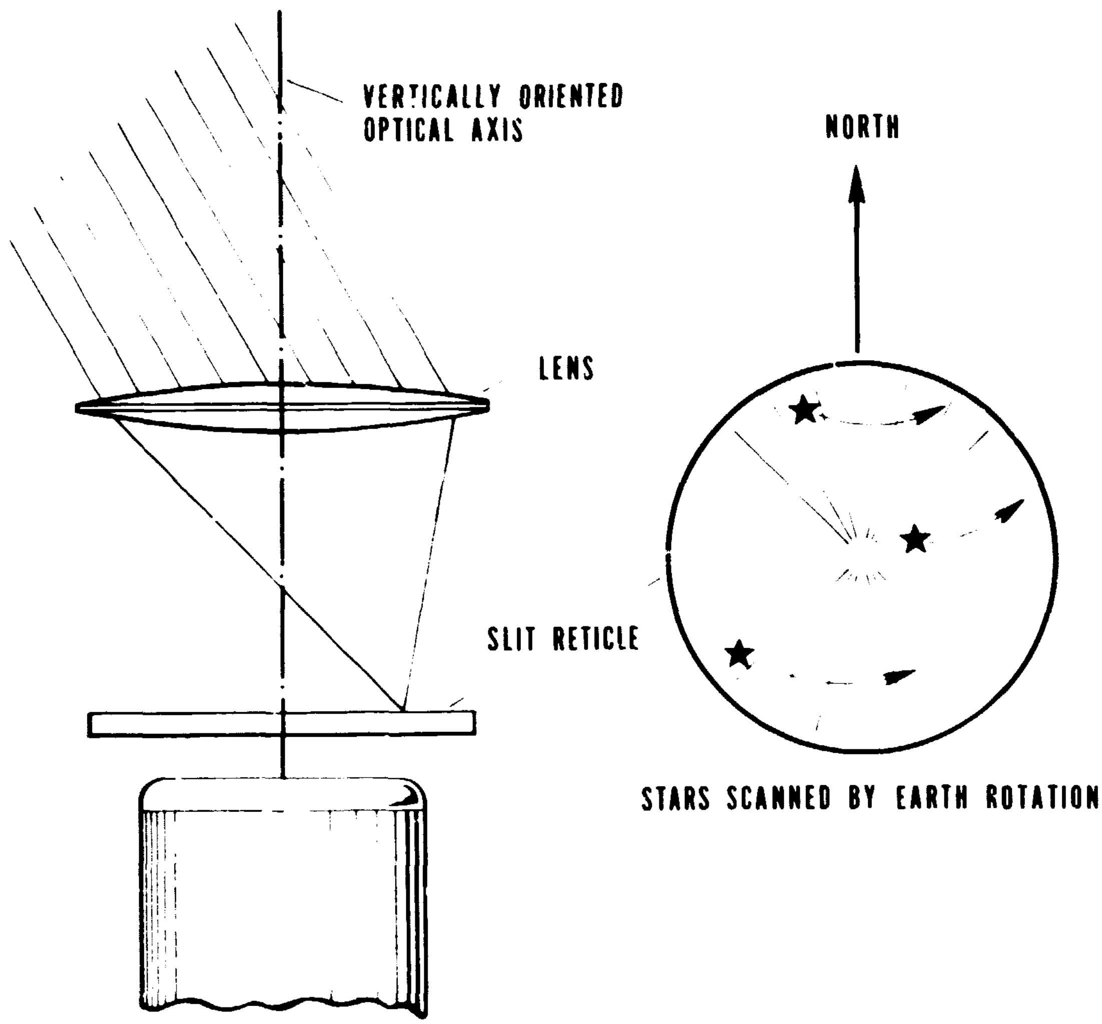
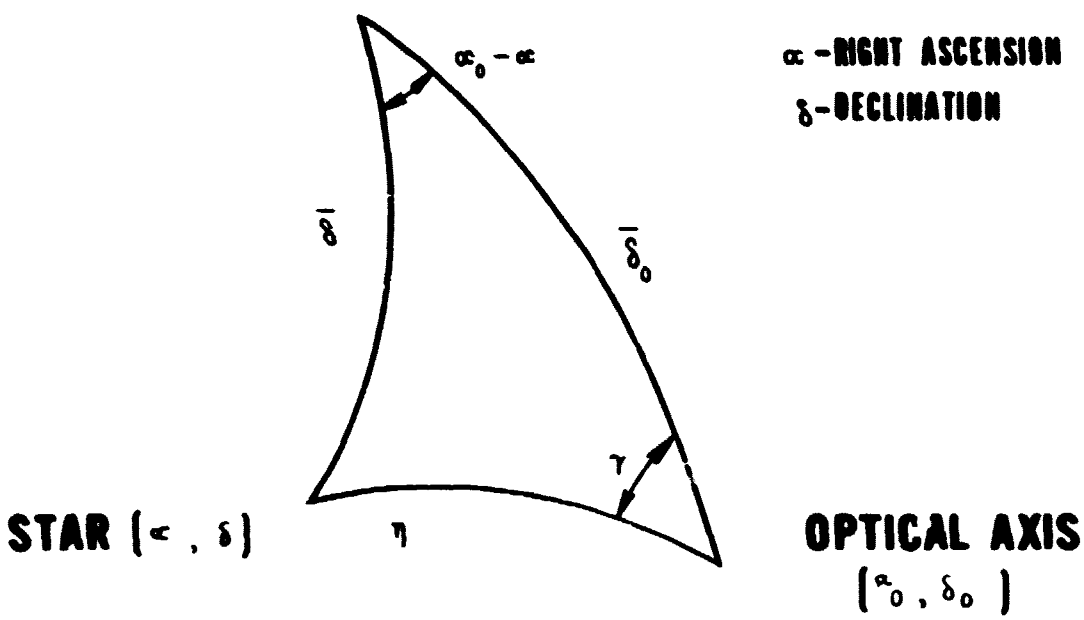


Figure 1

The basic identification process then becomes one of matching a measured transit with a predicted transit (for a given slit). Since small errors in azimuth orientation create large errors in the transit time, a preliminary course matching procedure is followed to produce a more accurate estimate of azimuth.

Upon identification of the transits, the assembly of the equations are solved for astronomic position in a least squares sense using an iterative technique.

After the first solution has been obtained, measurement residuals are calculated and the standard deviation found. Some multiple of the standard deviation is then used as a rejection limit and all observations with residuals exceeding this limit are momentarily deleted from the measurement set and the computation is repeated.



$$\mathrm{SIN}(\alpha_0 - \alpha)\ \mathrm{COT}\ \delta = \mathrm{SIN}\ \bar{\delta}_0\ \ \mathrm{COT}\ \bar{\delta}\ \ - \mathrm{COS}\ \bar{\delta}_0\ \ \mathrm{COS}(\alpha_0 - \alpha)$$

Figure 2. AAPS Geometry

(1) $$\alpha_0 = \alpha_Z + \dot{\alpha}\, t$$

(2) $$\mathrm{SIN}\,[\alpha_0 - \alpha] = \frac{-BC \pm A\sqrt{A^2 + B^2 - C^2}}{A^2 + B^2} = X$$

(3) $$t = \frac{\alpha_Z + \mathrm{SIN}^{-1}\ X}{\dot{\alpha}}$$

Figure 3

As the computed solution converges towards its final value, the predicted transits approach the measured ones. This permits the rejection limits to be successively reduced, thereby achieving finer resolution in the identification process and perhaps admitting previously ambiguous data to the solution.

How do we design an instrument which will use the theory to the best possible advantage? In addition, the position must be computed in real time excluding the effects of polar motion and any other unknown time off-set errors. Using the constraints previously discussed, the AAPS has evolved into a system containing two units, the sensor head, which weighs about 25 kilograms, and the control unit, which weighs about 15 kilograms. (Fig. 4)

The sensor head is a single package composed of: optical system, four photomultiplier detectors, filter and detection electronics, level control system, and reversal mechanism. (Fig. 5)

The design of the optical system was considered to be the most important, since analysis showed that it had to maintain an image size under 10 arc sec over a 23° field of view to meet the system accuracy and data rate requirements. That such a system has to operate over a temperature range of -35°C to +50°C without the luxury of field focusing posed an additional major problem. The optical concept chosen was a two-mirror concentric configuration. Concentric systems have all, or most, of their element radii concentric to a common point at the aperture. This means inherent freedom from astigmatism, coma, and distortion. Spherical abberration is minimized through the appropriate placement of stops and the ratio of primary to secondary mirror radii.

Optimum optical characteristics were derived from many computer simulation runs using different fields of view, focal lengths, number of slits, number of photo-multipliers, and star patterns over a 140° latitude range (70°S to 70°N). The final criteria were: sensor physical size, star transit data rate, and accuracy. The resulting optical characteristics are now shown. (Fig. 6)

The optical system is fairly unique. Thermal stability of the optical dimensions is achieved by employing a unique structural design. (Fig. 7) All structural members as well as the primary and secondary mirrors are fabricated from CER-VIT, a glass ceramic substance whose temperature coefficient is an order of magnitude smaller than that of INVAR. After considering a number of different configurations for the mirror supports, it was decided that a single major piece presented the fewest overall problems.

The AAPS level system keeps the sensor in the vertical and the top portion of the secondary mirror contains a level sensor. (Fig. 8) The base of the optical system rests on the releveling drivers. The electronics for the level system is

Figure 4

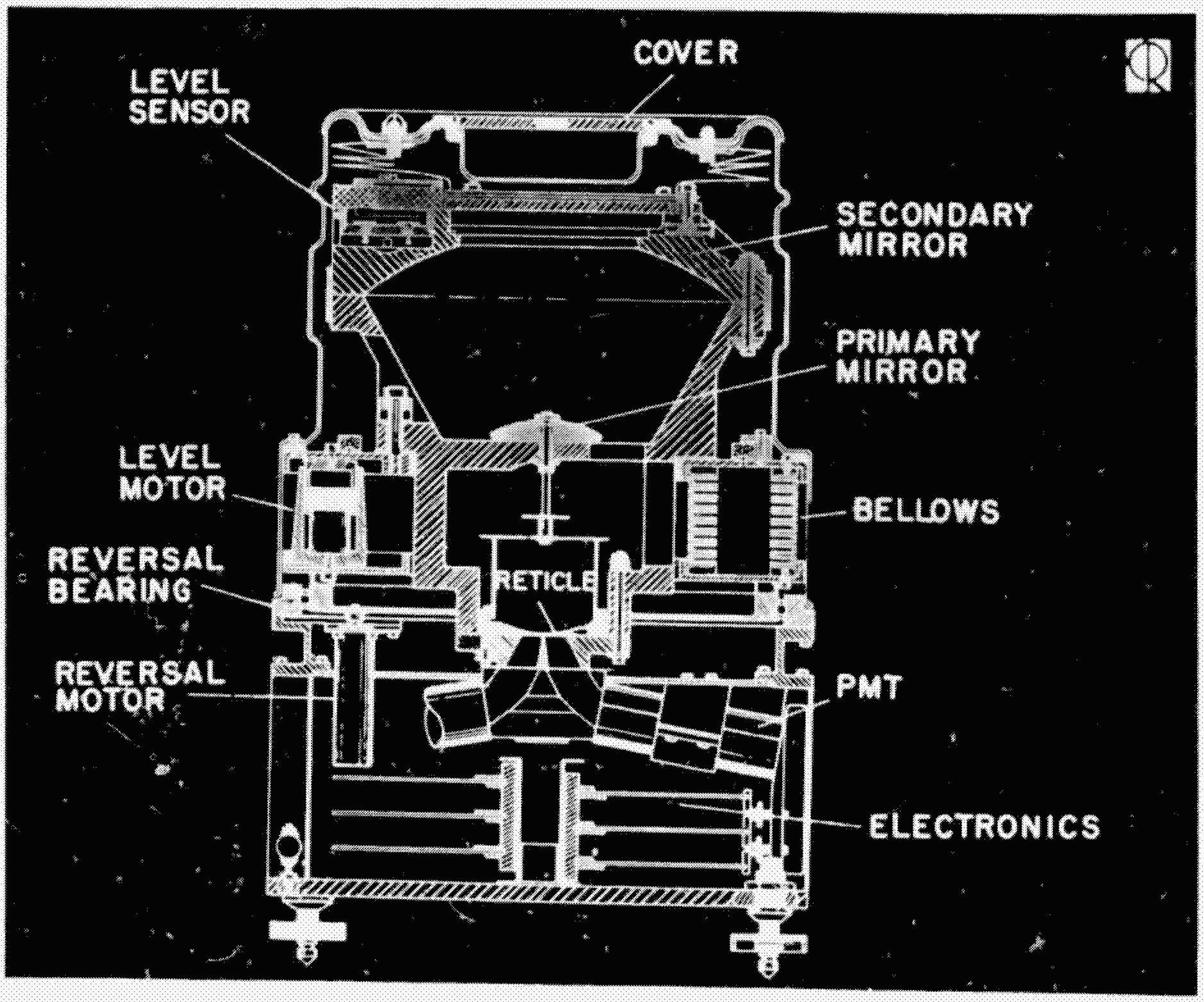


Figure 5

(1) FIELD OF VIEW :	23°
(2) FOCAL LENGTH :	5.58 CM
(3) APERTURE DIAMETER :	3 CM (CLEAR)
(4) OPTICS :	f/1.6
(5) IMAGE DIAMETER :	10 ARC SECONDS

Figure 6. Optical System Characteristics

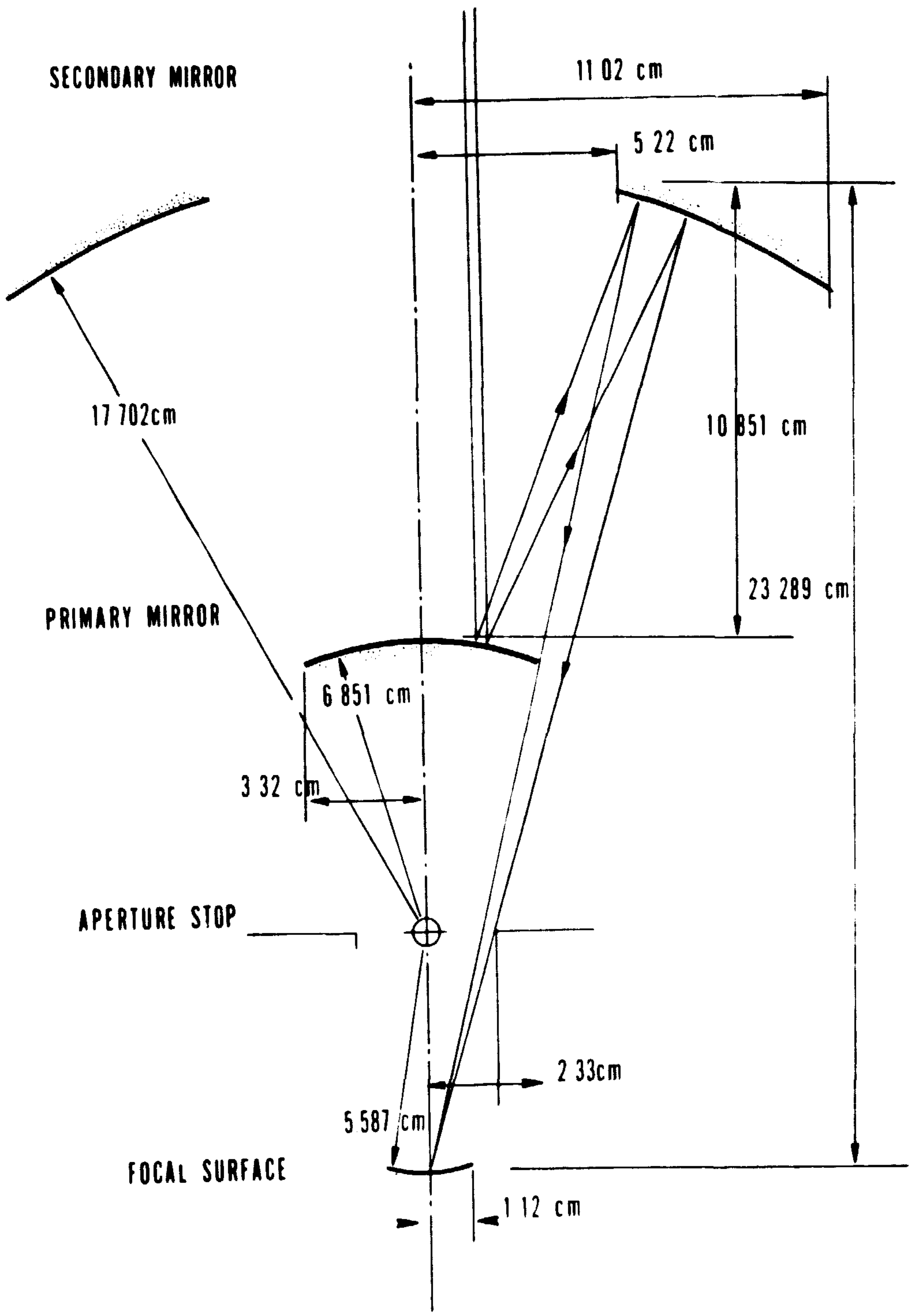
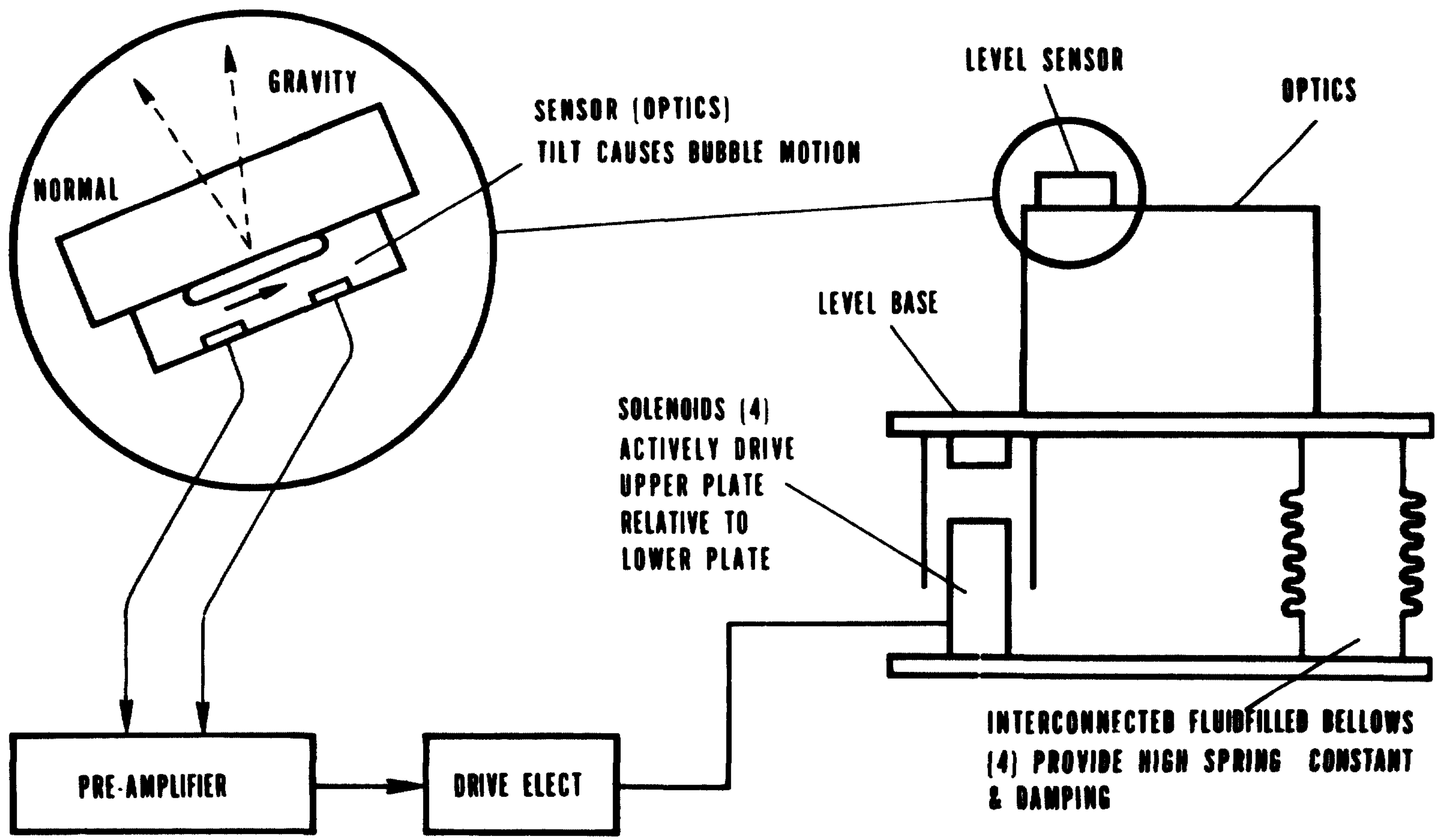

SECONDARY MIRROR
11 02 cm
5 22 cm
17 702cm
10 851 cm
23 289 cm
PRIMARY MIRROR
6 851 cm
3 32 cm
APERTURE STOP
2 33cm
5 587 cm
FOCAL SURFACE
1 12 cm

Figure 7



LEVEL SUBSYSTEM

Figure 8

located in the control unit. The level system will maintain the concentric mirror optical system within ± 0.1 arc sec of the vertical. Initially, the sensor head must be leveled by hand to within 50 arc sec to ensure proper operation of the level system in the automatic mode.

When a stellar image crosses a slit, a signal is generated by one of the photomultiplier tubes. This analog signal is filtered, differentiated, and sent through a zero-crossing detector. The output of the zero-crossing detector is a logic level signal which is sent to the control unit and interrupts the computer. The computer then reads the clock to determine the time of transit. Computations then proceed as previously described.

Data are taken for one hour and then the sensor head is reversed and data are taken for another hour. The two positions are then combined into one position. The sequence is repeated and final position computed. The computer controls the system throughout the observing and computing period, requiring the operator only to monitor progress.

The control unit consists of the computer, timing equipment and electronics for the level system.

The computer selected for the AAPS is the Control Data 469 computer which weighs about 1 kilogram, occupies less than 47 cubic inches, and requires only 12 watts of power. It has an 8,192 word (16 bits), non-destruct readout.

A precision clock is also contained in the control unit and consists of a crystal oscillator and the necessary divider circuits to maintain time for the system.

The AAPS requires a self-contained precision time source traceable to any of the internationally adopted Universal Time Scales. The overall requirement is that star transits must be timed with an error not to exceed two milliseconds. This is based on the reasoning that time errors are systematic, that systematic errors are to be kept down to 0.03 arc second.

The clock is set initially and operates continuously from an external power source supplemented during periods of transport by its own internal battery pack. The counter portion is capable of containing 1×10^{11} milliseconds.

It is impractical and fraught with error to require a time correction applicable to each transit. Thus, we require that the frequency remain sufficiently stable so that a drift of not more than two milliseconds will occur during a two-hour site sequence. This represents a maximum allowable frequency offset attributable to environment (especially temperature) and aging effects.

To remain within this amount of offset over a period of one hundred days requires a maximum allowable frequency offset of 2.8×10^{-7} per two hours or 3.4×10^{-6} per day.

The aging rate will require frequency adjustments once every 600 days. Also, temperature, shock and vibration, and voltage variation all produce frequency shifts that are an order of magnitude below that needed.

Oscillator outputs are counted directly in the BCD-coded hexa-decimal system. Setting is accomplished by disabling the normal count sequence and manually stepping seconds, minutes, hours, and days separately to their desired values. The normal sequence is then initiated when the set time is as near as possible to the same instant as received via a standard time service broadcast, which can be manually executed to about 0.1 second with relative ease.

Final synchronization is accomplished by the well-known method of displaying the received time service, one PPS "tick", on a portable oscilloscope, whose sweep is triggered by the one PPS clock output. The clock is advanced or retarded in one millisecond steps until the "tick" is occurring just a few milliseconds after sweep start. This delay can then easily be noted to a fraction of a millisecond. Frequency adjustment will be accomplished with an indicating knob (10 turn pot) which has been coarsely calibrated.

To avoid interpolating time corrections to the site time, the oscillator frequency should always be maintained within one part in 10^8. (This implies a 24-hour drift of less than one millisecond.) This is accomplished by recording the displayed delays on the scope on a regular basis. The mean slope drawn through about one week's data gives the frequency offset and averages through propagation delay variations. If the frequency is correspondingly adjusted, no difficulty should be experienced in maintaining the clock always within one or two milliseconds of the received time.

It is very important that the clock be powered at all times and that switching transients do not introduce count errors.

The current AAPS prototypes have two types of power source, lead acid batteries and Nicad batteries. The voltage, wattage and ampere hour requirements are shown here. (Fig. 9)

RESULTS

Now, let's discuss test results achieved with the AAPS to date. A limited amount of contractor test data was divided into five first order positions spanning seven nights during July 1973. A first order position consists of four sets, two in the

VOLTAGE	24V - 32V DC (Single Input)
WATTAGE	30 WATTS
AMPERE-HOURS	15 AMP-HRS

Figure 9. AAPS Power Requirements

direct orientation and two in the reverse orientation. The results shown should be used with caution due to experimental techniques used by the contractor. As shown in Table 1, we have the AAPS derived astronomic latitude and longitude differences from a standard position established by conventional Wild T-4 observations.

We show the horizontal displacement of each of the five first order positions from the standard position. (Fig. 10) Estimated standard errors of an AAPS first order position in latitude and longitude are ±34.3 meters and ±5.5 meters, as depicted with the dashed interval. The hashered area is contract goal.

Table 1

AAPS First Order Astronomic Results at Station Faribault

FO NR	DATE	LATITUDE DIFFERENCE(N)		LONGITUDE DIFFERENCE (W)		DEGREES OF FREEDOM
		ARC SECONDS	METERS	ARC SECONDS	METERS	
1	JULY 4, 1973	+1.06	+32.7	-0.04	-0.9	073
2	JULY 5, 6, 1973	+0.39	+12.0	+0.32	+7.1	080
3	JULY 6, 7, 1973	-0.35	-10.8	-0.10	-2.2	126
4	JULY 7, 1973	-1.40	-43.2	+0.23	+5.1	101
5	JULY 10, 1973	+0.78	+24.1	-0.19	-4.2	095

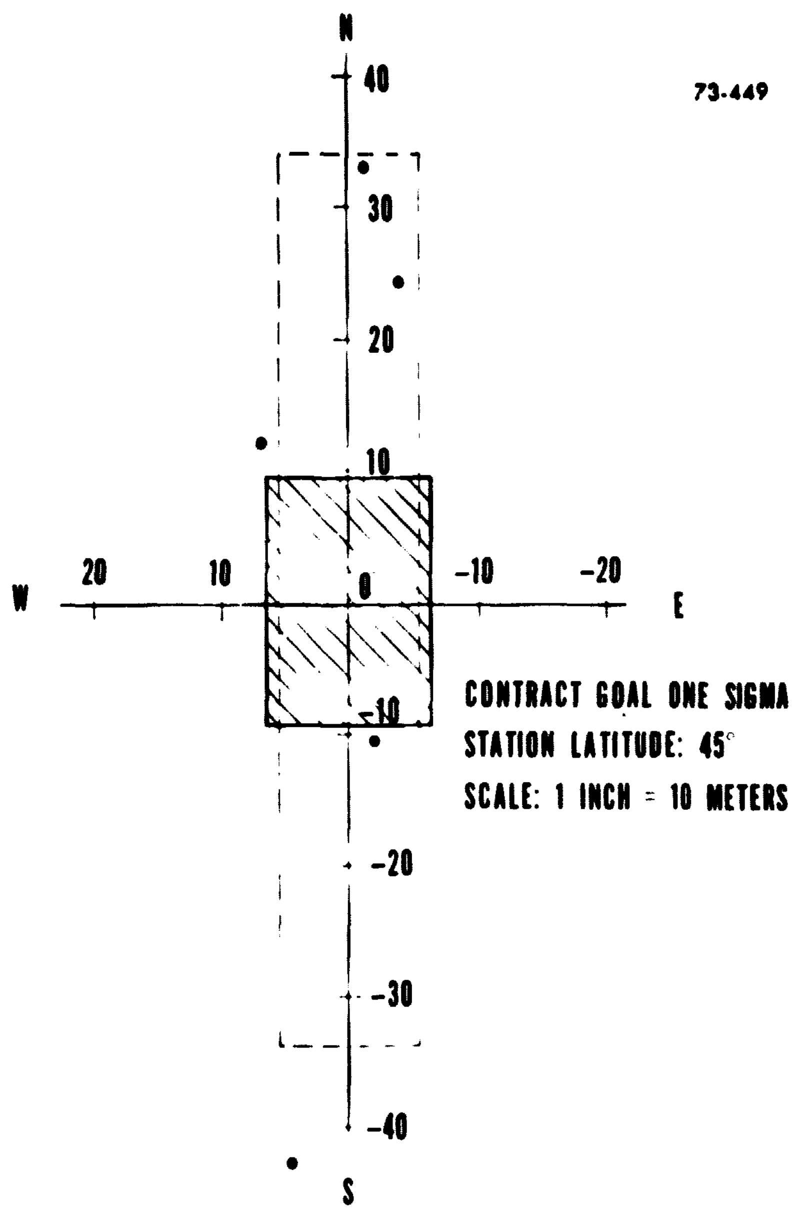


Figure 10. AAPS First Order Position Difference

The latitude displacement from the standard as a function of observation time is found in Figure 11 where the relationship between number of sets to time is one per half an hour. The longitude displacement is also covered in the same manner. (Fig. 12)

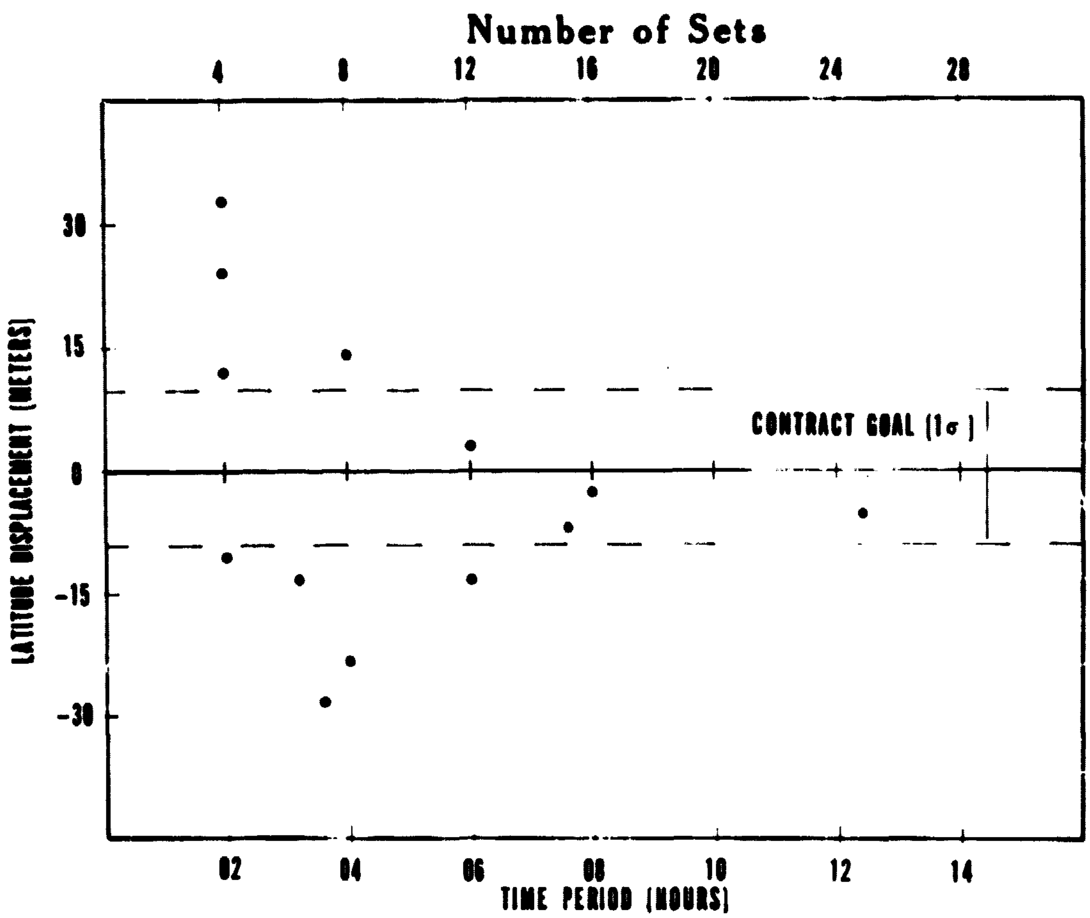


Figure 11. AAPS Accuracy Relative to a Standard

Some of the problems encountered in the AAPS R&D effort surfaced late in the program during environmental testing. Level sensors failed at high temperature (130°C) and fluid leaked through the optics onto the reticle and destroyed it. New sensors were obtained and again the failure occurred. Investigation revealed that temperature shock (rapid rise or fall) caused stress to build up due to non-uniform expansion characteristics of the quartz glass vial and the cup. Addition of a passive thermal blanket around the level sensor eliminated the problem. Environmental testing also revealed that some of the photomultiplier tubes were saturating the amplifiers by dark current rise with temperature cutting off at about 100°C. Since most of the photomultiplier tubes continued to operate up to the required 120°C, the problem can be solved by purchase of selected photo-multiplier tubes to replace those that saturate at lower temperatures. The fact that the 120° temperatures will seldom be encountered in field operations indicates

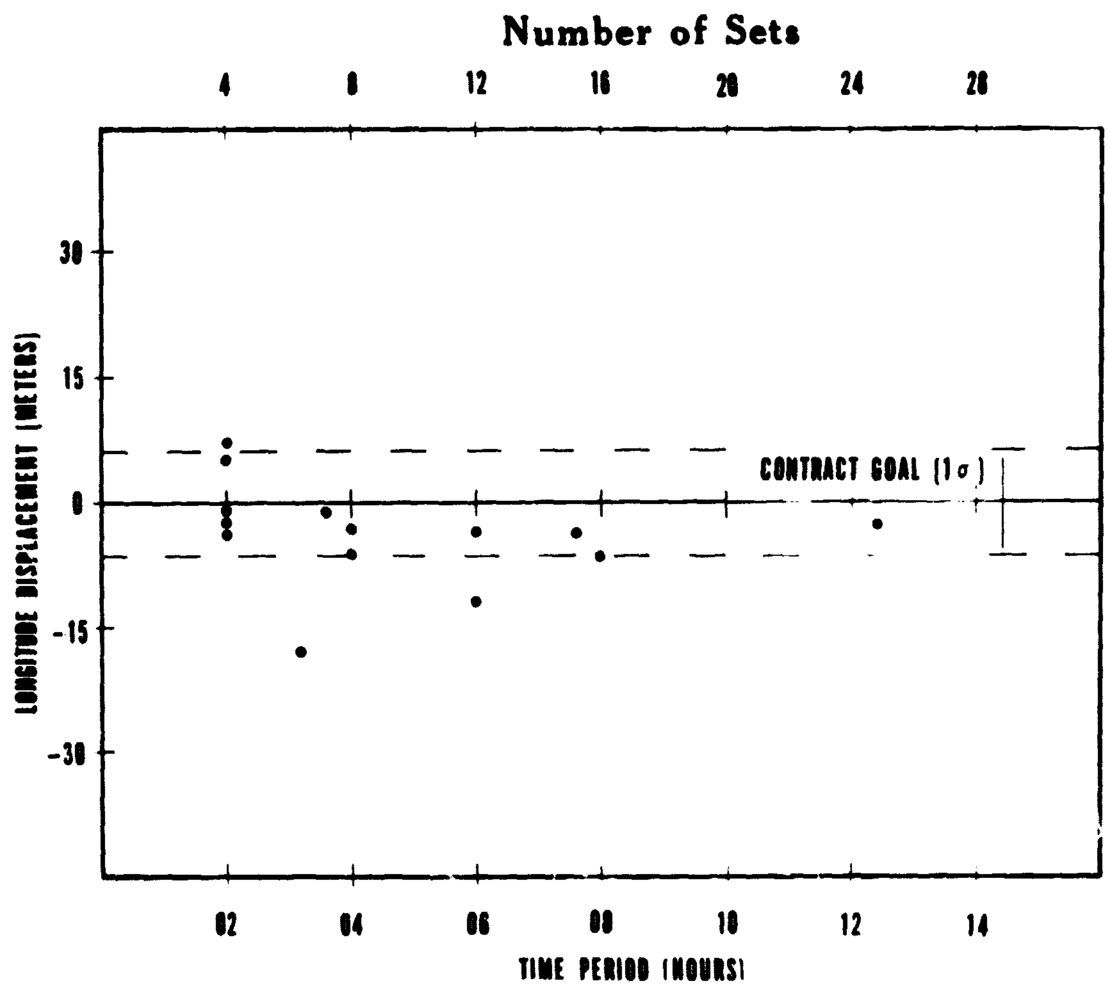


Figure 12. AAPS Accuracy Relative to a Standard

that the severity of the problem is low. Preconditioning the sensor head to the operational environment prior to operation will be made a part of the field operational procedure when unusually high temperatures are expected. A problem was encountered in fabricating the slit reticle to specifications for angular displacement and offset from the center. This was solved by computing slit azimuth and offset from field observations data and using the calibration data in the data reduction program as correction information.

OPERATIONAL TEST AND EVALUATION

The operational test and evaluation program for the AAPS calls for the two AAPS prototypes to be deployed on operational test sites to evaluate the field performance of the systems under operational conditions by field survey personnel.

Pre-acceptance tests have just begun at F. E. Warren AFB, Wyoming, where several high order conventional astro position stations are available. AAPS observations will continue at these stations between deployments to the "other" operational test sites, and after the operational test is concluded.

The data shown here (Table 2) are recent samples of test data collected at F. E. Warren AFB during November 1973. The corrected mean astronomic coordinates differ only 0″20 in longitude and 0″04 in latitude from conventional coordinates. This vividly demonstrates the potential of automated astronomic positioning.

We will deploy the prototypes for operational tests to Eielson AFB, Alaska (64°N, Subzero), Richmond, Florida (25°N), and the Canal Zone (9°N). A combination operational test and demonstration will be accomplished at the Naval Observatory in Washington next spring. A Southern Hemisphere test station is still a possibility but no firm location has been defined.

Table 2

Recent Test Data—AAPS Prototypes
10-11 November—F. E. Warren AFB, Wyoming

SET No.	LONGITUDE (W)	LATITUDE (N)
1	104° 51′ 57″.33	41° 08′ 05″.82
2	57″.05	04″.98
3	58″.70	05 .76
4	57″.86	05″.20
MEAN	57″.53	05 .44
UT1-UTC CORRECTION	-2″.25	0
SEA LEVEL CORRECTION	0	- ″.30
	55″.28	05″.14
CONVENTIONAL 1st ORDER POSITION	55″.48	05″.10

CONCLUSIONS AND FUTURE POSSIBILITIES

In summary, the desired AAPS accuracy and time requirement for the field observation (dependent on required accuracy) have not been achieved during contractor testing. The prototypes have recently demonstrated the potential for acquiring 0.3 arc sec astronomic position accuracy. The unit cost of the prototypes has been relatively high. This will be offset, however, by reduced training costs for the astro observing team and the rapid data collection rate of the sensor. One astro team should be able to accomplish at least one first order astro position observation on a clear night.

Possible future engineering modifications and applications of the AAPS are:

1. The AAPS can be modified to provide astro azimuth readout and transfer capability. AAPS generated azimuths could then be transferred to required lines by using an autocolimating theodolite.

2. Better star right ascension and declination data can be obtained by using AAPS observations at fixed locations. This would improve star catalog data and, ultimately, the accuracy of astronomic positions.

3. The AAPS could be used at current or new observatories for monitoring time and latitude.

4. The AAPS can be used for providing astronomic positions to improve and increase the information necessary for determining geoid heights or the difference in height between the geoid and the ellipsoid (a mathematical reference spheroid).

5. In the same manner, the AAPS will provide a more rapid means of accomplishing astro positions in conjunction with geodetic positions in determining astro geodetic deflections, or the angular difference between the plumb line and the normal to the reference spheroid.

6. The development of the AAPS should result in more available and less expensive astronomic position data in current or future geodetic networks. The astro positions will result in more deflection data for more rigorous adjustments in three dimensions.

There is no doubt this revolutionary approach to astronomic positioning will disclose applications not yet conceived as well as provide instrumentation capable of time dependent accuracies in the one-third arc sec region.

I gladly acknowledge the assistance of Mr. Charles Whelan of our Geodetic Survey Squadron, Mr. Donald Murray of our Aerospace Center, and Major Beers of our Headquarters in the formation of this paper. It is my hope that they will be able to participate in the next PTTI Planning Meeting and discuss specific results based on field operational experience of the AAPS.

QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

(No response.)

N75 11282

LOW COST AUTOMATED PRECISE TIME MEASUREMENT SYSTEM

A. Alpert
P. Liposchak
Newark Air Force Station

ABSTRACT

The Aerospace Guidance & Metrology Center (AGMC) has the responsibility for the dissemination of Precise Time and Time Interval (PTTI) to Air Force timing systems requiring microsecond time. In order to maintain traceability to the USNO Master Clock in Washington D.C., and accomplish efficient logging of time and frequency data on individual precision clocks, a simple automatic means of acquiring precise time has been devised.

The Automatic Time Interval Measurement System (ATIMS) consists of a mini-computer (8K Memory), teletype terminal, electronic counter, Loran C receiver, time base generator and locally-manufactured relay matrix panel.

During the measurement process, the computer controls the relay matrix which selects for comparison 13 atomic clocks against a reference clock and the reference versus Loran C. Because portable clocks are scheduled for periodical time synchronization trips, the computer performs a status check on the availability of each clock before attempting to read its time. Any clock not available is noted as such and no comparison is made. After all clocks are compared, the data is reported on the teletype. Only data and clock status at the 1800 UT reading are retained. ATIMS then becomes dormant until the next automatically scheduled execution period.

At any time during automatic operation, manual mode may be employed. This permits the operator to control the execution of ATIMS and thereby measure all clocks at his discretion. Also at this time, Loran C phase values for a particular day can be entered via the teletype. The times of all available clocks, relative to USNO, for that day (up to 10 days past) are then computed and reported on the teletype. When this process is completed, the operator then reschedules ATIMS so that operation is cued by the system clock.

Through use of the system teletype, the operator is able to set the system clock (hours, minutes and seconds), examine and/or modify all clock data and constants, and set measurement intervals. This is done in a conversational manner. A logic flow diagram, system schematic, source listing and software components will be included in the paper.

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INTRODUCTION

The Aerospace Guidance and Metrology Center (AGMC) has the responsibility for the dissemination of Precise Time and Time Interval (PTTI) to Air Force timing systems requiring microsecond synchronization. In order to maintain traceability to the USNO Master Clock in Washington D. C. and accomplish efficient data logging of individual precision clocks, a simple automatic means of acquiring precise time has been devised.

To appreciate the magnitude of the data collected, the AGMC timing teams now visit over 36 sites every 6 months. Most Air Force systems have installed a parallel system consisting of 2 or more clocks per site. Raw data retrieved by the teams include initial and final frequency offsets, "C" field or Zeeman calibrations, pulse characteristics, and 6 month maintenance where apropos.

Before the installation of the Automatic Time Measurement System (ATIMS), data logging of portable clocks and the laboratory standards that make up the AF which is described below could not readily be made on the weekend or after normal working hours. In addition, LORAN C phase information related to 1800 UT and critical for steerage of the reference standards, required that personnel be "on hand". Another important feature of the ATMS is its ability to make repetitive measurements at scheduled times. This is advantageous for recording warm-up time of oscillators and time drift of less stable quartz crystal clocks.

The Automatic Time Measurement System consists of a minicomputer, teletype terminal, electronic counter, LORAN C receiver, time base generator and locally manufactured relay matrix panel. The physical location and configuration of these items in the PTTI laboratory are shown in Figures 1 and 2.

The Air Force Master Clock consists of five cesium beam oscillators (HP 5060A) and dividers (915 Timing System Incorporated) that provide a basic stability and parallel reliability to the timing system. Steering of the AF Master Clock is accomplished by phase tracking the US Coast Guard LORAN C broadcast originating at Cape Fear, North Carolina. Phase information is obtained from an automatic tracking LORAN C receiver (Aerospace Research Incorporated 504) that has a built-in epoch monitor. The epoch monitor compensates for the offset in the specific pulse repetition rate (99,300 microseconds) of the Cape Fear transmission and produces a time of coincidence (TOC) pulse every second. The epoch monitor was an important ingredient in the Automatic Measurement System because it provides direct readout of the propagation delay on the counter. This makes for ease of storage and computation by the computer without additional programming steps to mask unwanted numbers.

Basically, data acquisition and manipulation of data by the computer occurs in the same sequence as previous manual operation. Daily at 1800 UT the TOC pulse from the receiver is compared via an electronic counter (HP 5245L) to a reference clock (usually one of the five (5) clocks that make up the AF Master Clock). The reference standard is then compared against the other working standards and portable clocks. At some later point in time, phase corrections for Cape Fear are received by routine Navy TWX from the USNO. These corrections are added algebraically to the previous logged data to obtain a time drift history.

SYSTEM DESCRIPTION

The Central Processing Unit (CPU) shown in the Figure 3 is the HP 2100A Minicomputer. The Time Base Generator (TBG), Teletype (TTY), Counter and Relay Output Register input/output devices are plug-in interface cards that are located inside the HP 2100A. The Minicomputer has an 8K magnetic core at the present time, but can be expanded up to 32K maximum. Of the 8K available memory, approximately 5K words are used for manufacturer software, including DACE (Data Acquisition Control Executive), library routines and drivers. Of the remaining 3K memory, our User program incorporates 1800 words (decimal). While the block labeled CPU indicates 4 subsystems or interface cards, a total of 14 interface slots are available inside the HP 2100A to control peripheral devices.

The TBG measures real time intervals in decade steps from 0.1 ms to 1000 seconds. The 100 kHz crystal controlled oscillator used as the frequency standard for the Time Base Generator allows generation of timing signals to within 1/2 second per 24 hour day. The Time Base Generator is used to provide timing pulses to the software counter that can be initialized to a real time clock. The software program that allows scheduling data acquisition at preset times is called DACE and will be discussed in more detail.

The TTY interface card provides control of the TTY and allows the operator to examine and/or modify constants and clock data. The time of day, scheduling of clock readings and manual operation is also entered via the TTY.

The Counter interface card enables the Counter to take the clock readings. After the CPU directs the Counter interface card to take a reading, a sub routine called "EPOCH SELECT" drives the relay register card which in turn closes various coaxial relays supplying the START-STOP signals to an Electronic Counter. A time delay of 200 milliseconds is provided within the subroutine to permit contact bounce to subside. Another User written subroutine, called "TIME OUT", checks the Electronic Counter for a start signal as each clock pulse is selected by the relay register. Each clock is permitted a maximum of 10 seconds to supply a start signal. If a clock pulse is present within the 10 sec·nd interval, the computer stores a "1" and a "2" if not present. This is called the status check of the clocks and the ones and the twos for a given day's readings can be printed out upon operator's request.

The four coaxial relays shown are Amphenol 50 ohm 1P 6T. The relays are 26 VDC with a maximum operate and release time of 20 ms.

As the relays are activated, each clock pulse in turn gates the start input of the Counter. The reference clock pulse is normally switched through the 4th relay (right hand side of slide) into the STOP input of the Counter. Because the last reading is the LORAN C delayed signal, the reference clock is switched to the start input and the LORAN pulse to the STOP input of the Electronic Counter.

SYSTEM SOFTWARE

The software for the Automated Time Measurement System consists of HP supplied program called DACE and the User Written Program. The User Written Program selects clocks to be read, checks status of clocks and calls upon DACE to automatically schedule measurements.

The Data Acquisition and Control Executive (DACE) program shown in Figure 4 performs specified tasks at specified intervals. In other words, DACE in conjunction with the Time Base Generator can take a clock reading every hour and relate it to time of day. The DACE also allows the operator to examine and/or modify the scheduled time intervals, starting times, clock data and constants such as LORAN C propagation delay without interruption of the program. The scheduled clock readings (at 1800 UT) are done in automatic mode operation. DACE also allows the operator to check that clock readings in automatic mode will perform as planned. This is done by executing or stepping through the program in the manual mode.

Every 10 milliseconds, the Time Base Generator interrups and increments the system clock. If present time matches or coincides with the next scheduled time, the task is put into operation. If not, the task remains dormant.

The maximum time interval that can be scheduled is 9 hours, 6 minutes, 6 seconds (32767 seconds). Therefore, 8 hour interval (submultiple of 24 hours) was chosen. Clock comparisons are printed out every 8 hours and the User Written Program checks for the 1800 reading.

In automatic mode, several operations are accomplished by the User Written Program (see Figure 5). If the time of day coincides with the 1800 UT ±2 minute window, the computer stores the clock readings in a floating point array. This array is associated with the last digit of the Julian date. Up to 10 days readings can be stored, recalled at a later time and corrected to the USNO. Also stored are the status or availability of the clocks at the time of measurement. The status which is reported by 1 for available and 2 for not available, is also stored up until 10 days in a linear integer array. The reason for the status check is that clock readings are corrected by recalling from memory a group (array) of data related to a Julian date. The status check reveals whether the clock was "on hand" that day or 10 days previous, since clock readings are replaced every 10 days.

In Manual mode, the TTY asks whether EPOCH or LORAN C (LC) phase measurements? By typing a number other than one, the clocks are compared to the reference standard only. The TTY then prints out clock # vs. AGMC reference. Entering 1 requests LC phase information. The TTY then asks for the Julian date and the USNO phase correction. The clocks versus USNO are then printed out on the TTY.

AUTO: Tasks are automatically executed at intervals specified.

EXECUTE TASK N: Task may be called up for manual execution.

SET TIME OF DAY: Time of day may be entered. The executive program will keep a 24 hour digital clock to within 0.5 second/day.

RELEASE: Parts of the executive program may be released to the output buffer. This provides additional memory locations for storing outdata.

TASK TIMES: Interval and phase times are entered by the operator. For instance, Interval = 8:00 and Phase = 0:0:15.

TASK CONSTANTS: Change clock data, replace lost data, change LORAN C delay, etc.

ENABLE EXAMINE: Provides option of the examination of current values before new values of times and/or constants are entered.

TTY/PHOTOREADER: Provides option of entering new task times and constants through TTY or photo reader.

SUMMARY

This ATMS is a means of automatic measurement, collection and correction of the epoch times of the primary standard and portable clocks, with a minimum of laboratory personnel intervention. Measurement can be set to execute at prescribed times of the day with only those measurements at a selected time of the day being stored in the computer memory.

Manual operation is provided so that laboratory personnel may check past data, (Maximum of 10 days) relative to the USNO master clock.

The collection of data will occur only when the time of automatic execution falls within a time window, the hours, minutes, and seconds parameters of the integer array. Outside this window, execution is exactly the same as those measurements in the manual mode where the clocks are read, not stored or reported on the teletype.

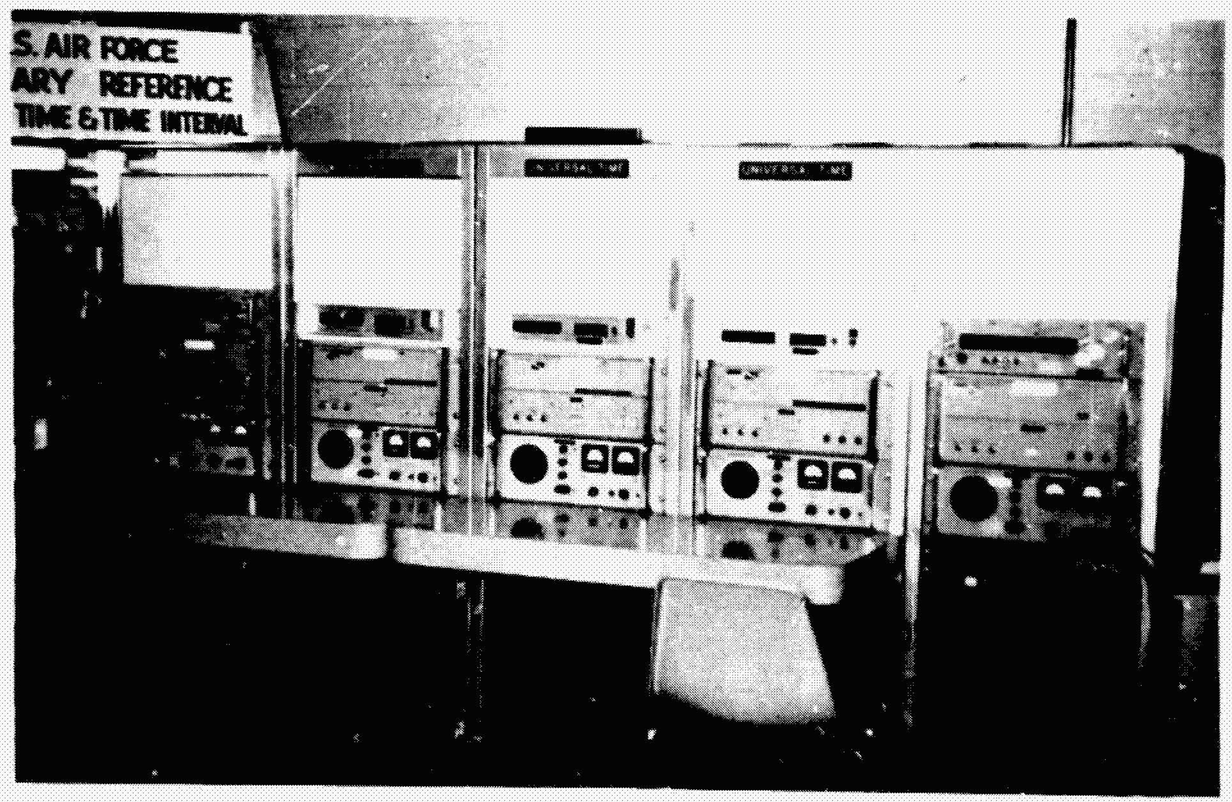

Figure 1. USAF Master Clock

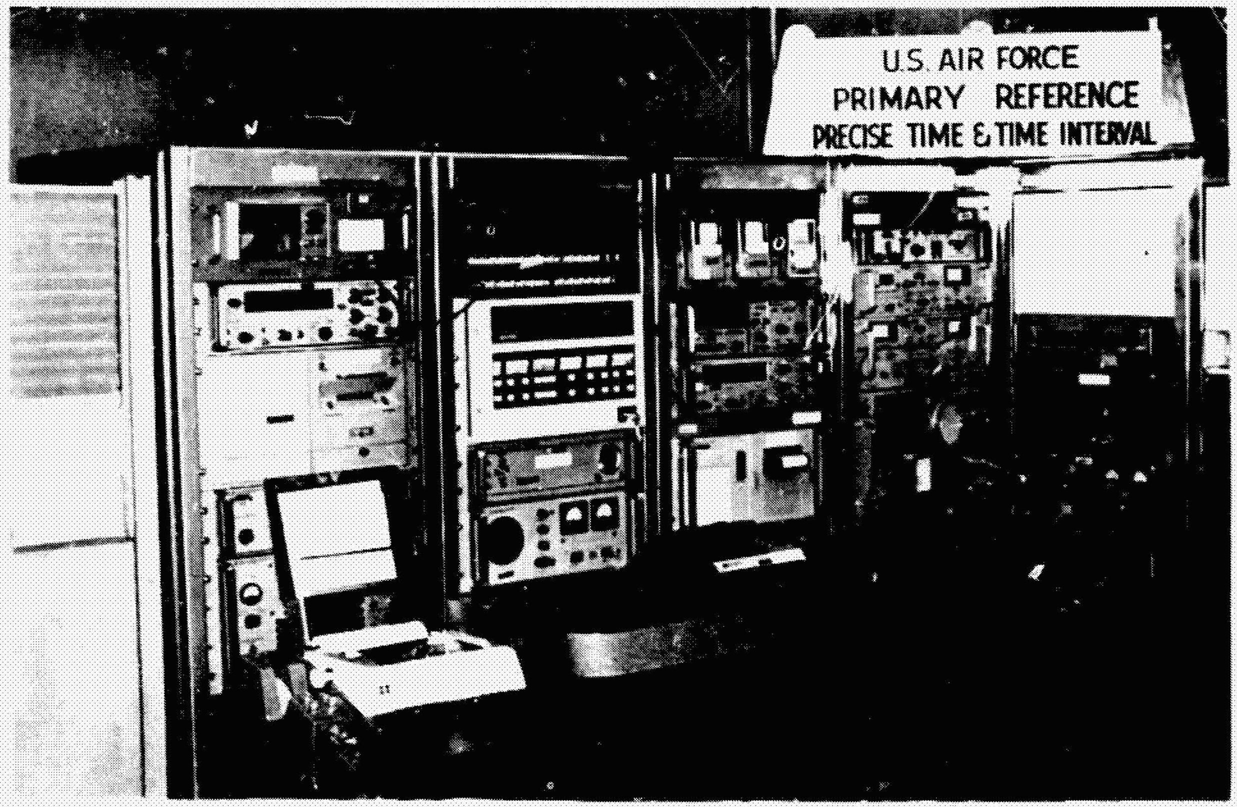

Figure 2. Computer, TTY, and Relay Panel

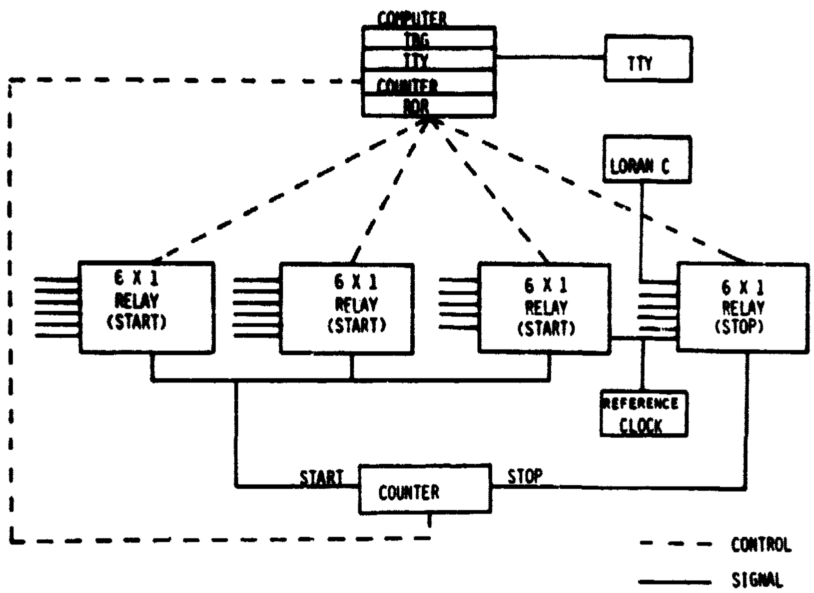

Figure 3. Automatic Time Measurement System

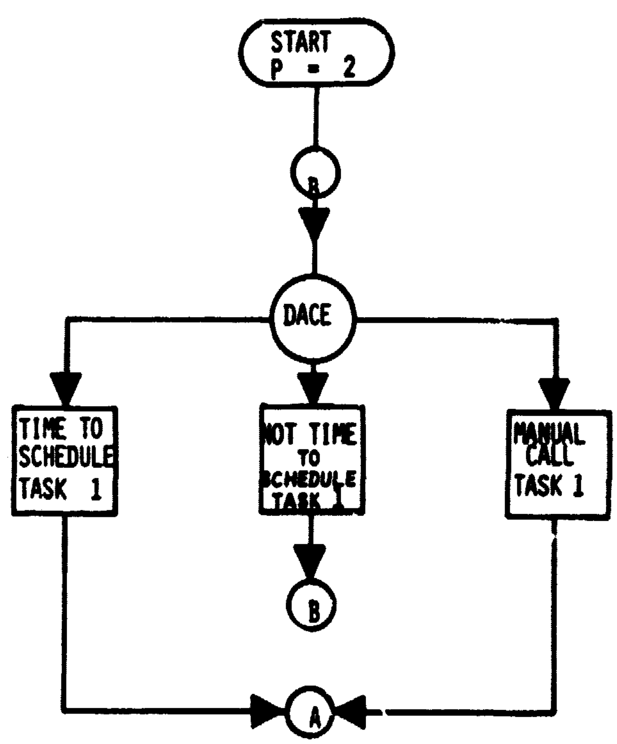

Figure 4. General Logic Flow Diagram

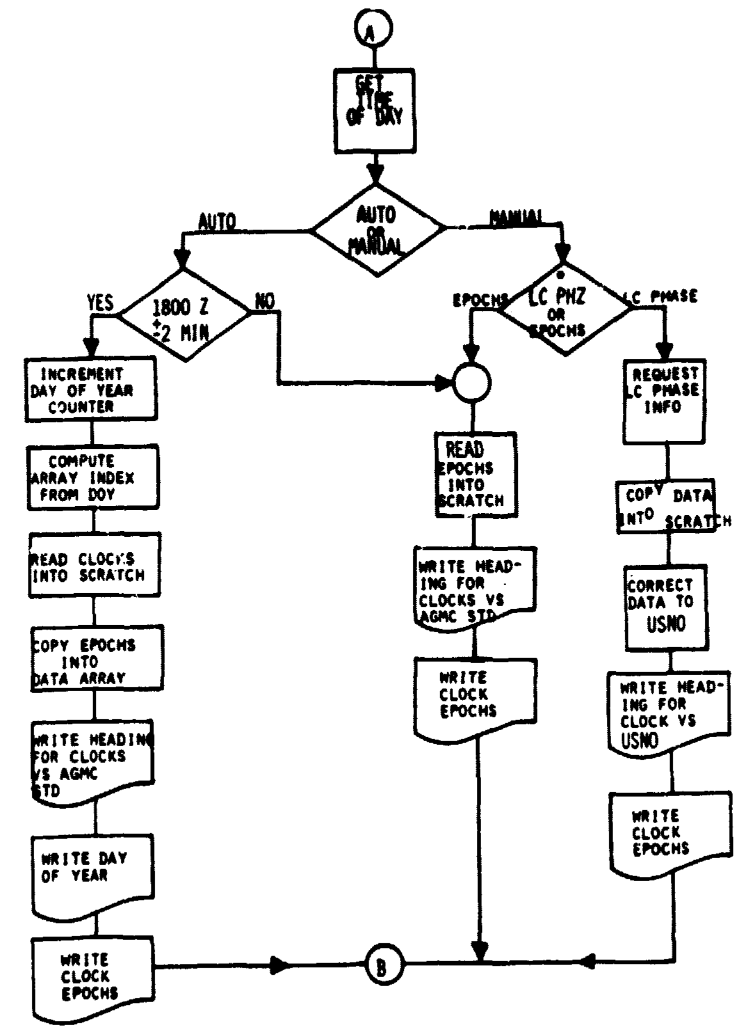

Figure 5. General Logic Flow Diagram (Cont'd.)

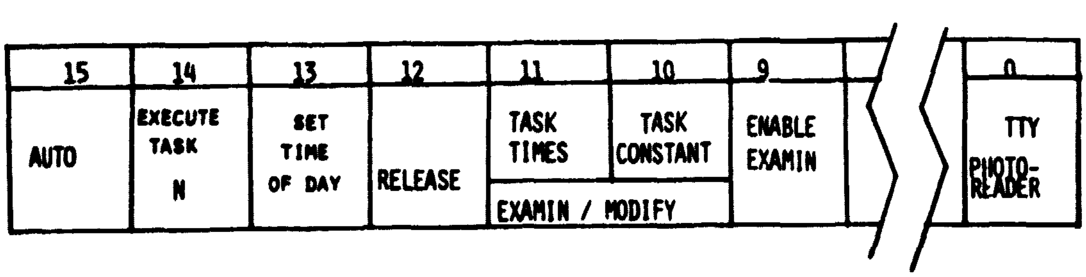

Figure 6. HP 2100 A Program Switches

QUESTION AND ANSWER PERIOD

MR. ALPERT:

Any questions?

(No response.)

MR. CHI:

That was a very good paper.

N75 11282

PRECISE TIMING CORRELATION IN TELEMETRY RECORDING AND PROCESSING SYSTEMS

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F. L. Matthews
ITT Federal Electric Corporation
Vandenberg Air Force Base

ABSTRACT

Independent PCM telemetry data signals received from missiles must be correlated to within ±100 microseconds for comparison with radar data. Tests have been conducted at the Space and Missile Test Center (SAMTEC), Vandenberg Air Force Base, California, to determine RF antenna receiving system delays; delays associated with wideband analog tape recorders used in the recording, dubbing and repdocuing processes; and uncertainties associated with computer processed time tag data. Several methods used in the recording of timeing are evaluated. Timing error versus tape recorder head alignment is plotted. Tape recorder phase lead effects on time code formats and data are given. The time bias associated with computers processing of data is presented. Sources of timing errors and the calibration and operating techniques available to minimize these errors are discussed. Through the application of a special time tagging technique, the cumulative timing bias from all sources is determined and the bias removed from final data. Conclusions from test data show that relative time differences in receiving, recording, playback and processing of two telemetry links can be accomplished with a ±4 microseconds accuracy. In addition, the absolute time tag error (with respect to UTC) can be reduced to less than 15 μsec. This investigation is believed to be the first attempt to identify the individual error contributions within the telemetry system and to describe the methods of error reduction and correction.

INTRODUCTION

Missiles launched from Vandenburg Air Force Base in California are tracked by systems located throughout the world. Radars provide position and velocity data in terms of range, azimuth, elevation and range rate. Telemetry stations receive information encoded and transmitted from the missile. For missiles configured with inertial guidance systems, position and velocity information in terms of X, Y, Z and $\dot{X}$, $\dot{Y}$, $\dot{Z}$ is transmitted on the telemetry link.

The continued improvement in ballistic missile performance places an ever increasing accuracy requirement on position and velocity data. When sensor performance capabilities do not meet the accuracy requirements directly, analysts use multistation solutions to refine the trajectory data. Such solutions may include inputs from widely spaced radars as well as the inertial guidance data. When merging the sources, timing offsets are particularly troublesome, as such errors propagate in a complex manner during the merging.

In order to avoid these problems, timing offsets are limited to ±100 microseconds (μ s) or less. This reduces the position error due to timing alone to less than 2.4 feet, even at escape velocity. In practical terms, this means that data received at stations throughout the world must be synchronized to within ±100 μs of UTC.

Range Timing System

The SAMTEC timing system accuracy is directly traceable to the U.S. Naval Observatory's Coordinated Universal Time (UTC). This traceability is maintained as shown in Figure 1 through the SAMTEC Precision Measurement Laboratories (PML) Precise Time Reference Station (PTRS). The PML maintains a calibration accuracy of ±2.0 μs of epoch USNO-UTC master clock. The PML has the responsibility to maintain the four SAMTEC Central Time Signal Generators (CTSG) Cesium Beam primary frequency and clock standards in calibration and synchronization with UTC (USNO). The CTSG systems are installed at Vandenberg Air Force Base and Pillar Point Air Force Station, California; Kaena Point, Oahu Island, Hawaii; and Canton Island, Phoenix Island Group. Each CTSG is equipped with dual cesium standards, frequency dividers and clocks, alarm and transfer circuitry, Inter-Range Instrumentation Group (IRIG) Time Code Generators and distribution amplifiers. At specified calibration periods, the PML transports a portable cesium "flying clock" to each CTSG to calibrate and synchronize the CTSG cesiums with UTC (USNO). Any drift in the "flying clock" is accounted for in the PML.

As shown in Figure 2, the distribution of the IRIG time code formats A, B, D, E and H and 1, 10, 100 pps and 1, 10 and 100 kpps pulses is generally accomplished over telephone plant cable pairs or a UHF radio system. The timing circuits provide radar, telemetry and other instrumentation systems with standard time code formats. Total delays at each site are then determined with a portable frequency standards and a computing counter, as shown in Figure 3.

Radar Synchronization

As shown in Figure 4, the master timing pulse at each radar station is routed from the timing center to the radar area and then to radar equipment where interrogate pulses are initiated. It is these 20 pps pulses which actually "freeze"

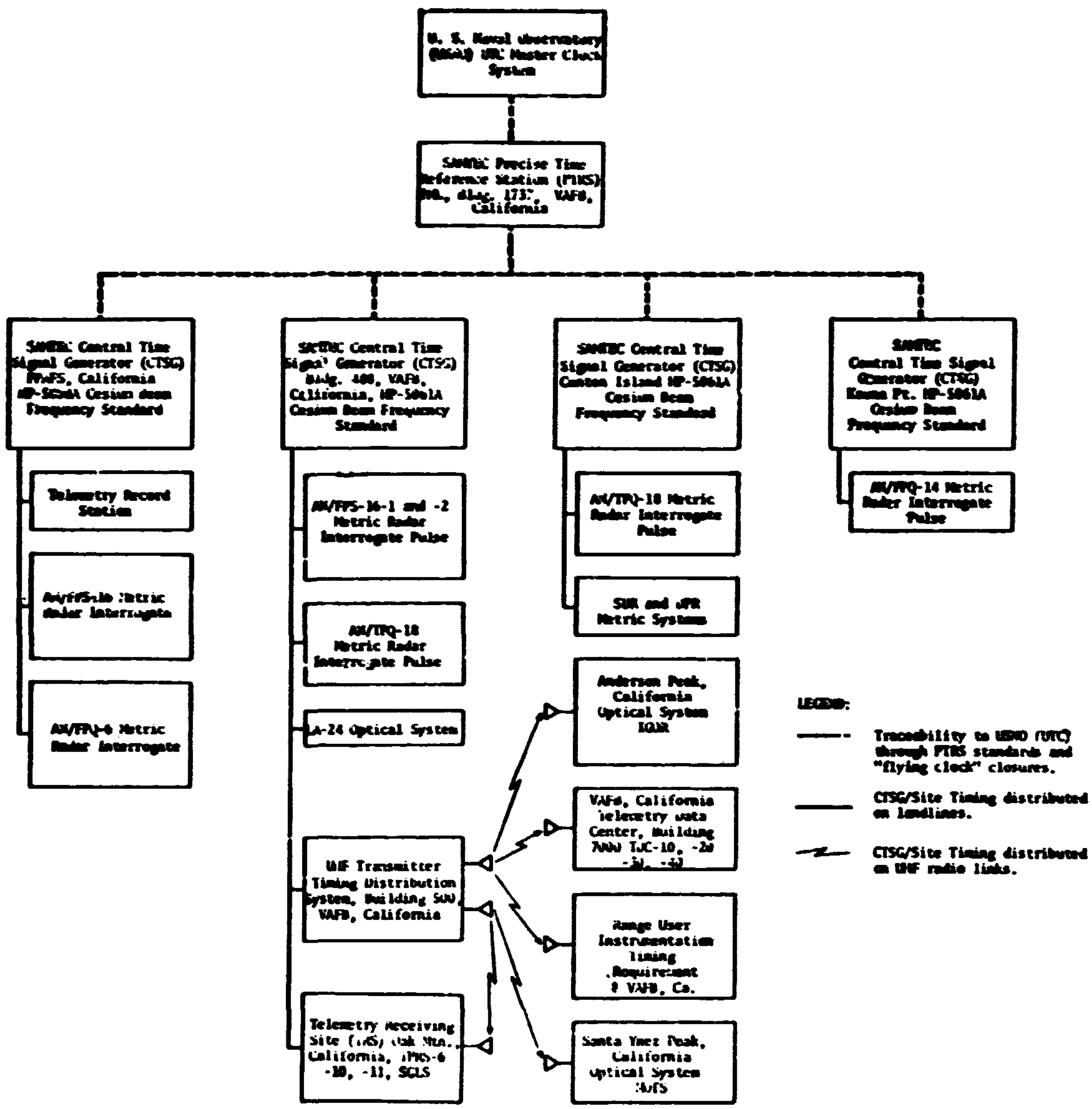


Figure 1. SAMTEC Instrumentation Systems UTC/IRIG Timing and Frequency Accuracy Traceability to USNO

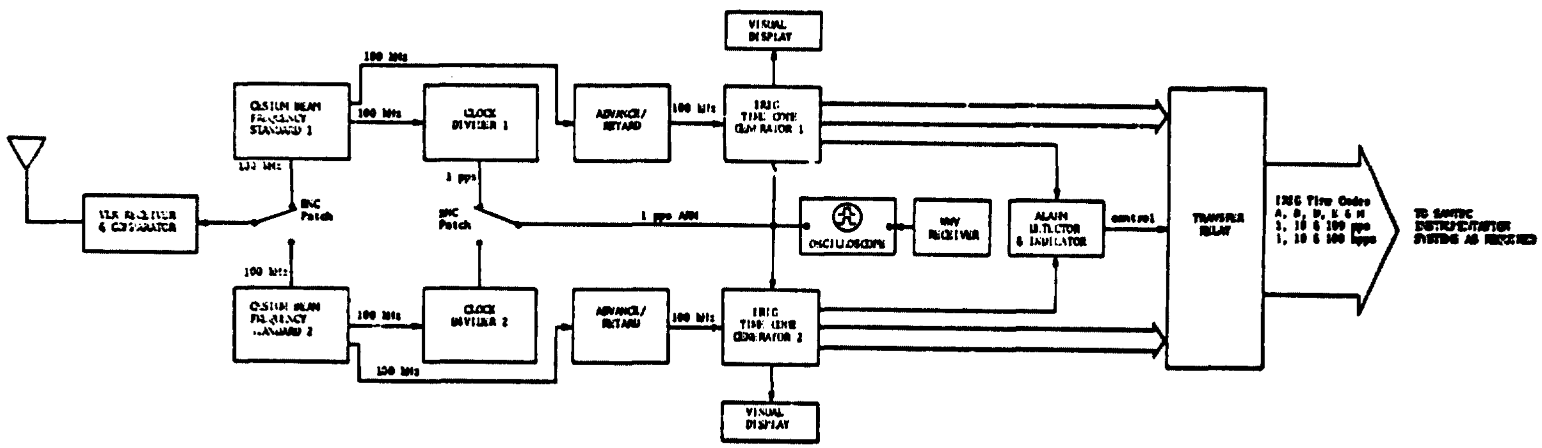


Figure 2. Typical Central Time Signal Generator

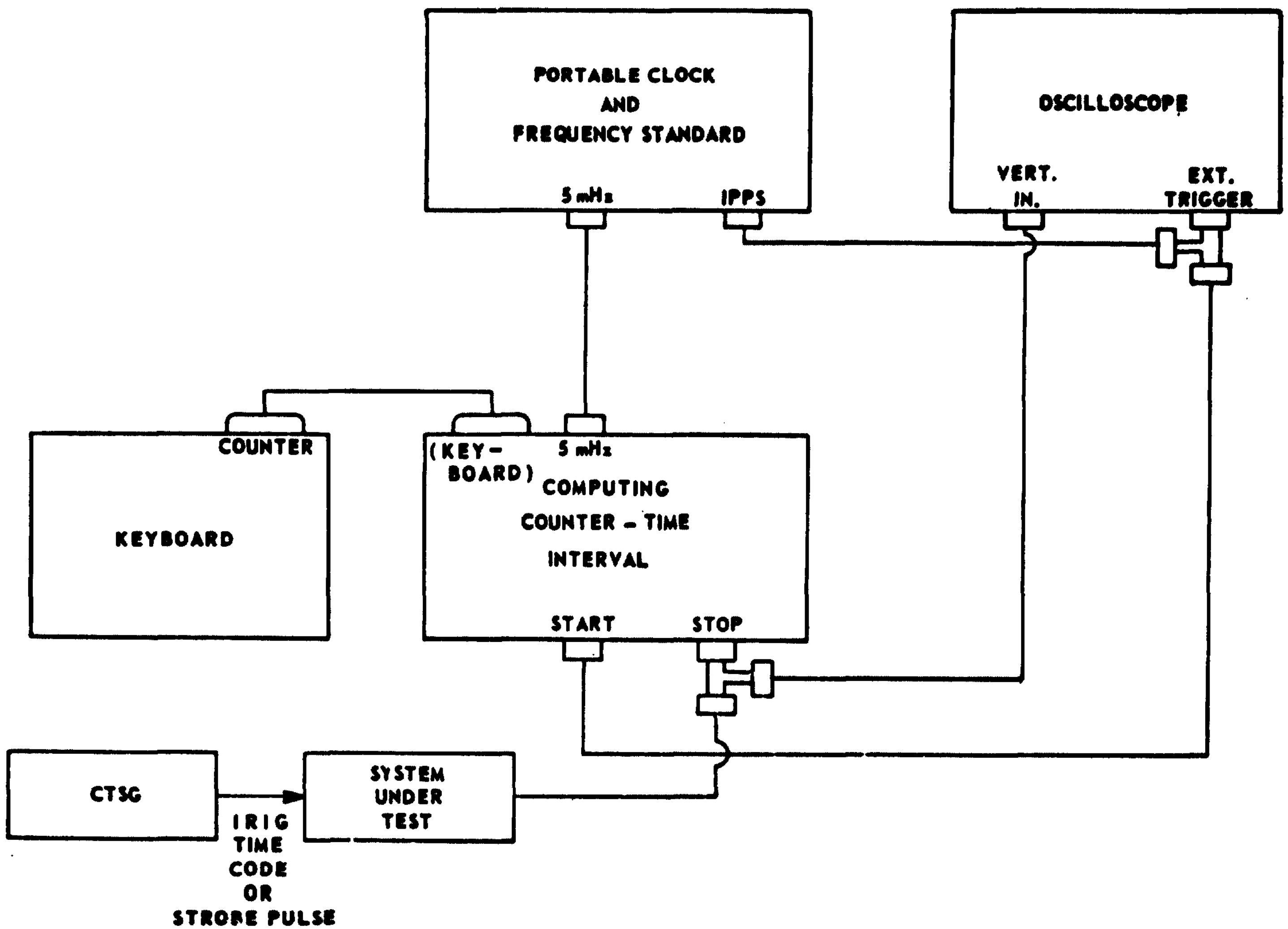


Figure 3. Typical Instrumentation Timing Accuracy Test Equipment Configuration

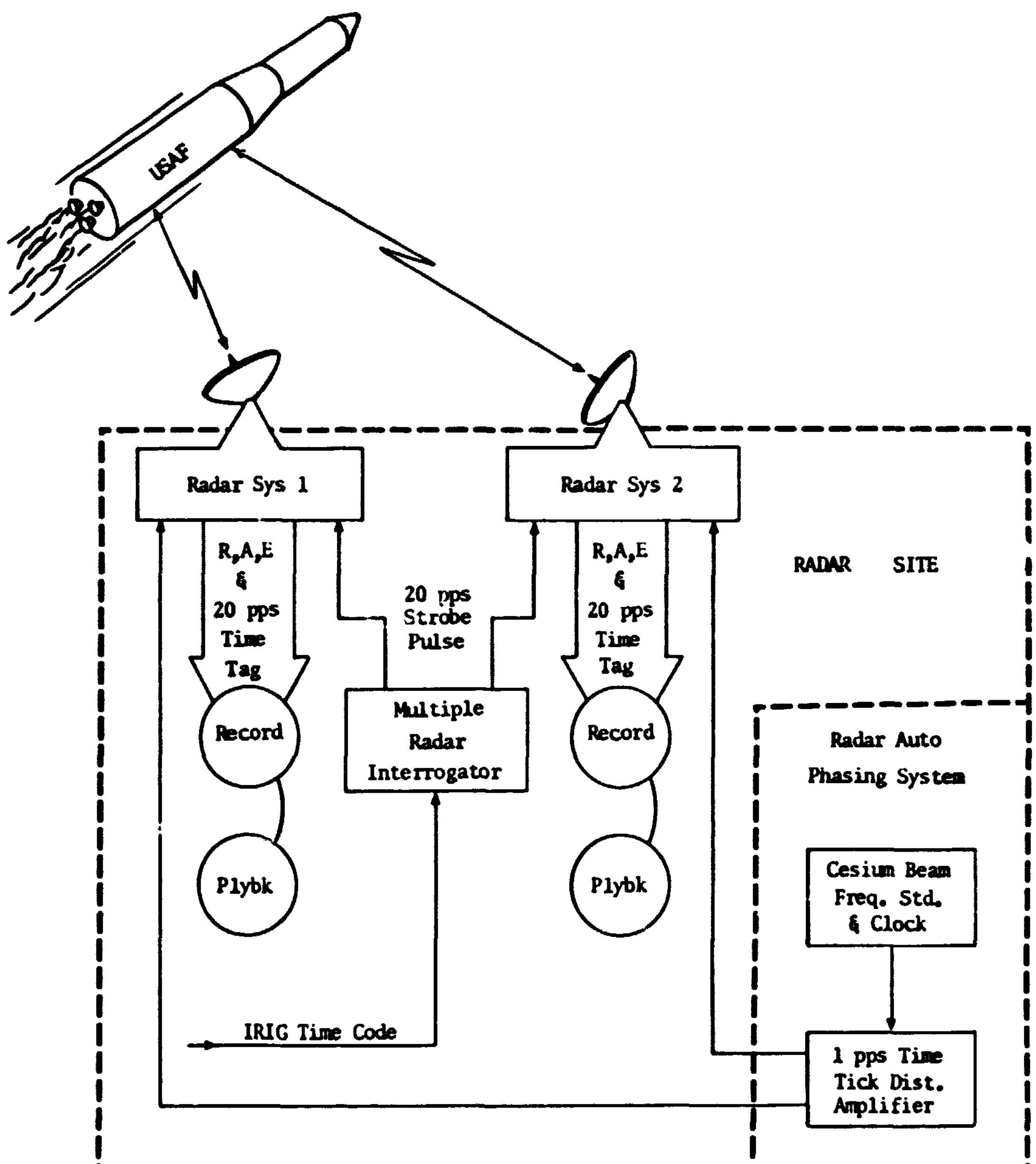


Figure 4. Multiple Radar Interrogator Time Tag Data Synchronization

the data registers. The data is then "dumped" and stored on tape, along with timing. The delay of the strobe pulse in relation to UTC is directly measured quarterly. This delay is added to the computed drift of the master clock to obtain an estimate of the total offset on each operation.

As an additional precaution, a backup cesium standard is located at the radar site. The 20 pps pulses are compared with the cesium 1 pps "on time" pulse prior to each operation. If the difference in time between the pulses is not within ± 25 μs of the designated delay for the site, the actual difference must be logged by the operator. Thus quarterly measurements plus pre-operational checks assure that all radar data can be accurately aligned for merging.

Telemetry Synchronization

As shown in Figure 5, telemetry stations synchronize a time code generator to the incoming IRIG signal. The generator then outputs "clean" IRIG timing which is recorded on magnetic tape. Also, data from the receiving system is recorded on adjacent tracks of the same tape. During post flight processing, the magnetic tape is replayed, data and timing signals are shaped, and both are inputted for computer processing. Part of the processing requirement is to correlate range timing to the time of data reception at the station to within one computer word time. (Typically ± 78 μs on critical programs). Unfortunately, errors in the recording/reproducing system may accumulate to several hundred microseconds and must be corrected on the final data product. The significant contributions to the accumulated error have been measured, and are discussed below.

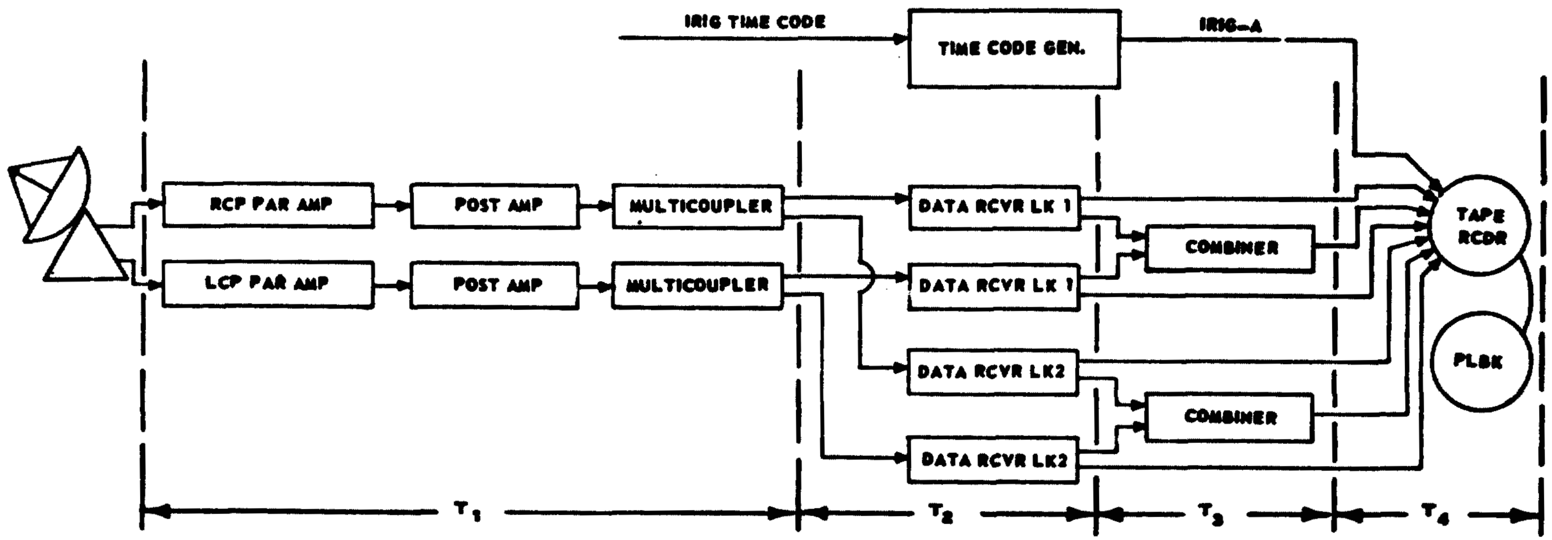
a. Figure 5 shows the mean RF receiving system and recorder time delays from three antenna systems for both predetection and post-detection recording.

b. Several models of tape recorders were tested. Figure 6 illustrates that each type of recorder reacts differently to the IRIG A 10 kHz and IRIG B 1 kHz carriers. It was found as shown in Figure 7, that a dubbed tape had approximately doubled the time delay of the orginal tape.

c. Head azimuth alignment causes only 1 μs of timing error, as shown in Figure 8, if heads are aligned within IRIG specifications.

d. As shown in Figure 9, and error of up to 33 μs may result from allowable even and odd head placement tolerances.

e. During playback, the time code generator decodes the IRIG timing signal and outputs timing pulses for computer use. As shown in Figure 10, it was found that jitter on the pulses was significant for IRIG B codes.



	PRE-DETECTION TIME DELAYS (ηS)	POST-DETECTION TIME (ηS)
T 1 = ANTENNA SYSTEM	508	508
T_2 = DATA RECEIVER	2035	1318
T_3 = COMBINER	237	78
T_4 = TAPE RECORDER	50	50
TOTAL RECEIVE SYSTEM TIME DELAY	2830 ηS	1954 ηS

Figure 5. Absolute RF System Receive/Record Time Delays

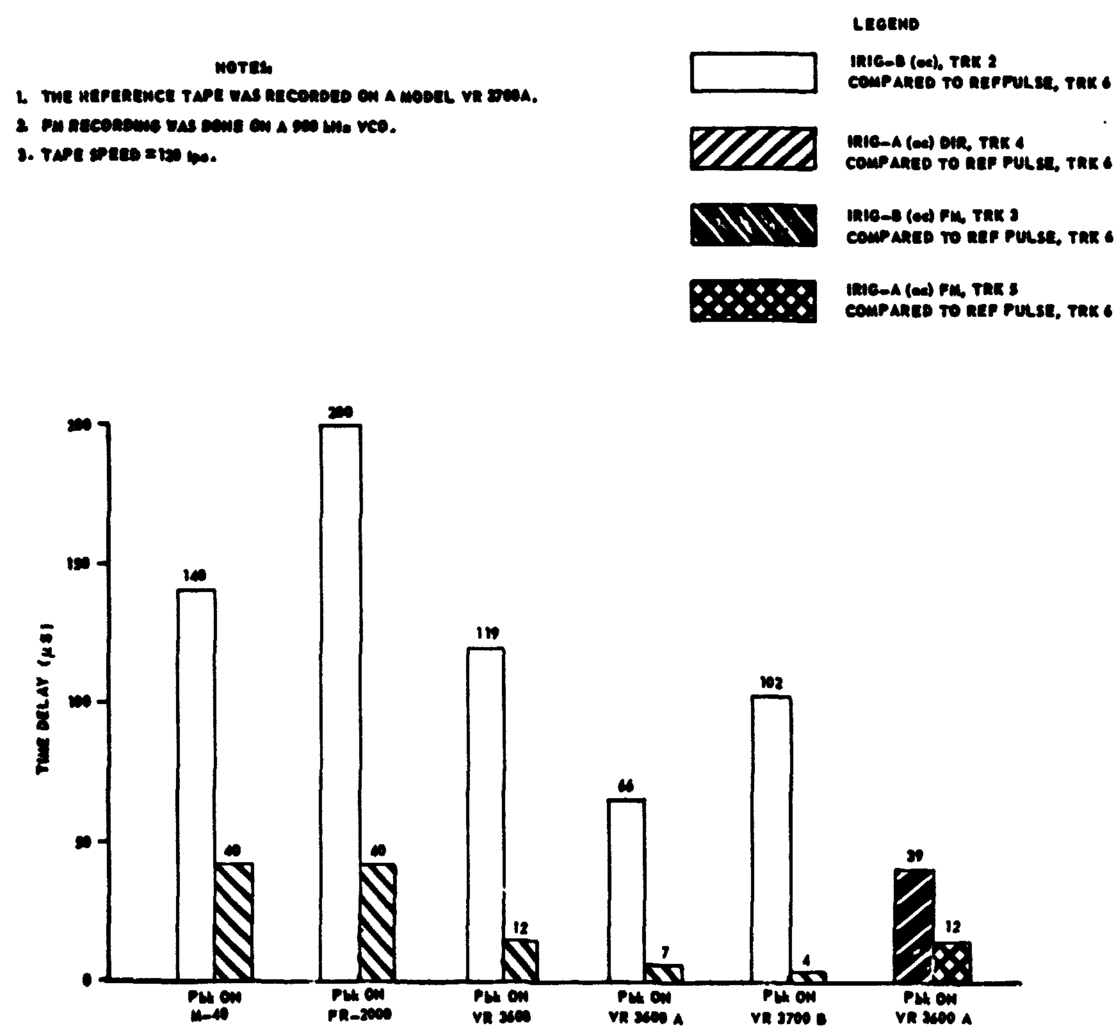


Figure 6. Comparison of Playback Time Delays of Different Brands of Recorder

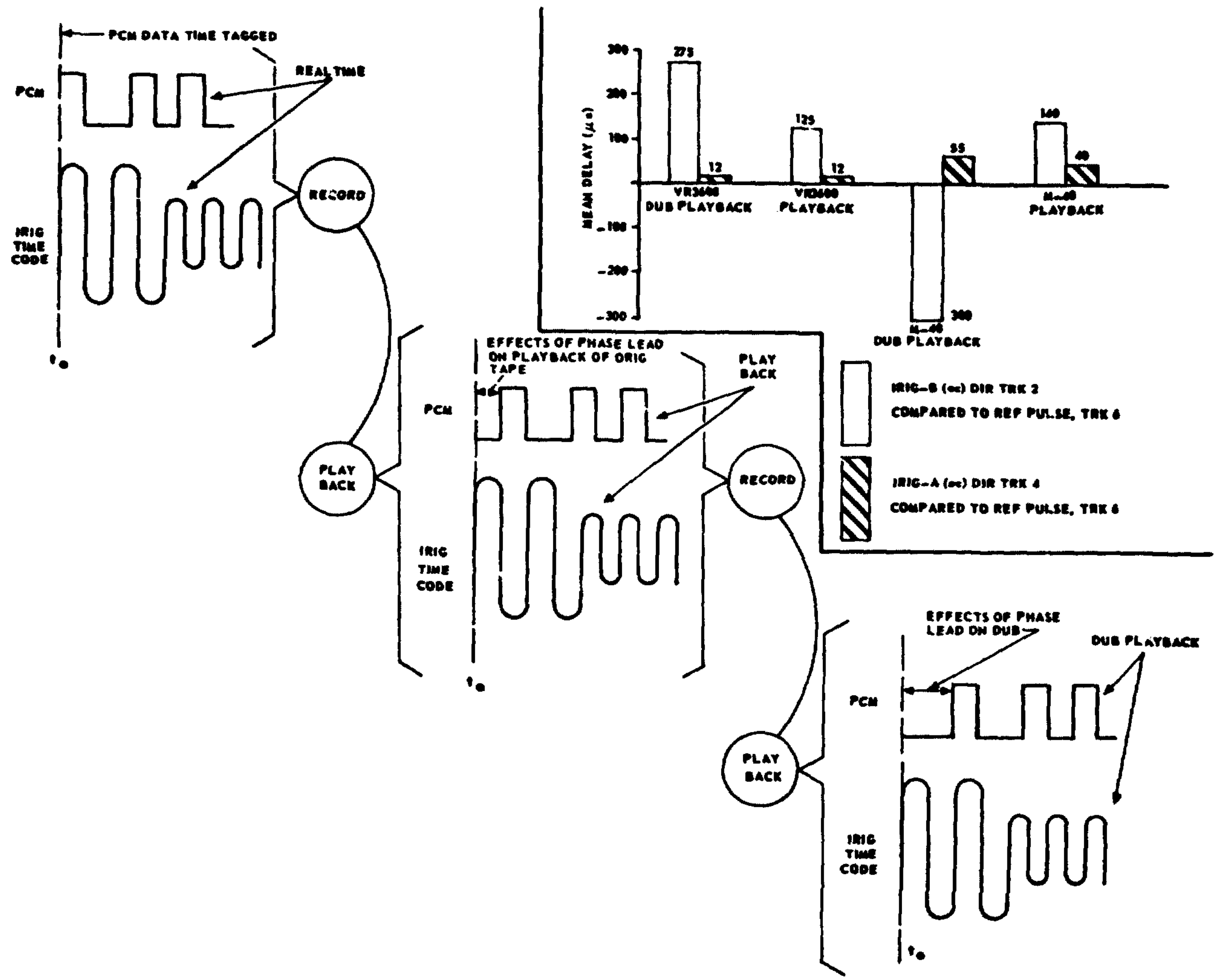


Figure 7. Time Delay Effects of Phase Lead on Dubbing

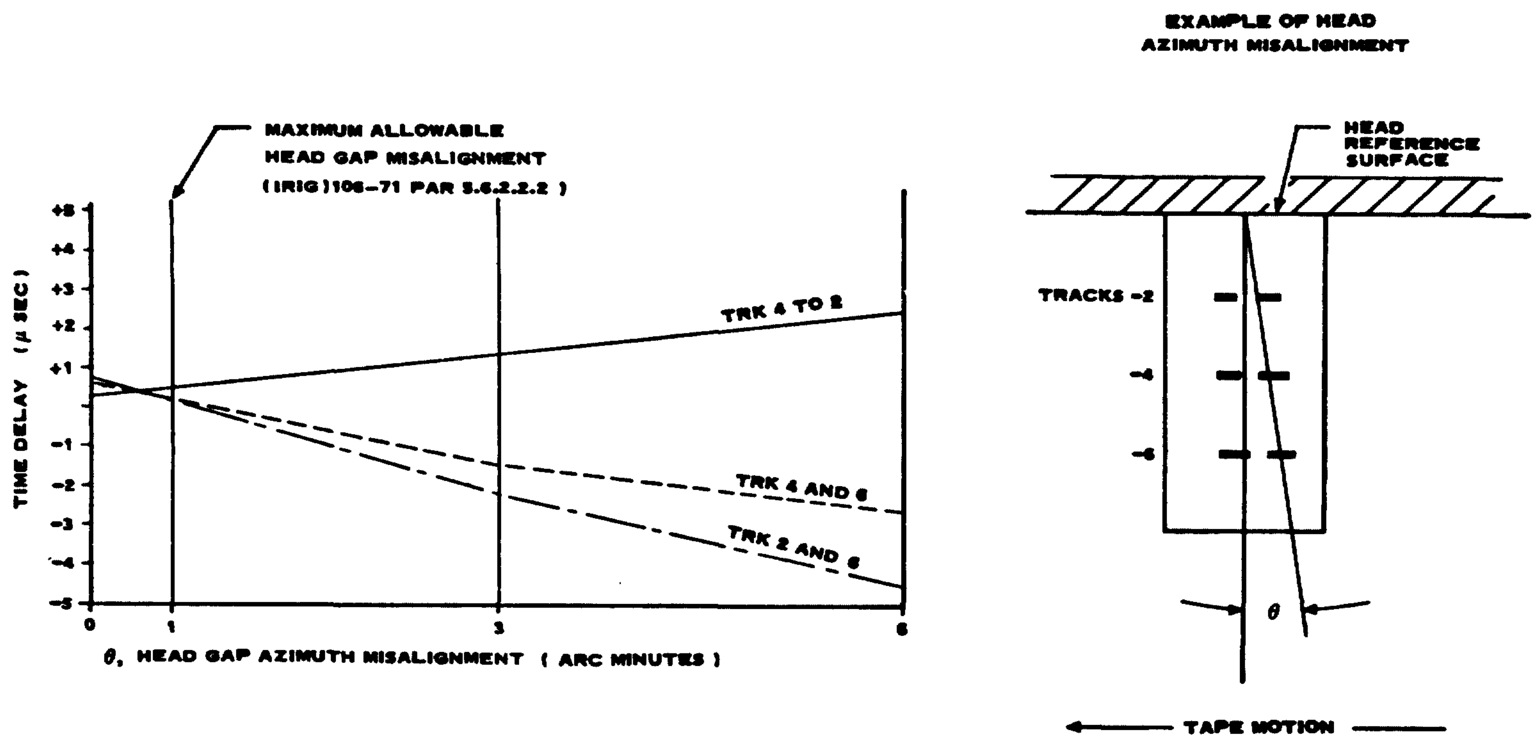


Figure 8. Time Delay Contributions Due to Recorder Head Gap Azimuth Misalignment

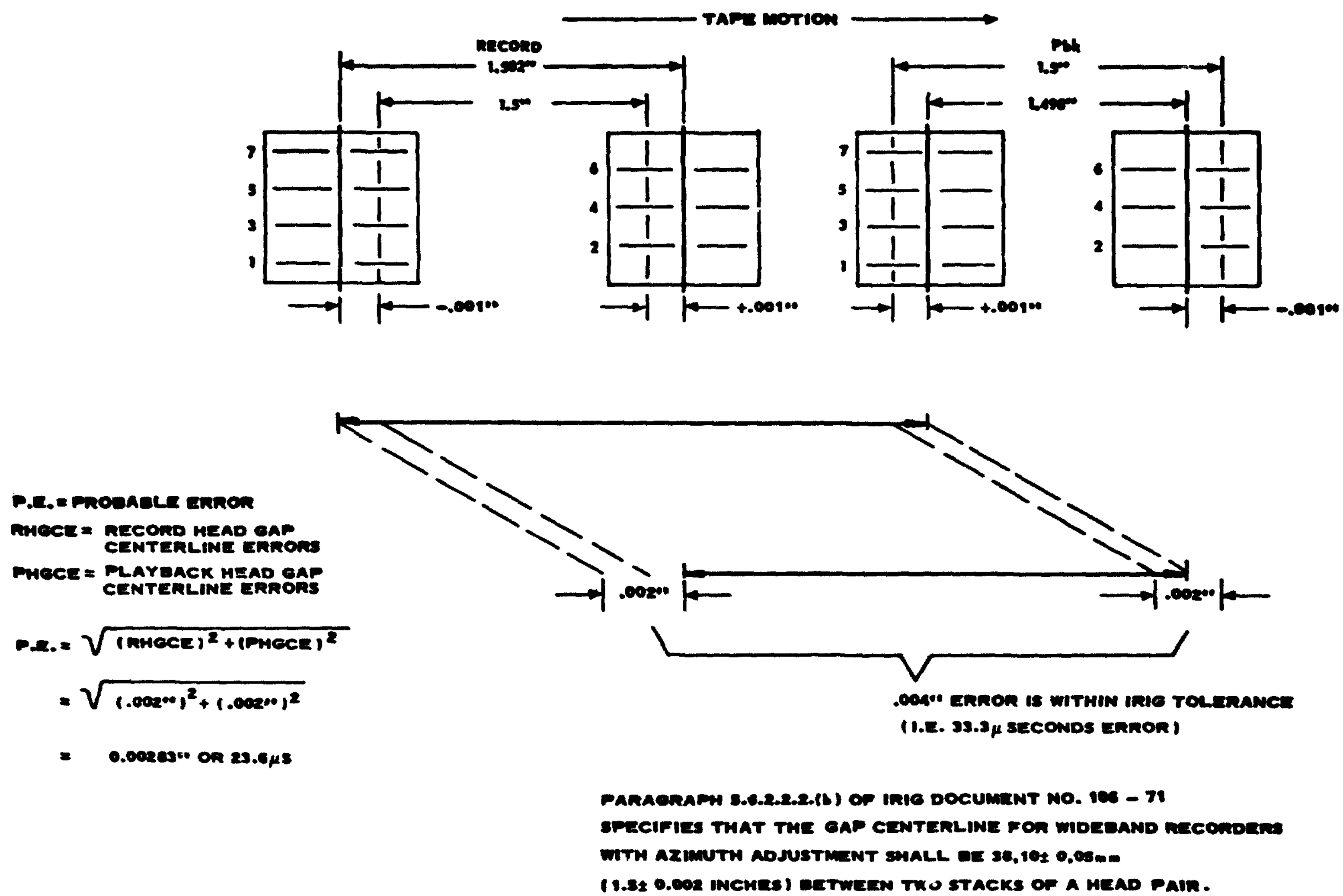


Figure 9. Effects of Recorder Head Stack Mechanical Placement

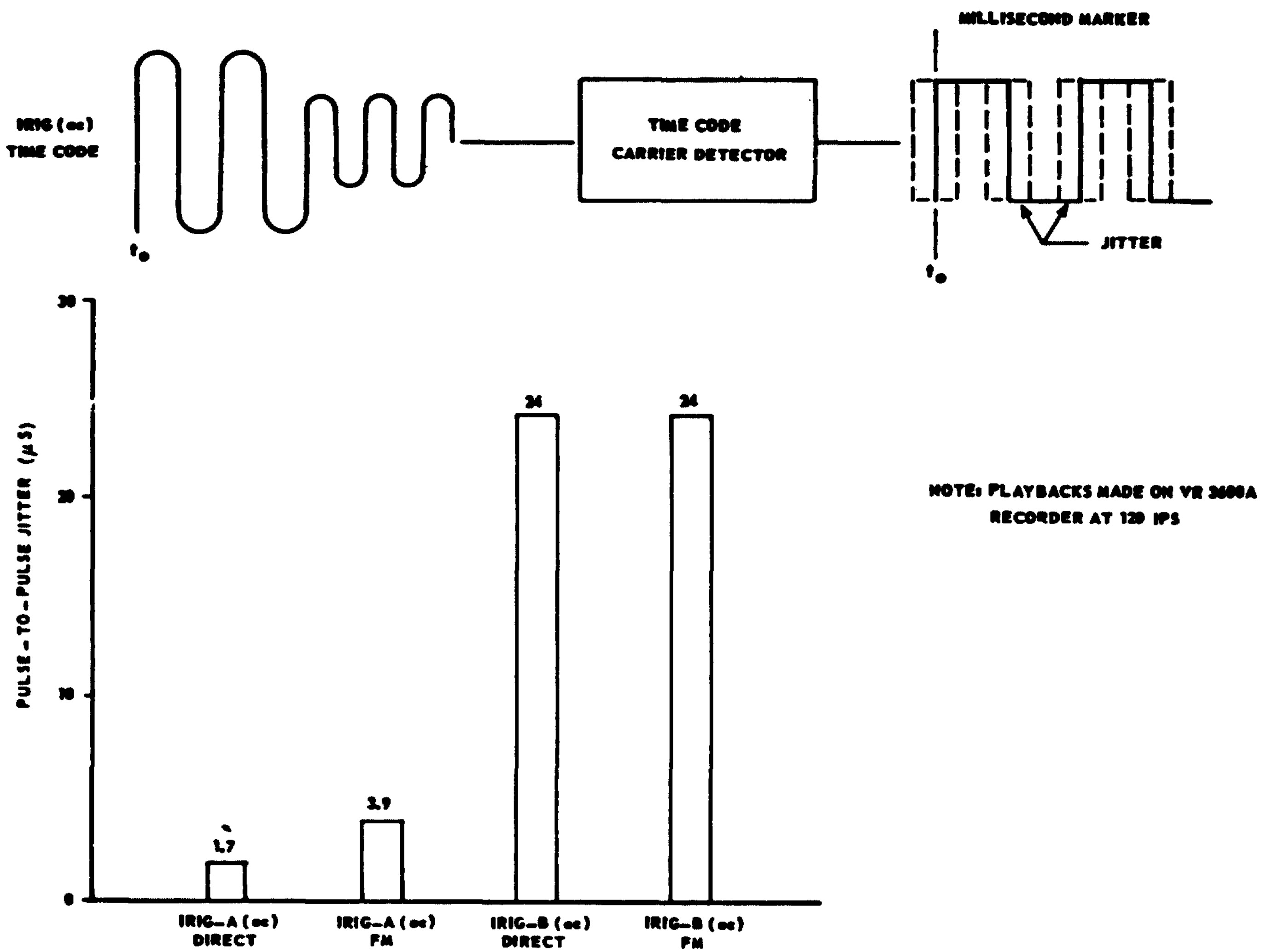


Figure 10. Examples of Pulse-to-Pulse Jitter Caused by the Time Code Translator

f. An unmodeled error occurs from time to time when the recorder IRIG timing is noisy. Operators may filter the data to obtain better lock. Such filtering introduces additional delay and amplifier inversion of the code may introduce an unexpected time delay of one half cycle (500 μ sec for IRIG B). Such errors, of course, destroy the carefully controlled timing correlations.

Correction of Telemetry Errors

The errors outlined above may accumulate to several hundred microseconds on a given data run. Fortunately, the error is a reasonably constant value and can be easily determined as follows.

Referring to Figure 11, the delay to the signal conditioner 1 is known to be less than 2 μs and is ignored. The conditioner introduces a 1 bit data delay and its output is recorded on a redundant recorder track. Each 1 pps pulse from the time code generator switches the data off and inserts a pre-programmed word in the data. During processing, the special word can be easily identified and the last data bit prior to the word inserted is noted. This is the data bit which was received within 1 bit time of an even second mark (less the delay through the receiving system). The actual data produced from an uninterrupted (normal) input is then examined and the time provided by the computer for the reference bit determined. This time should be an even second. Any deviation is the accumulated timing error which existed at the even second. The mean and standard deviation of all 1 second measurements is obtained. This provides the timing bias caused by the accumulated error. The bias can be removed in subsequent processing operations.

Future Requirements

A range requirement may be received which requires that the data received on two separate links be correlated to within ±10 μs. From the data provided above, it can be seen that even if the two data streams are recorded on the same head stack and high frequency IRIG codes are used, it will be difficult to control the computer inputs to within the required tolerance. Of greater significance, however, is the software resolution of ± 1 word time in assigning timing "tags". This resolution must be reduced to ± 1 bit time to meet program objectives.

Future Needs

Although cesium standards have proven reliable, failures require that a "flying clock" be sent to the remote site between normal calibration intervals. What is needed is a technique for synchronizing remote standards to within ±1 μs

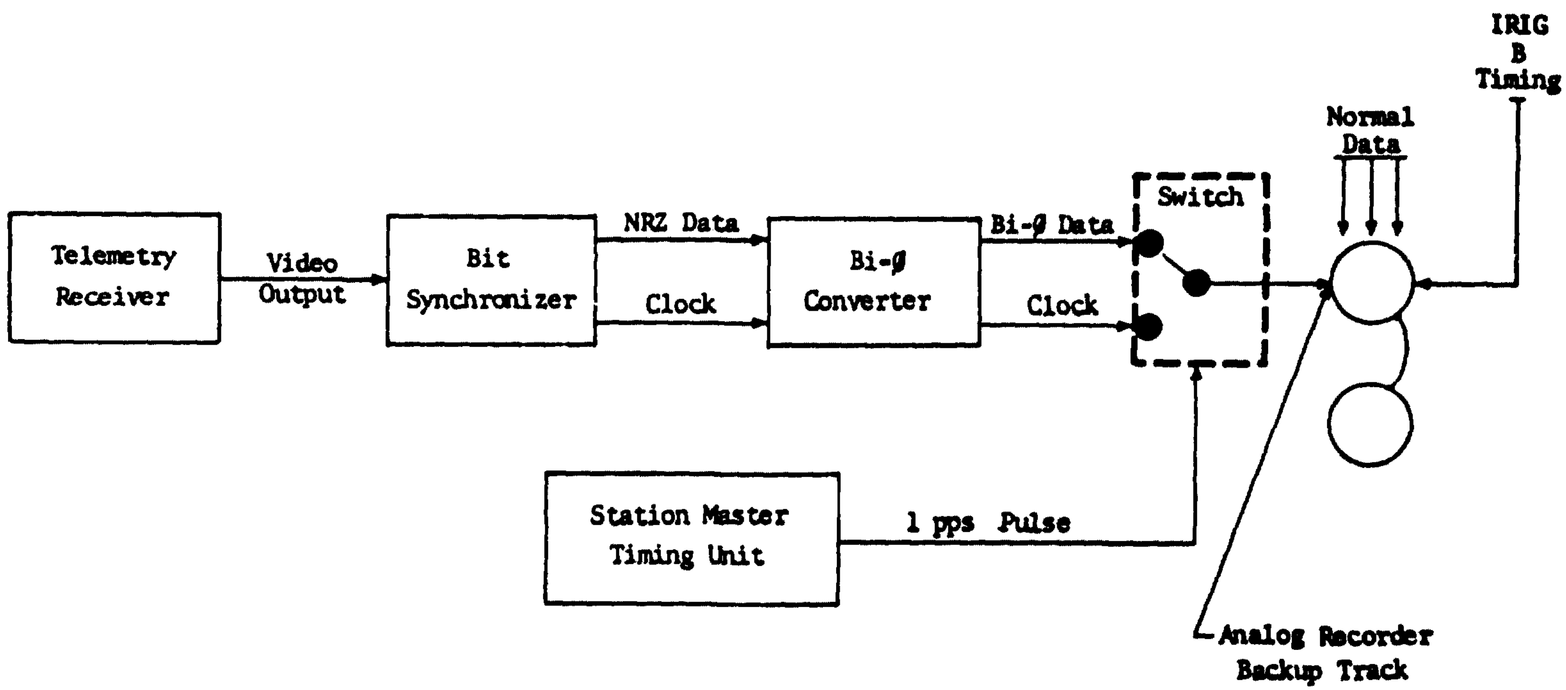


Figure 11. Real Time Telemetry Timing Marker System

without relying on a portable clock. The application of satellites has been considered and the accuracy appears to be satisfactory. However, its application depends on the availability of inexpensive receiving equipment which can compete, from a cost effectiveness standpoint, with the flying clock concept.

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3. Matthews, F. L. and Streich, R. G., "Timing Correlation in Telemetry Recording and Processing Systems", International Telemetering Conference Proceedings, 1973.

4. "Telemetry Standards", IRIG Document 106-73 (Revised May 1973).

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6. "IRIG Standard Time Formats", IRIG Document 104-70 (Revised August 1970).

QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

DR. COSTAIN:

You never mentioned the quality or band width of the lines that you were using. I found that IRIG-B was even beyond the capability of commercial telephone lines, and the error rate was unacceptable, and we went to the FSK coding modems.

You are talking about using 100 kilohertz. You must have pretty good lines.

MR. MATTHEWS:

If and when we do go to the 100 kilohertz, of course it would be in the coax type line.

Normally, our IRIG-B is distributed, when it is on telephone lines, on a 3 KC circuit, and IRIG-A requires coax.

DR. WINKLER:

I am very impressed by the work which you have described. There are several comments and ideas which I would like to explore here with you.

Isn't it true that the absolute time difference which you have between your various channels on one and the same tape recorder, is less of a problem than the fluctuations which you have not only from gap misalignment, but even more so from changes in the tape tension, and changes in the tape type? If you use a different tape, I would expect you to have quite a different delay from channel to channel.

Don't forget that five microseconds at a speed of 120 inches per second amounts to just a few microns of difference in position at any one moment.

For that reason, it appears to me that it may be useful to make a test of trying to superimpose a low level sine wave, which is derived from your standard, on the very same channel on which you have your timing data coming in, which are, of course code modulated at any rate.

So, you could separate them electrically, but you would have the advantage of having passed all the signals, the timing signals, and your information over exactly the same channels on the tape.

Another possibility, of course, would be to use a wide band video recorder, and to put all your channels onto one carrier, and use actually a carrier frequency type of recording system.

But it is definitely pushing the possibilities to the very end.

MR. MATTHEWS:

Well, I failed to mention that we, in the alignment of our recorder heads, used the lissajous patterns to make our alignment, and have found it very effective in aligning up the head, as to the azimuth alignment.

MR. KLEINKOPF:

Jack Kleinkopf here, from NASA Flight Research Center, at Edwards Air Force Base.

One thing that I didn't get clear -- maybe you covered it -- was the discrepancy between your sample data system, the PCM system, and the sample rate on board, and the ground timing.

How do you go about resolving that?

MR. MATTHEWS:

I should say airborne timing is not available on the missiles that are flown out of Vandenberg, and therefore all of the timing is generated from the ground system.

Does that answer your question?

MR. KLEINKOPF:

Well, do you have an oscillator in your airborne sample data system, and do you have a frame of PCM data coming in, so that the post reduction analysis can go back and determine where the beginning of the frame of the PCM data is with respect to your ground base time.

MR. MATTHEWS:

Okay. Normally, there are specific points in the flight that are known very accurately, and we can align our data up with time at these points, such as when they go through staging. These represent specific time intervals which we know. At those points we know that at a certain time that, because of separation or attenuation, we get dropouts. We also know that these particular points in our data stream are exact and that we can line the timing up with that.

MR. KLEINKOPF:

I see. You are saying this is all based on a launch time, or something like that, initialization point.

MR. MATTHEWS:

We record the liftoff time. But one of the points that I was pointing out, I believe on the last slide there, was that in order to measure the absolute time, we need to know very accurately what the time delay difference is between UTC and this one pps pulse where we insert the pre-programmed word into the data stream with a special recorded track.

That data is pulled off, put into the computer, and stored. It is also looking and averaging the time of the millisecond marker — that is, the IRIG time code goes into the time code translator. It then inputs the millisecond markers into the computer, and it knows at a certain point this one pps pulse takes place where that millisecond marker should be. We then correct for that millisecond marker.

MR. CHI:

Thank you again.

N75 11283

DIGITAL FREQUENCY CONTROL OF SATELLITE FREQUENCY STANDARDS

S. A. Nichols
Naval Research Laboratory

ABSTRACT

In the Frequency and Time Standard Development Program of the TIMATION System, a new miniaturized Rubidium Vapor Frequency Standard has been tested and analyzed for possible use on the TIMATION IIIA launch, scheduled for early 1974, as part of the Defense Navigation Satellite Development Program. The design and construction of a Digital Frequency Control by NRL, was required to remotely control this Rubidium Vapor Frequency Standard as well as the quartz oscillator in current use. This control must be capable of accepting commands from a satellite telemetry system, verify that the correct commands have been sent and control the frequency to the requirements of the system.

The Digital Frequency Control consists of several daughter boards mounted on a mother board. The various daughter boards process the incoming digital information, convert to an extremely stable analog voltage; convert it to the proper levels for use by the frequency standard, and route it to the appropriate frequency standard. The Digital Frequency Control was designed to control one quartz oscillator and two Rubidium Frequency Standards. It makes extensive use of low power miniature TTL circuitry and hybrid miniature D to A converters to keep size and power consumption as low as possible. Control circuitry not in use is turned off and, except for the command system, the Control is redundant. Special isolation circuitry has been incorporated to protect the digital-to-analog converter from being falsely triggered by noise or spurious signals.

Several modifications must be performed to the Rubidium Vapor Frequency Standard to allow it to be compatible with the Digital Frequency Control. These include the addition of a varactor to voltage tune the coarse range of the "flywheel" oscillator, and a modification to supply the "C" field current externally.

Quartz oscillators in TIMATION I and II used a motor-driven glass capacitor for tuning, however the oscillator to be used for TIMATION III A uses a varactor which can be directly used with the Digital Frequency Control.

The Digital Frequency Control for the Rubidium Vapor Frequency Standard has been successfully tested in prototype form. Work is now being done on a flight version for TIMATION III A.

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INTRODUCTION

The TIMATION satellite navigation project depends on an ultra stable oscillator in the satellite as a basis for its accuracy. TIMATION I and II successfully used quartz oscillators, especially built by Frequency Electronics Inc. for space use.[1,2] The TIMATION III satellite (Navigation Technology Satellite I) is scheduled for launch in early 1974 as part of the Global Positioning System Program. Figure 1 is a picture of the satellite which will also have a quartz oscillator as its primary frequency source; however while TIMATION I and II used mechanical tuning (stepper motor), TIMATION III will use varactor tuning controlled by a Digital to Analog Converter. In addition two experimental Rubidium Vapor Frequency Standards are being tested for possible use.[3,4] These units would also be controlled by D/A converters[5], which, with associated circuitry is combined in the Digital Frequency Control. The Frequency Standard System will be configured to provide redundant frequency sources, with the ability to select, by command, one of the three RF outputs for the experiment. A system block diagram is shown in Figure 2.

Digital Frequency Control

The Digital Frequency Control[6] is a circuit which converts digital information to analog signals which control the frequency of various frequency standards. To do this effectively the output stability must be low compared with the frequency sensitivity of the frequency standard control. Extensive use has been made of components and techniques that have been developed and refined in the past few years.

The Digital Frequency Control has four main functions: dc power control, digital word control, D/A conversion and analog control voltage processing. As the primary frequency source, the Quartz oscillator has dc power applied to all times. It uses +15 v for the oscillator, ±15 v for the D/A converter and operational amplifiers and 5 v for the logic control. The Rubidium units use 28 v as well as ±15 v and 5 v. Only one Rubidium unit can be turned on at any one time. Separate regulators are used for these voltages, except the logic supply, to provide redundancy. The command system and associated logic circuitry is not redundant. The oscillator system will continue to run in the event of a command system failure, but there could be a frequency shift.

The Digital Frequency Control has four switches to control these voltages. The satellite command system switches power to the Rubidium units. In addition there is a precision 10 volt regulator in the control to supply the reference for the D/A converters.

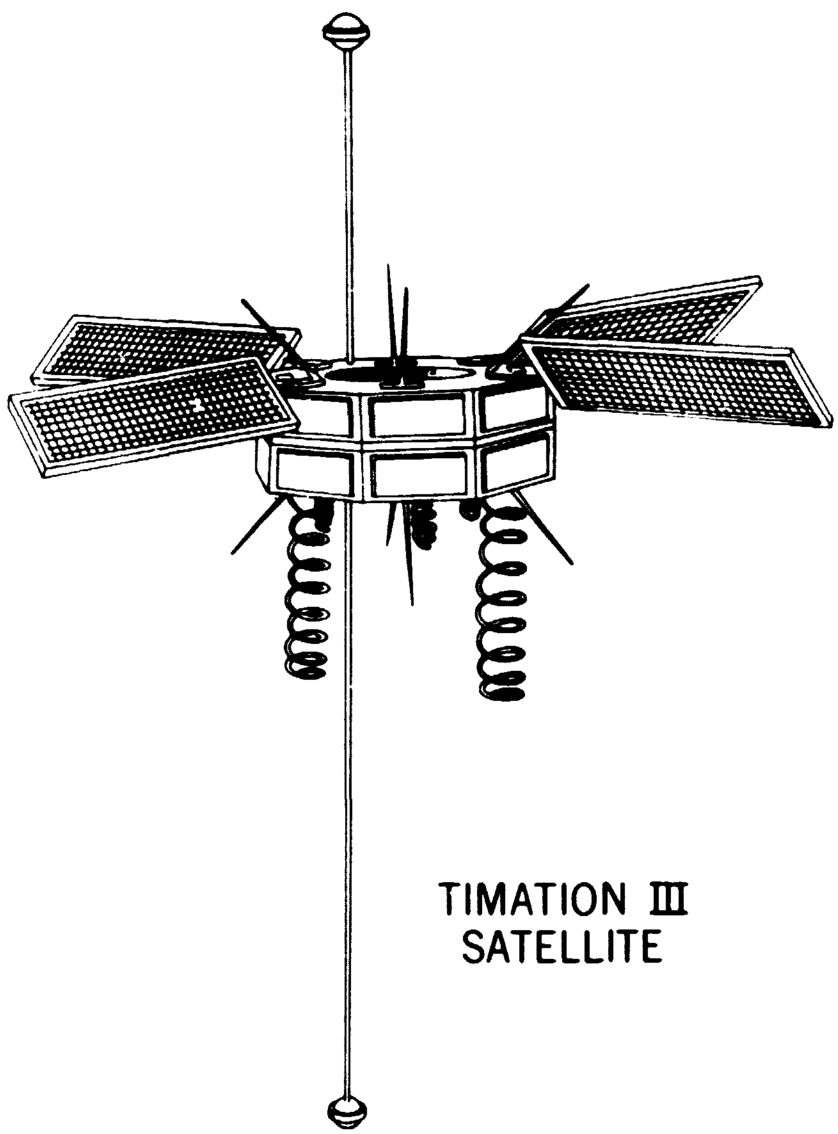


Figure 1. Navigation Technology Satellite I

Tuning the Digital Frequency Control is accomplished by sending a 14 bit serial word. This word can be loaded into one of three registers as determined by two of the bits. There is a 12 bit storage register to tune the Quartz crystal oscillator, a 10 bit storage register to fine tune the Rubidium Frequency Standard ("C" field adjust) and an 8 bit storage register to keep the Rubidium crystal oscillator within the lock limits of the control circuitry. The loading of the 14 bit word can be verified by digital telemetry before it is transferred to the appropriate storage register. There are also several provisions made to prevent spurious

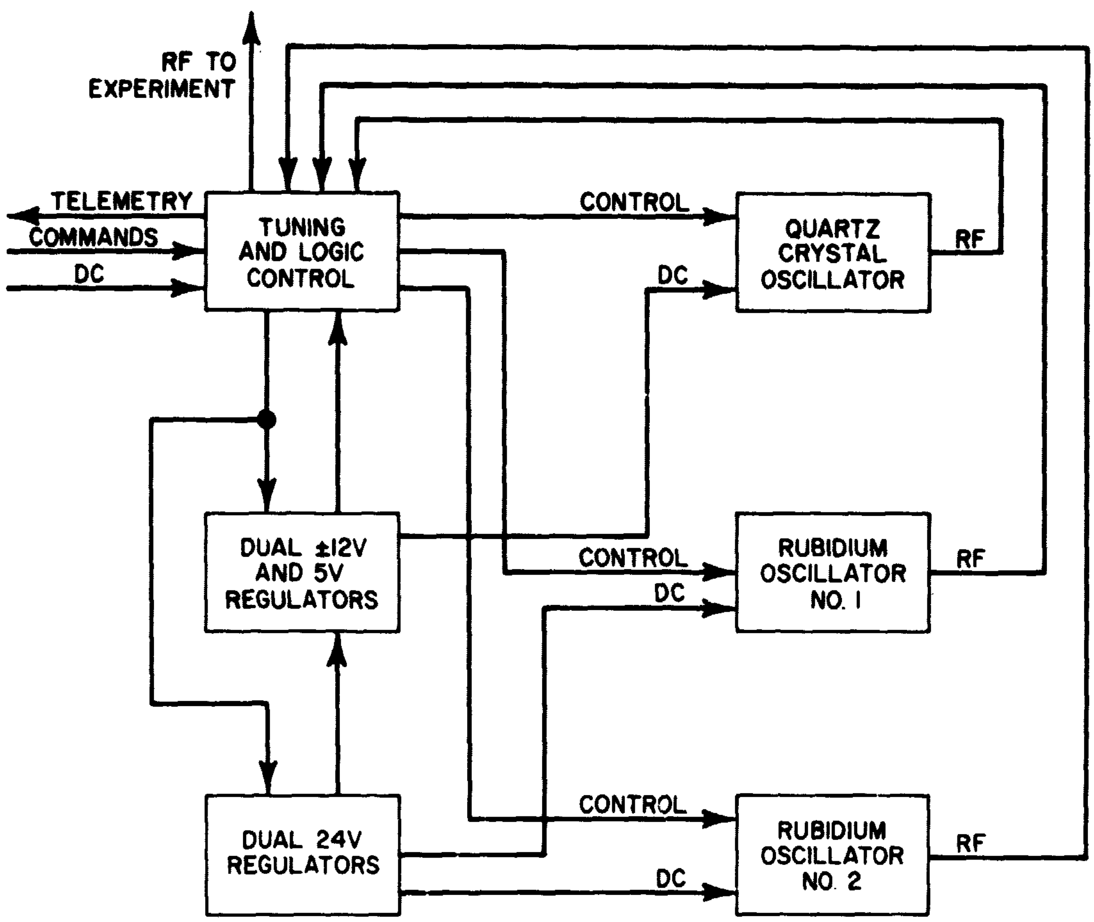
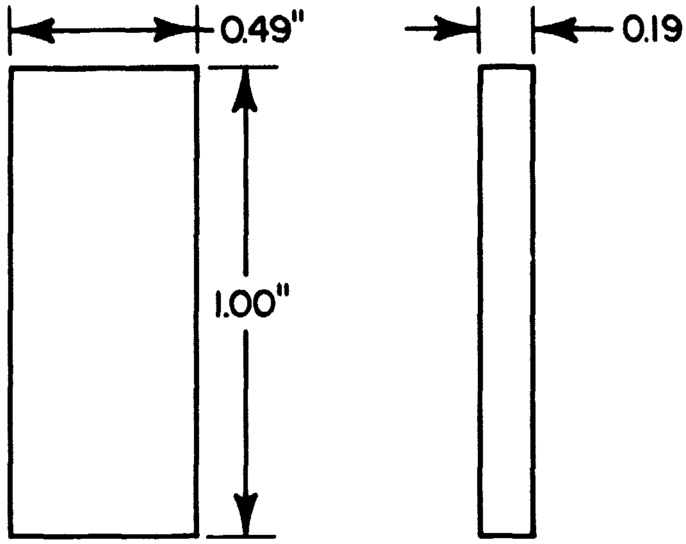


Figure 2. Frequency Standard System Block Diagram

signals from entering the Digital Frequency Control by disabling the input circuitry when it is not needed.

The D/A converter used for all three tuning commands is a 12 bit, thin film, hybrid low power module. Its specifications are shown in Figure 3. The pins have the same spacing as a dual in line integrated circuit package. It uses an external voltage reference which was mentioned earlier. Test of this voltage regulator showed a voltage change of about 0.7 mvolts from 10° to 40°C. This circuit was designed to be insensitive to supply voltage changes. In the satellite, the precision regulator will be temperature stabilized to within 200 millidegrees[7] and 200 millivolts supply voltage will be available. The 12 bit D/A converter will also be temperature stabilized to provide the necessary voltage stability to the Quartz oscillator varactor control. An operational amplifier circuit is used to convert the 0 to -2 ma D/A converter output to the 1 to 6 v output required by the



12 BIT DIGITAL TO ANALOG CONVERTER

POWER CONSUMPTION:	570 MW
LINEARITY:	± 1/2 LSB
TEMPERATURE RANGE:	-25°C TO +85°C
CONSTRUCTION:	HERMETICALLY SEALED DIP PACKAGE
INPUT:	TTL COMPATIBLE
OUTPUT:	0 TO -2 MA

Figure 3. D/A Converter Specification

oscillator. The output voltage of this D/A converter is expected to be stable to within one millivolt. The requirements for the D/A converters to be used to control the Rubidium units are not as stringent and therefore these units are not temperature stabilized. They do, however use the same precision voltage reference. The output voltage range of the 8 bit Rubidium crystal D/A converter is 0 to 5 v and the 10 bit Rubidium C field D/A converter output is 5 to 6.5 ma.

Provision has also been made to exercise the Rubidium units independently of the command system on the ground. In addition, several monitor points have been brought out to the satellite skin to allow performance monitoring during system checks. Figure 4 is a block diagram of the system.

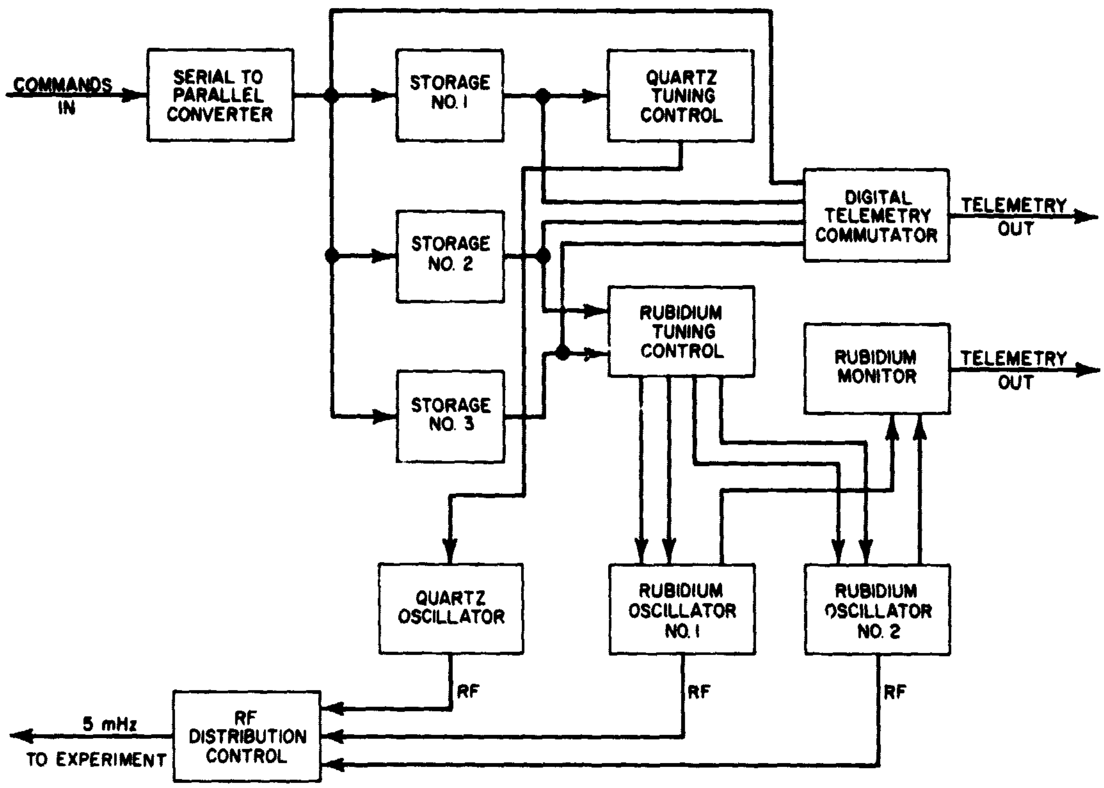


Figure 4. Logic and Tuning Control Block Diagram

Figure 5 is a photo of the prototype tuning the logic control box. This box will weigh 2-1/2 pounds and will contain most of the frequency control circuitry. Figure 6 shows the sizes and weights of the frequency standards and circuits.

Frequency Standards

The primary frequency standard for TIMATION III will be a 5 MHz quartz oscillator. A block diagram is shown in Figure 7. This is a 5th overtone, AT cut, double oven, oscillator that was built on contract for this satellite. This oscillator will have a natural aging rate of less than 1 pp 10^{12} per day or 2 pp 10^{9} over the planned 5 year lifetime. However, the calculated radiation induced frequency shift is -5 pp 10^{11} per day or 9 pp 10^{8} over 5 years, therefore the tuning range has been selected to be 1.5 pp 10^{7} with the smallest increment to be 2 to 4 pp 10^{11}, the range of values being due to the nonlinearity of the varactor response. This curve is shown in Figure 8. This oscillator, along with the precision voltage reference and the 12 bit D/A converter will be mounted on a thermal electric control device which will maintain the base plate temperature at 25°C ±0.1°C.

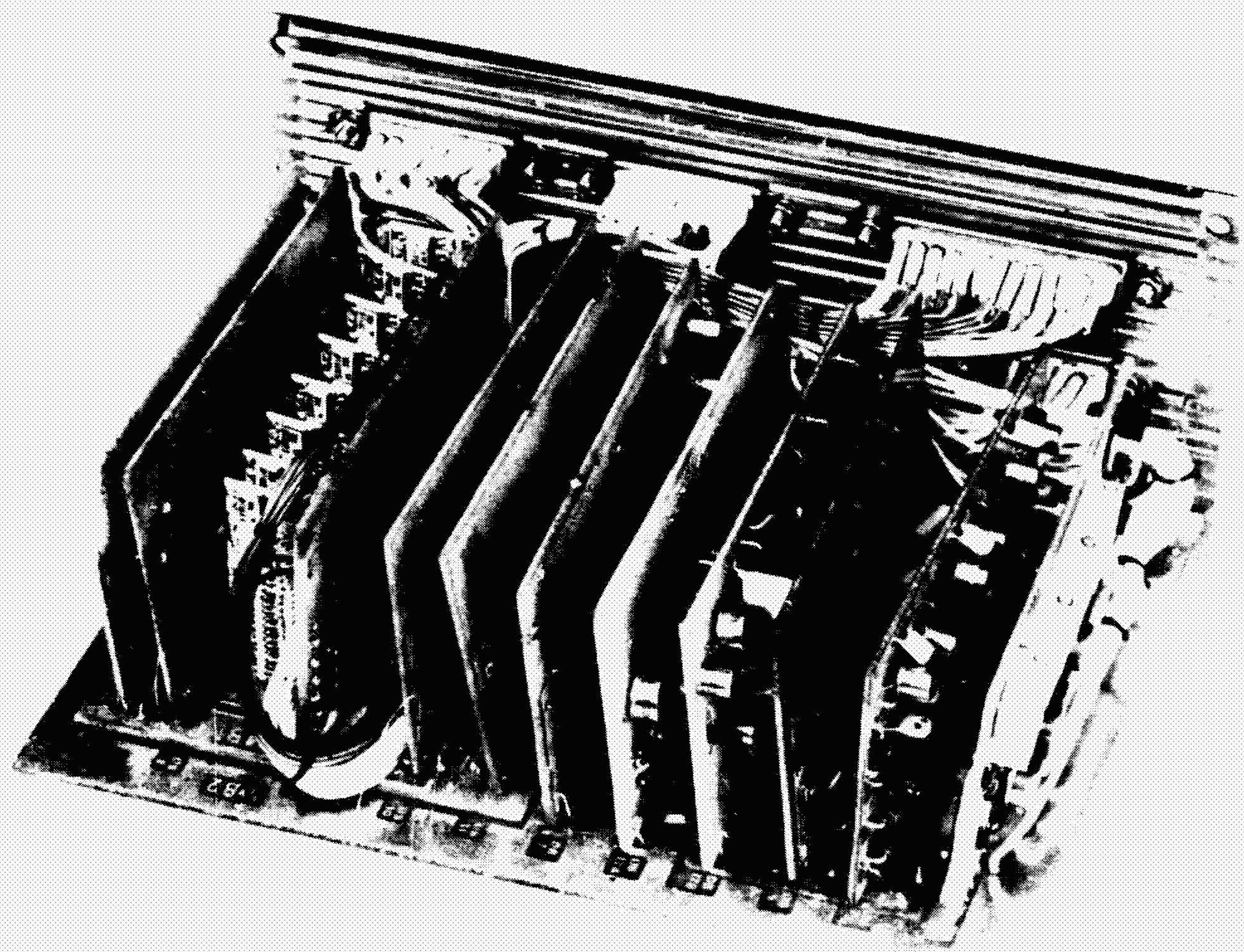


Figure 5. Logic and Tuning Control Photograph

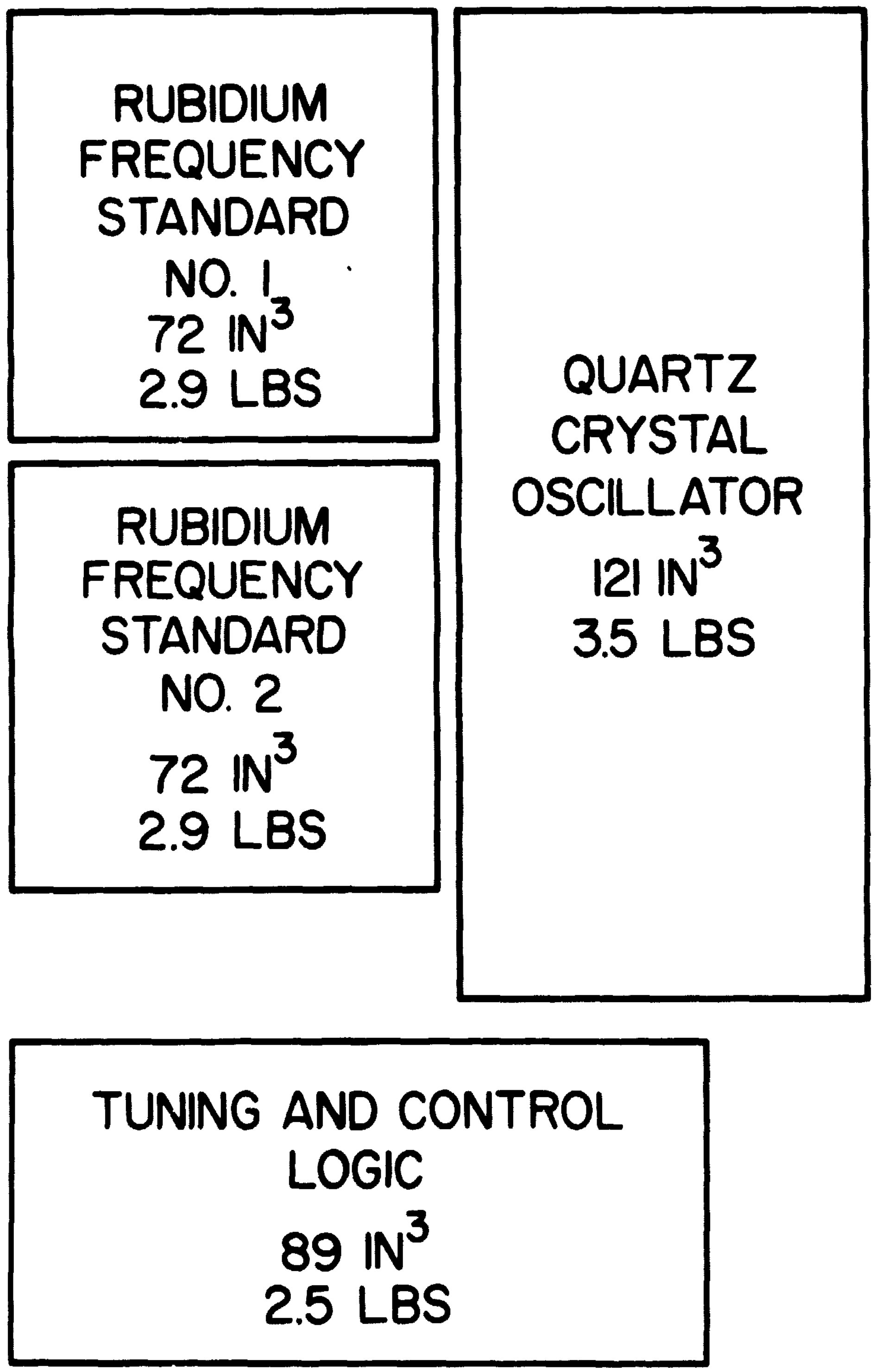


Figure 6. System Mechanical Details

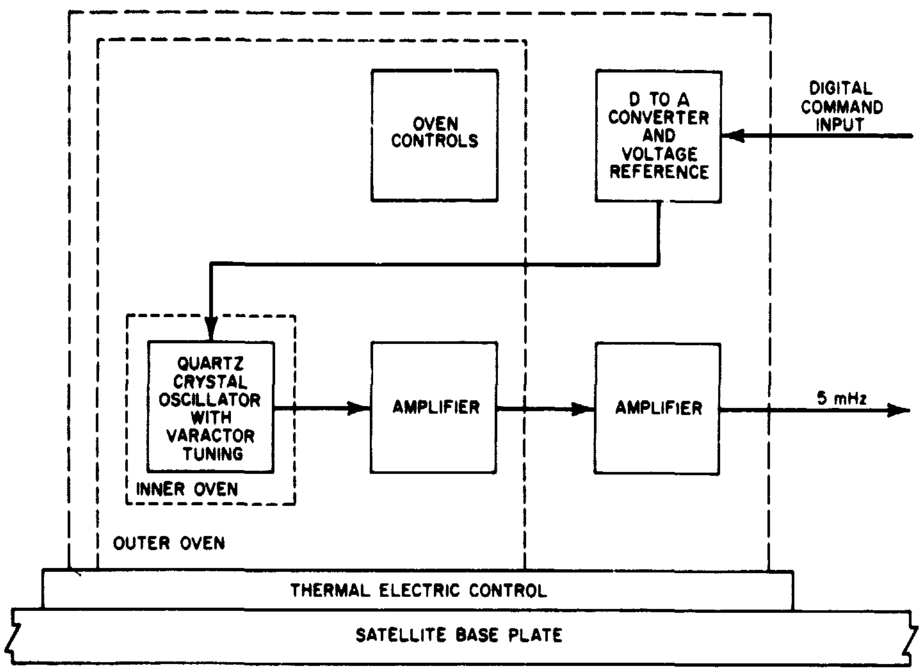


Figure 7. Quartz Oscillator Block Diagram

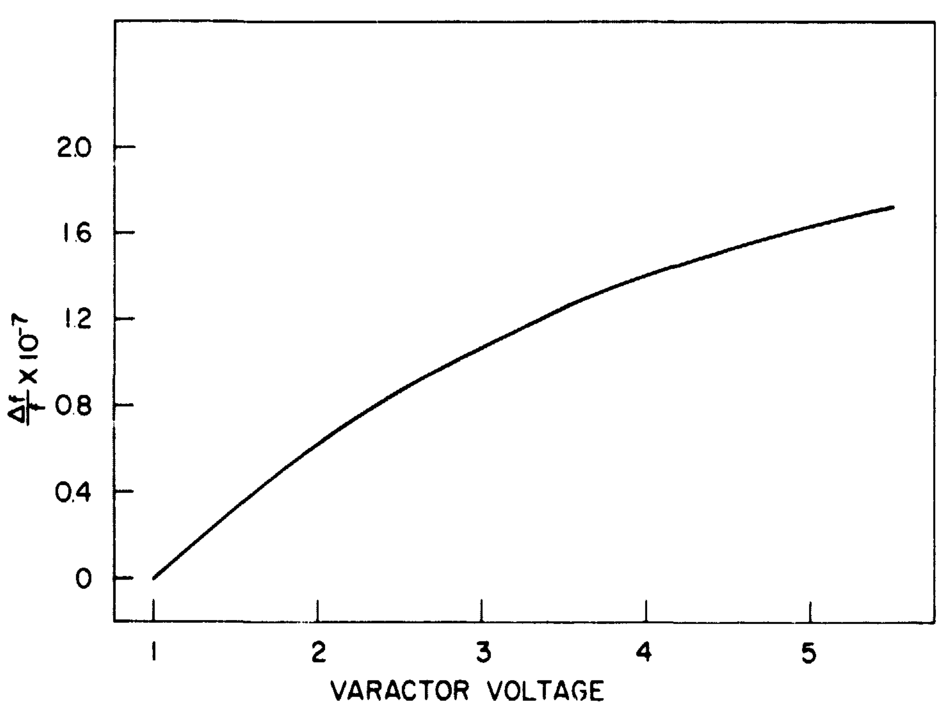


Figure 8. Quartz Tuning Curve

Two Rubidium Vapor frequency standards[8,9] will also be flown to test their feasibility for space use. A block diagram is shown in Figure 9. Two units are to be flown for tests and reliability although only one can be turned on at any one time. These units are commercial units manufactured by Efratom Elektronik Gmbh, Munich Germany, which have been extensively used by NRL and modified for space use. Remote control of this unit is accomplished by controlling the Rb crystal oscillator, the C field current and monitoring the loop control voltage. The Rb crystal oscillator has two varactors, one for the loop control, and another to set the oscillator within the loop lock range. This oscillator has an expected aging rate of 3 pp 10^{8} per month which is ten times the anticipated radiation effect. The 8 bit D/A converter will give this oscillator a range of 2 pp 10^{6}. By monitoring the Rubidium control voltage the oscillator may be periodically adjusted to keep it within the lock range of ±5 pp 10^{7}. The frequency output of the Rubidium unit can be adjusted by applying an external current changing the magnetic field around the resonance cell. A 10 bit D/A converter will give a range of 2 pp 10^{9}. The tuning curves are shown in Figure 10.

The dc power budget is shown in Figure 11. The tuning command power is shut off when not in use. The quartz system uses almost 3 watts and the rubidium system uses almost 13 watts.

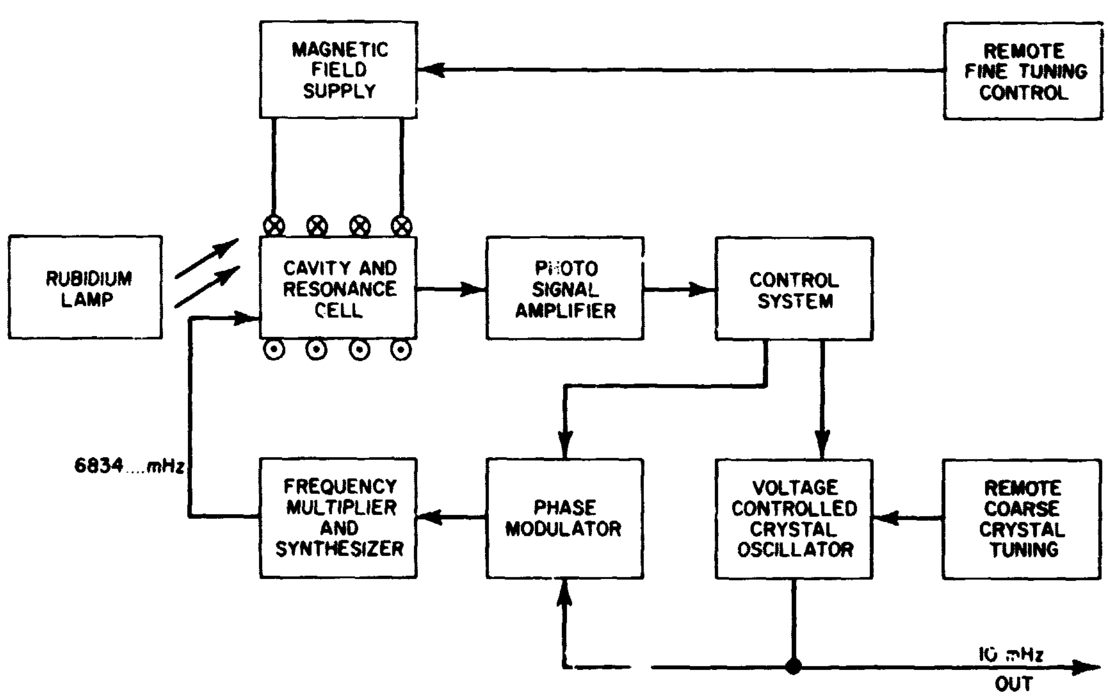


Figure 9. Rubidium Block Diagram

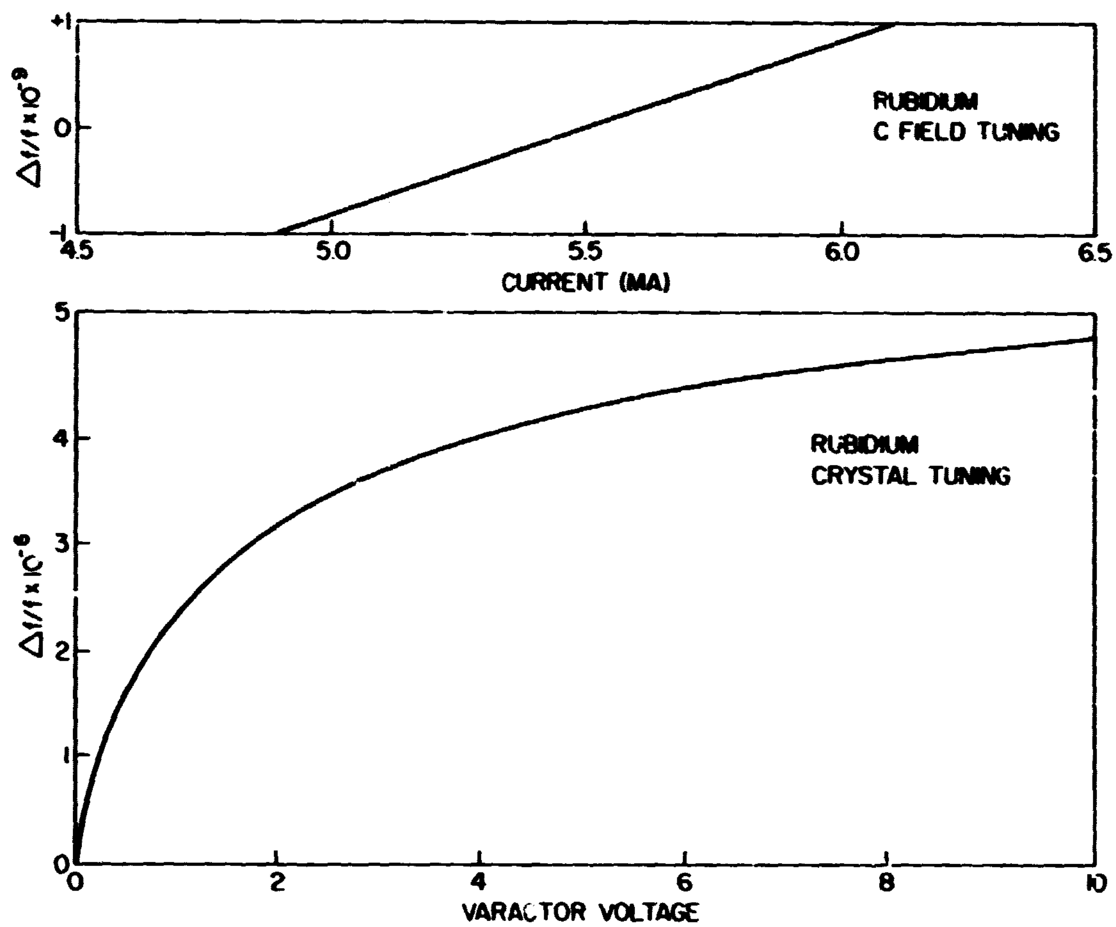


Figure 10. Rubidium Tuning Curves

DC POWER FOR OSCILLATOR EXPERIMENT	QUARTZ ON	RUBIDIUM AND QUARTZ ON
OSCILLATOR	1.8 W	12.8 W
TUNING COMMAND	0.3 W	0.5 W
CONTROL LOGIC	0.4 W	0.6 W
D/A CONVERSION	0.7 W	1.3 W
TOTAL FROM REGULATOR	3.2 W	15.2 W
TOTAL FROM BATTERY (90% EFF)	3.6 W	16.9 W

Figure 11. Dc Power Budget

CONCLUSION

The TIMATION III satellite frequency standard system will use a digital control system which will provide control of several frequency standards for spacecraft use for the purpose of testing new concepts and redundancy by the use of digital techniques, integrated circuitry and modern construction techniques. It will be a compact size, low weight, low power consumption device capable of being used with a variety of frequency standards.

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QUESTION AND ANSWER

MR. CHI:

Are there any questions?

(No response.)

MR. CHI:

According to the schedule, there will be a question period open to all the papers. Before I do that I should like to use the opportunity to restate the objective, which is to communicate the activities among the people working in different fields, from different agencies.

Now, I would like to open the session for questions of any paper which were presented during the day.

Please identify yourself, and also the paper or author to whom the question is addressed.

MR. MITCHELL:

I am Donald Mitchell. I am from the Kwajalein Missile Range, and I have a question on Mr. Matthews' paper.

Perhaps I misunderstood, but correct me if I am wrong. Did you state that you only made the evaluations of your delay measurements once every three months at your remote locations?

MR. MATTHEWS:

On the radar systems, yes, that is correct. On the telemetry system, it is as the mission is flown. The time bias is determined on an op-to-op basis. Does that answer your question?

MR. MITCHELL:

Yes, it does. Thank you.

MR. KRUTENAT:

Bob Krutenat, Naval Torpedo Station, for Mr. Nichols, the last speaker.

How severe were the vibration requirements for your rubidium standard, and how did they hold up?

MR. NICHOLS:

This was for an Atlas F launch, which is 13 GRMS overall and a fairly severe vibration. If our parts aren't very carefully mounted, we have trouble. We had problems with broken transistor leads and glass capacitors that short out on us and things of this sort.

The problem is mainly solved by making the printed circuit boards more rigid. The boards were originally mounted in the corners. We felt they were giving the parts a lot rougher ride than they should have.

We have now succeeded in getting past vibration, with four units, but it took a lot of work to get there.

MR. CHI:

As I can recall, you made four units, of which you had two, or did all four pass?

MR. NICHOLS:

In this program, we purchased a total of 10 units. We purchased four initially for prototype testing. We then purchased six more, of which we hope to get two good ones to fly. Of those six, we have taken the four best ones and got them through vibration testing. We will choose the flight one from one of these four.

MR. CHI:

Are all 10 modified?

MR. NICHOLS:

No, at this point only four are modified. The modification is so elaborate and complex that we only modified as many as we felt were necessary, and two of these have been destroyed in testing, taking them apart and putting them back together so many times. We now only have eight operational units left.

MR. CHI:

Dr. Kartaschoff.

DR. KARTASCHOFF:

Do you have some aging data over a long period of time on these rubidium cells? I tested one for 45 days and it remained within plus or minus one part in 10 to the 13th. So, it was much better than stated by the manufacturer.

MR. NICHOLS:

In general, we found the aging to be much better than the manufacturer by a factor of two. We have one on continuous aging for about seven months, and the aging has changed as the units have aged. It generally started off high and improved. I believe the units that we have aged the longest are somewhere around a part in 10 to the 12th per day, or less.

But I think more typical numbers are two to three parts in 10 to the 12th per day.

MR. WILCOX:

My name is Doug Wilcox, and I am from the Defense Mapping School at Fort Belvoir. I would like to ask Mr. Knowles a question on his paper, Applications of Radio Interferometry to Navigation.

Concerning this navigation system which uses quasars as a natural source, what would be the effect on it of a hostile environment, such as a war? How reliable would a quasar be for a navigation of a military vehicle?

MR. JOHNSON:

It would be as reliable as without a war. It is impossible to jam these sources, since they give out a noise spectrum over a very wide range. So, it would be impossible to jam them, so they are very good sources for that. The problem is that they are not very strong.

DR. WINKLER:

I would only have a comment, which does not apply to a single paper, but I would repeat my appeal that we should use a common language. I have found a couple of very strange numbers on some of the slides. For instance, the rubidium standard operating at 6,800 millihertz, or a crystal oscillator which requires 3.5 megawatts for its operation, or data which were given for Julian day "331", which indicates an event very early in human history.

Things like that, I think, again point to the need to be careful in our terminology and to use at least what we have already agreed on. Hopefully we will also agree on some additional terms which may be found useful.

MR. CHI:

Are there any more questions or comments?

MR. KAUFMANN:

I have a question for Mr. Matthews.

Have you considered the use of Loran-D now that it is available on the West Coast in the Vandenberg complex, as opposed to UHF?

MR. MATTHEWS:

Mr. John Schmid here is currently with SAMTEC engineering, and is currently implementing a Loran receiver at our Peno Point facility. Because our precision measurement lab is located at Vandenberg Air Force Base, there is not going to be a receiver located there. The Pemel lab will have the receiver, and they are like our quality control. They monitor our timing and they tell us when we are getting bad. They are immediately right there to repair the cesium if it is in trouble.

MR. KAUFMANN:

I was wondering about your remote locations.

MR. MATTHEWS:

At Kanton Island there were two Loran C receivers. I am not sure if there are any at Kaona Point; no.

MR. KAUFMANN:

I was really thinking about the Vandenberg complex where you transmit, as I understood, over UHF from your central time standard to other remote locations 100 miles or so away. Do you use Loran-C at those remote locations and at the Vandenberg complex?

MR. MATTHEWS:

No. We are using an IRIG-A time code, which we are transmitting on this 1750 megahertz frequency, at each of the 12 remote locations that we have receivers at. We are currently under implementation to put dual receivers in at our telemetry data center, our tracking and receive site at Oak Mountain, which is south of Vandenberg, and at our launch control facility for Minuteman.

At each of these locations, both on the dual receiver basis and on the single receiver basis, we have time code generators there which are phase locked to that incoming IRIG time code, and that provides us the synchronization with our range time.

MR. CHI:

Are there any more comments or questions?

(No response.)

MR. CHI:

Perhaps Dr. Winkler would use one minute or so to inform people how good is Loran-D, and the availability of receivers and so on.

DR. WINKLER:

Well, it is certainly as good as any Loran station for at least differential measurements. The signal can be received with regular Loran-C timing receivers. It gives a signal which you can receive all over California, and a considerable part of the other Western States.

In addition, we are publishing regularly now in our Series 4 bulletins, times of emissions, which are obtained by the Camp Roberts SATCOM terminal in direct synchronization back to the observatory. We are also benefiting from some additional monitoring which is reported back to us.

We hope eventually we are going to have two independent links back to the observatory.

Also, I think that as the number of users has increased, particularly within the Air Force and the Navy and other organizations, that it will be possible to increase the periods of operations.

We have had an increase recently, and maybe another one later on, as more users inform us and the Air Force of their needs.

So, I have a feeling that this is at least one useful system now in existence which from day to day is certainly as precise in its operation as the standard Loran, except there are some slight problems in regard to operator convenience, since the chains are still turning off during the night, or are only in operation during the daytime. The receiver will unlock, and the next day when the station comes back on, it does require a manual intervention to lock it back on. And there is some initial searching procedure on the part of the Loran operators which we are trying to improve. We are preparing some equipment, in cooperation with the Air Force, to assist in eliminating that searching procedure on the transmitter part.

I point this out, because it certainly is not yet completely comparable to the standard Loran as operated by the Coast Guard, which is a real fine operational system has made a remarkable record.

However, we do feel that anyone who keeps these few inconveniences in mind can get high precision timing service.

MR. MERRION:

Mr. Merrion (DMA). I would like to just ask you, are these stations permanently located here now? Are they going to be here for the next 10 or 15 years?

DR. WINKLER:

I think they are as permanent as anything we do nowadays, which cannot be predicted more than maybe a week in advance with real certainty.

It is certainly correct, and I have to tell you this, that these stations originally are contingency stations which may be cut off. However, the need for such a service is so great that I think I would recommend that anyone who can, get a Loran receiver and use it, until the signal disappears, and in the meantime we will see what in addition can be done.

We have some other things in preparation. We have hopes to be able sooner or later to improve the timing available from local television stations on the West Coast. Some development is underway.

We come back again to the question of reliability of service. I think we come back also to the fundamental principles in timing that we had better use what is available; and we had better have some redundancy in service and in our sources for timing — which is even more important. Some redundancy is indispensable in our operations.

For the foreseeable future, let's say a year or several years hopefully, I think the Loran D West Coast service has an excellent capability, and within that period of time other things will be developed.

I think we will hear about that tomorrow.

MR. MONTGOMERY (WSM Radio in Nashville):

We have been operating phase lock with the Bureau of Standards, WWVL, for some three or four years now, and if you have a receiver that will tune in 650, you can get this standard carrier there.

DR. WINKLER:

And a good program also.

MR. MONTGOMERY:

Right.

(Laughter.)

DR. KLEPCZYNSKI:

I just have one small comment to make in view of the energy crisis that is coming along.

Somebody mentioned in one of the talks earlier that the biggest problem they had in a remote area was power supply. I feel that perhaps in the future it might not only be in remote areas that we will have this problem.

MR. CHI:

Are there any more questions?

(No response.)

MR. CHI:

If not, I would like to turn the session over to the general chairman, Dr. Klepczynski, for the closing remarks.

SESSION III

Chairman: Dr. G. M. R. Winkler
U.S. Naval Observatory

N75 11284

FACILITIES AND SERVICES IN THE TIME DEPARTMENT OF THE ROYAL GREENWICH OBSERVATORY

H. M. Smith
Royal Greenwich Observatory
Haelsham, Sussex, England

INTRODUCTION

The Royal Greenwich Observatory plays a unique role in timekeeping, having both national and international significance. When the Observatory was founded in 1675, two specially-designed clocks by Thomas Tompion were installed to enable the first Astronomer Royal to check on the regularity of the diurnal rotation of the Earth. In the nineteenth century distribution of time signals by electric telegraph became increasingly popular and by 1880 Greenwich Mean Time (GMT) was adopted as the standard time throughout England, Scotland and Wales. Following a meeting of scientific experts in Rome in 1883, the Washington Conference of 1884 recommended the use of the Greenwich meridian as the reference meridian for the worldwide measurement of time and longitude.[1] The designation GMT is still in very widespread use, but in many branches of scientific work it has, since 1928, been known as Universal Time (UT).[2]

CLOCKS

Quartz clocks came into use at Greenwich in about 1938, and by 1944 had completely replaced the former pendulum clocks.[3] From the middle of 1955 the rates of the Observatory clocks were checked in terms of the caesium beam frequency standard at the National Physical Laboratory, and in 1966 a commercial atomic clock (HP5060A) was installed at the new location of the Royal Greenwich Observatory at Herstmonceux in Sussex. The time department now operates five caesium standards, which are housed in cellars at sub-basement level. Each standard has an independent earthing system, an individual emergency power supply, and the distribution of time and frequency is by buffered screened balanced lines. On initial installation, each standard is carefully set up according to the manufacturers recommended procedure, the C-field being adjusted to the optimum level. No subsequent frequency adjustment is made by off-setting the C-field. In these strictly controlled conditions, the standards are capable of a stability of mean rate over periods of weeks of better than 0.01 microseconds per day. (1 in 10^{13}). The rates of individual standards can differ by as much as 0.5 microseconds per day, and occasional inexplicable changes of rate of a few tenths of a microsecond per day can occur.

COMPARISON EQUIPMENT

In the twenty years up to around 1955, most of the equipment used in the time service was designed and made in the department [4,5], but in more recent years many electronic instruments have become commerically available. The primary system of clock comparisons utilizes a 10 nanosecond time resolution counter, programmed by a digital clock, to compare the clocks in groups of three, giving both a printed and a punched tape record. These time comparisons are supplemented by continuous records of linear phase comparators with a full scale deflection of one microsecond.

International comparisons are normally effected by reception and measurement of the Loran-C emissions. At Herstmonceux routine measures are made on Ejdes (master) and Sylt (slave) of the Norwegian Sea Chain and on Estartit (slave), Mediterranean Chain, using Austron 2000 C receivers checked differentially and by a simulator. Supplementary comparisons are made using VLF emissions and Tracor 599 and 599T receivers.

CHECK COMPARISONS

The Royal Greenwich Observatory is indebted to the US Naval Observatory for carrying out periodic traveling clock trips, which serve as a valuable check on the routine linkages via Loran-C. The continuation and extension of this service is essential to the task of the Bureau International de l'Heure (BIH) in the formation of an international scale of atomic time.

Comparisons have also been made by the Office National d'Etudes et de Recherches Aerospatiales: a clock carried in an aircraft was compared with clocks on the ground while the aircraft was in flight[6]; and by the US Naval Research Laboratory using the clock carried in the Timation II satellite. [7]

INTERNATIONAL CO-ORDINATION

A significant feature of recent developments in timekeeping has been the acceptance of the need for full international co-ordination, and the Royal Greenwich Observatory has cooperated fully in these projects[8]. There are three major areas of co-ordination:

a. Astronomical—Corrections for the effects of polar variation (p. v.) on astronomical time determination have been applied to the RGO observations since 1948, and for the seasonal fluctuation in the rate of rotation of the Earth since 1950. [9] The "smoothed" scale of astronomical time thus achieved was designated Provisional Uniform Time (PUT) and was the forerunner of UT2 used internationally since 1956.

The observations made with the Herstmonceux PZT are of a very high standard of accuracy and an interesting development has been the establishment in Canada of a PZT at Calgary at the same latitude[10]. The two instruments employ the same stars, the same adopted star places and the same basic methods of reduction. Full co-ordination permits the separation of errors associated with a particular instrument and site from those common to both. These two instruments together make a valuable contribution to the work of the BIH in computing current values of UT and p.v., and to the work of the International Polar Motion Service (IPMS) in the calculation of the definitive polar motion. During periods when the BIH data are required with the minimum delay by the Jet Propulsion Laboratory for the navigation of space vehicles, the Herstmonceux observations are communicated daily to the BIH by Telex.

b. Time Signals—International co-ordination of radio time signal emissions was pioneered by the British and United States time services in 1961 under the joint direction of the USNO and RGO, using the "offset and jump" method introduced in the MSF emissions in 1958[11]. The obvious practical advantages of such a scheme led to the recommendation by the International Astronomical Union (IAU 1961) and the International Radio Consultative Committee (CCIR, 1962) of the extension of the system to worldwide co-ordination under the control of the BIH. This system was modified by the elimination of the offset in 1972, and is now universally adopted.

A CCIR Working Party (IWP 7/1), has the continuing task of studying the implementation of the system and its possible improvement.

c. Atomic Time—The Greenwich Atomic Time Scale GA was established in 1955, and an adjustment was made (GA2) in 1958 to bring it into step with other national and international scales. The international scale (IAT) formed by the BIH was adopted by the International Committee of Weights and Measures in 1972 and is proving to be indispensable. Until mid-1973 the IAT scale was formed from seven independent scales (of which GA2 was one): since that date it has been formed using the data from individual atomic standards. The data are made available to the BIH by using Loran-C comparisons. The UTC scale used in radio time signal emissions is based on IAT, and differs from it by an exact number of seconds. This has become the "de facto" civil time in most countries, and the implications of this are being studied by a working party set up by the Consultative Committee for the Definition of the Second (CCDS of the CIPM).

CURRENT WORK

The vital role of the Loran-C system in the formation of IAT and in the co-ordination of radio time signal emissions on the UTC system, has led to a review of the factors affecting the accuracy of Loran-C measurements. Differential measures can be made on a routine basis to an accuracy of 0.01 microsecond, but there is still some confusion regarding absolute measures. It is recommended by the USNO that calibration of a reception station should be performed using a whip aerial: most users are forced to employ frame aerials for their routine operational work. European reception sites suffer a high level of interference, and cycle identification is difficult. With the cooperation of the USNO, and of the US Coastguards (responsible for the Loran-C system) many tests have been made. Some adopted propagation times appear to be in need of revision. A puzzling feature is the apparent drift between the Loran-C comparisons and those made with a travelling clock (see Table 1).

Another point of interest concerns the IAT scale. This is formed almost entirely of commercial (Hewlett Packard) standards. The occasional measures made with long-beam laboratory standards (which have a range of the order of 1 in 10^{12}) indicate a systematic departure of IAT from the SI definition of the second[12]. There is a considerable body of opinion in favour of preserving the uniformity of the IAT scale to the highest degree possible so as to form a continuous uniform scale even if this entails a gradual drift from the best contemporary determinations of the SI second. It is a matter for discussion whether the IAT scale should be re-assessed and, if so, how often.

The arguments in favour of changing from a mean of independent scales to a statistical mean of individual standards carried weight: the new system permits the use of more standards (including those of establishments having only one or two atomic clocks), eliminates the uncertainties as to the procedures used at independent establishments in the formation of their own scales, and makes it reasonable for the BIH to adopt objective statistical methods of weighting. Nevertheless, there is a feeling that the ideal method has still to be found.

A promising development is foreseen in the successful tests made, both in the U.K. and in Australia, using Timation II. With the improvements planned in subsequent satellites, there is a prospect of achieving an accuracy no less than that of Loran-C under favourable conditions, and with the possibility of a full worldwide coverage. Long-term parallel operation of Loran-C and Timation is necessary.

Table 1

Traveling Clock — Loran-C

unit : microsecond

Date	OP	Date	RGO	Date	PTB
1969 Feb. 24	-0.1	Feb. 25	0.0		
July 11	+0.2	July 10	+0.4	July 21	+0.4
Oct. 29	-0.3				
1970 Feb. 16	-0.5	Feb. 17	0.0		
June 22	0.0	June 22	-0.3		
Aug. 15	-0.6				
Sep. 10	-0.6	Sep. 14	-0.6		
		29	-0.4		
Oct. 20	-0.4			Oct. 13	-0.1
1971 May 16	-0.8				
Sep. 23	-0.3	Sep. 30	+0.1	Sep. 25	0.0
1972 Apr. 11	-0.6	Apr. 19	-1.8	Apr. 14	-0.3
Dec. 7	-1.0	Nov. 30	-1.5		
1973 May 7	-1.3	May 15	-2.2		
Sep. 26	-1.1	Sep. 17	-1.3		

Differences of UTC comparisons with USNO using traveling clock and Loran-C.

It will be evident that in the collation of data and in the operation of an international service, the BIH is fulfilling an even more important function. The existing and predictable demands for accuracy can only be met by combining worldwide observations to determine UT and by syncretizing atomic clocks to establish an international standard atomic clock time. If this essential service is to be maintained, and is to be developed, adequate financial provision is obligatory, but practical assistance in the loan of equipment and staff could also be of assistance.

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QUESTION AND ANSWER PERIOD

DR. WINKLER:

We are open for questions.

DR. REDER:

Mr. Smith, wouldn't it be good, if you do make this comparison which you showed in the last two slides, to have at least one of those equipments which are used in France brought to your place or the U. S. Naval Observatory for comparison to be sure it is not due to an equipment difference?

MR. SMITH:

I am sorry, but in the limited time at my disposal, I couldn't explain the experiment in detail. I should have said that the receivers and full measuring equipment from the United States Naval Observatory were taken both to Herstmonceux and to Paris.

The agreement between the onsite equipment at Herstmonceux and Paris with that which was brought from the USNO was absolutely first class, and therefore there was the common element which you so rightly point out is necessary to an experiment of this type.

DR. WINKLER:

Mr. Lavanceau?

MR. LAVANCEAU:

In regard to the Loran C measurements of 1973 on two different occasions in Europe (Paris, Royal Greenwich Observatory, Germany, and also in the Faeroe Island, near the master station of the Norwegian Loran C chain), extreme care was taken in taking the measurements, i.e., during the same week, using the very same equipment, including antenna cables. All measurements made in Paris, BIH, and the Royal Greenwich Observatory did agree very, very well. I think one should realize and recognize that Loran C is a marvelous transfer tool. When one wants to make relative time transfer measurements, extreme precision can be achieved, such as perhaps tenths of microseconds or better.

But, when one is trying to make absolute measurements, there are so many variations, so many variables which sometime cannot be controlled that the scatter of the data, which we have seen here, is actually not really very large.

In most cases, it is 0.5 microseconds, and if one realized that some of this linkage is built by using 5 or 6 different sources of data, like for instance, when one is trying to relate measurements made at the U. S. Naval Observatory to measurements made at the same time across the Atlantic.

You know, one may not appreciate the fact that any small errors which one will encounter at one of these locations will of course add in some statistical way, and perhaps create that scatter. The Loran C system is capable of achieving greater accuracy, but a considerable price may have to be paid for that. This may not be easy to cope with.

DR. WINKLER:

I would like to make a comment myself. There are really two issues here. Mr. Lavanceau mentioned the small (0.5 microseconds) scatter in the measurements across the North Atlantic.

The question which we are also debating is the difference between making absolute measurements and relative measurements which you calibrate by visiting portable clocks, and this is what we have done from the beginning of the use of Loran C in the international system of atomic time keeping.

The observatory, for that very reason, has sent portable clocks to various establishments about twice every year.

We have kept a check on the propagation delays. But when you talk about absolute time transfer, i.e., when you set up equipment at the new location, and compare the computed delays with your own calibrated delays including the equipment, what is then the error, in an absolute sense of your time transfer?

We are talking about a problem which is common to every synchronization system in existence. It is only the magnitude which is different for the various systems.

If you take a VLF timing system, the magnitude is ten times larger. The differences between computed delays and actually calibrated delays are as large as 10 microseconds.

In a satellite system you also have exactly the same situation that one must calibrate a path or location. I think we will hear more about that this afternoon.

Again, we have to understand that difference between an absolute and a relative measurement where you calibrate overall by bringing a portable clock to the point of use, from time to time, to check everything, to certify the operation, and that it is one operation which essentially will have to be done in every system of time transfer.

Now, the magnitude of the specific effects we are here concerned with is for me startlingly great. I would think that what we have to accomplish urgently is a standardization of methods.

We have found between the various stations which we have visited that if we do the same things, with the same equipment, everywhere, we find a very high degree of conformity and repeatability of results.

But the general problem arises, I think, in using equipment which has been calibrated in entirely different ways, and then, of course, you could expect such discrepancies as discussed before. The discrepancy, in fact, has been two and a half microseconds roughly.

I am afraid we will have to stop here, because time is pressing. I will have to defer any further discussion to the outside or after the break.

N75 11285

SOME APPLICATIONS OF TIME AND FREQUENCY *DISSEMINATION SYSTEMS IN ITALY*

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Isituto Elettrotecnico Nazionale
Torino, Italy

PAPER NOT RECEIVED

SOME SERVICES OF THE TIME AND FREQUENCY DIVISION
OF THE NATIONAL BUREAU OF STANDARDS

J. A. Barnes
National Bureau of Standards, Boulder

ABSTRACT

The Time and Frequency Division of the NBS provides several services to the general public. The radio broadcasts of WWV, WWVH, and WWVB supply reliable, unambiguous time signals to many, many users, if at a modest level of accuracy. Surprisingly, the NBS telephone time-of-day service also attracts several hundreds of thousands of calls each year. Periodically, the NBS provides courses on specific topics relating to time and frequency technology. In March 1974, the NBS will hold a general course on time and frequency. In addition to numerous technical papers published each year, the NBS has prepared the first volume of a comprehensive monograph on time and frequency which is at the printers now and is scheduled for delivery in January 1974.

The results of research in the Time and Frequency Division of the NBS have had significant impact. An active TV time system capable of serving most of the U.S. currently awaits a ruling by the FCC on a petition filed last year on behalf of the NBS by the Department of Commerce. Three more recent developments are: (1) a TV frequency comparator (patent applied for); (2) a method to perform an independent (absolute) frequency evaluation of commercial cesium beam oscillators; and (3) a method of removing one source of frequency drift in commercial cesium beam oscillators.

DR. BARNES:

It is true, I believe, that we at the Bureau of Standards, in our work, do see frequency changes which are due to the microwave power level, depending on the excitation.

This is what one would expect, in fact, it is due to two effects. The power level will affect the velocity distribution that is important in the transition, and hence if there is any cavity phase shift in the cavity itself, this will manifest itself as a frequency dependence on the power level.

This is an important thing in evaluating a primary frequency standard, and if you are interested in pursuing that, I would say talk to Helmut Helwig, who can give you much more detail on the matter.

N75 11287

SUBMICROSECOND TIME TRANSFER BETWEEN THE UNITED STATES, UNITED KINGDOM, AND AUSTRALIA VIA SATELLITE

R. L. Easton
Naval Research Laboratory

H. M. Smith
Royal Greenwich Observatory

P. Morgan
Australian Division of National Mapping

ABSTRACT

During 1972 time transfer experiments were run between the U. S. Naval Observatory and the Royal Greenwich Observatory and, in 1973, between the U. S. Naval Observatory and the Division of National Mapping in Canberra, Australia.

In both cases the time transfer agent was the TIMATION II satellite, 1969-82B. The satellite ephemerides were computed by the Naval Weapons Laboratory from data provided by the Defense Mapping Agency TRANET. This net tracked the satellite's doppler transmissions.

The phase of the satellite clock was determined from knowledge of the position of the satellite and of the observer and the computed distance between the two. By monitoring the clock on successive passes the rate of the satellite clock was determined at Washington. By again monitoring the satellite clock at the distant station the satellite clock could be compared to the local clock and this local clock compared to the U. S. Naval Observatory clocks.

In 1972 the RMS of observations at Greenwich deviated by approximately 1/4 microsecond from a straight line when compared to the Naval Observatory. In 1973 the observation errors at Canberra were approximately half as great.

TIME TRANSFER

A number of time transfer experiments have been run by means of low frequency navigation systems (LORAN-C, OMEGA) and by clocks carried by aircraft and satellites.

The low frequency systems are useful and provide a large number of users with inexpensive clocks that have new atomic standard stabilities. The problem with these systems is the shifts that occur in the propagation paths.

Atomic clocks carried in aircraft are again a good solution to the problem of time transfer. This technique suffers only from the errors due to transportation time and the costs of this transportation.

The satellite carried clock suffers from a number of error sources that at first might make this technique appear inferior to the others. A closer look makes this one appear to have both the best present day capability and the best chance for improvement.

The problems with the satellite carried clock transfer method are (1) In contrast to the low frequency broadcast station and the aircraft carried clock one must now determine where the satellite (and its clock) is at the time of measurement. (2) The second problem is the instability of the satellite clocks, which are at present crystal controlled.

The first problem, that of the satellite location, is reduced by using a fact of satellite orbital mechanics. This fact is that the principal error in satellite orbits is along track. By making the measurement when the satellite is at its closest point this error becomes negligible. This satellite location error is further minimized by using a navigation satellite for which the techniques of location prediction and postdiction are well known.

The second problem of clock instability is partially solved by the high speed of the satellite. The speed reduces the effect of the instability. For instance, in some cases the satellite clock measurement was made in the U. S. barely 15 minutes before the similar measurement was made in England. A check carried by air and road would take roughly 50 times as long. From this calculation one can see that the satellite clock can have only 2% of the stability of the aircraft carried clock to have equal performance. The satellite clock has another advantage. By waiting an entire orbit and measuring the satellite clock again from the same site and thereby determine much of the clock's instability during the interval between the two previous measurements.

THE SATELLITE

The satellite used is TIMATION II, launched on September 30, 1969 and shown in Figure 1. The orbit of the object is circular, inclination 70°, and altitude 500 n. miles.

The TIMATION II satellite transmits in both the 150 MHz and 400 MHz bands. The satellite carries a clock driven by a very stable quartz crystal oscillator operating at 5 MHz.[2] Active temperature control of the quartz crystal frequency standard to within a fraction of a degree is achieved by (a) careful design of the

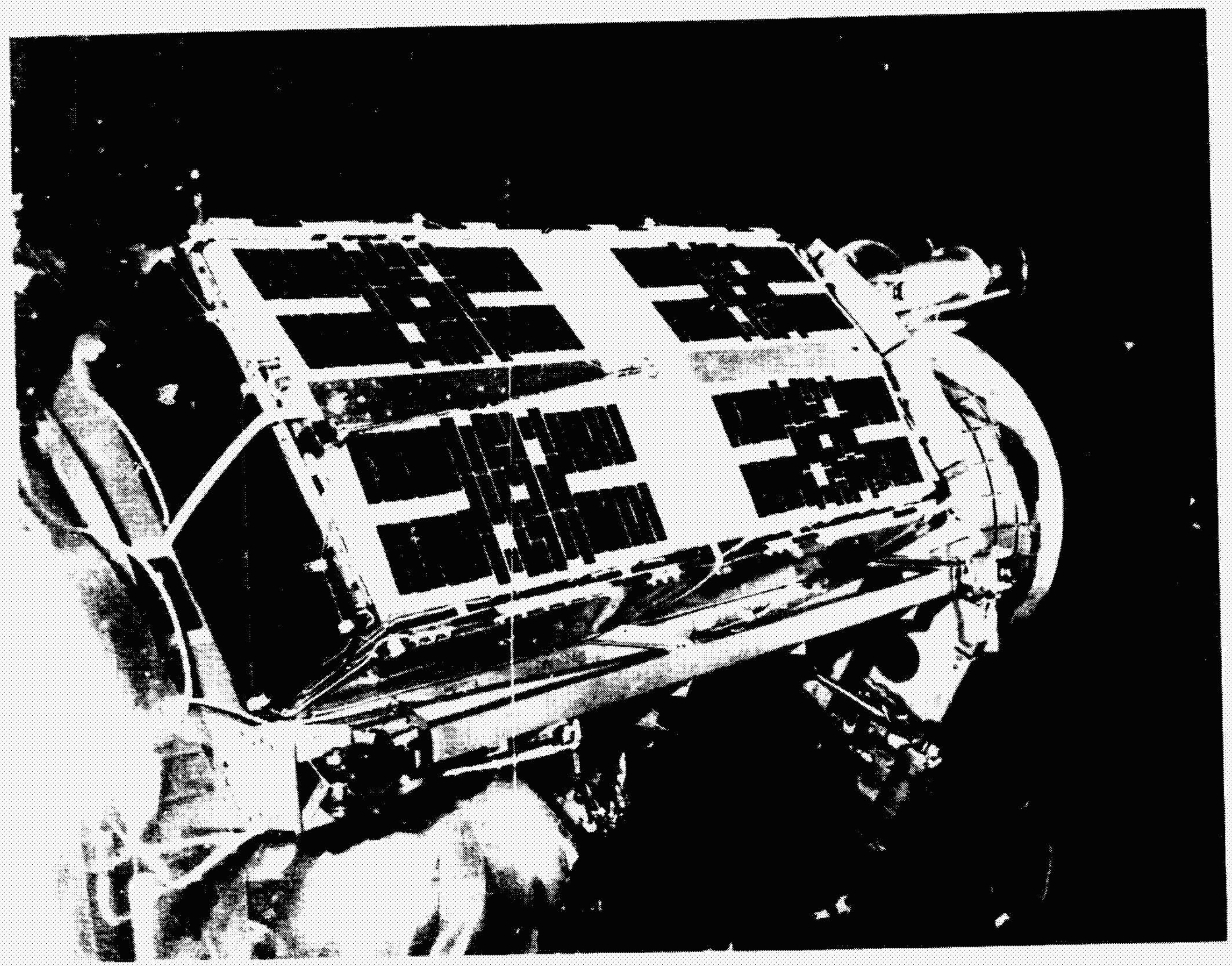

Figure 1. The TIMATION II Satellite

satellite and (b) use of a thermoelectric device for fine temperature control. The satellite antennas are kept earth-pointed by a two axis gravity gradient stabilization system.

Two carriers are coherently derived from this signal, one at 149.5 MHz and the other at 399.4 MHz. Other frequencies are derived in the 149.0 to 150 MHz and 398.9 MHz bands to provide the nine modulation frequencies from 100 Hz to 1 MHz.

The carriers are transmitted continuously to allow doppler tracking or orbit computations. The use of two frequencies provides the data necessary to correct for both range[3] and doppler ionospheric effects and thereby insure a more accurate orbit trajectory.

The range tones are transmitted in a time sharing mode 4.8 seconds every minute. This transmission allows a user with a TIMATION II receiver, which also contains a clock, to measure the time difference between the signal received from the satellite and the ground receiver clock. This time difference includes the propagation time of the signal from satellite to ground plus the synchronization error between the satellite and ground clocks.

ORBIT DETERMINATION

Since launch the satellite has been tracked by the TRANET doppler tracking sites listed below.

Brazil	Philippines
Japan	Australia
Alaska	Seychelles
England	South Africa
New Mexico	Thialand
APL	Wake
Samoa	Cyprus

The data has been sent by the AUTODIN circuit to the Applied Physics Laboratory of Johns Hopkins University at Howard County, Maryland for preprocessing before being sent to the Naval Weapons Laboratory in Dahlgren, Virginia for use in the computation of the orbital elements. The orbit is computed using observed data over a two day span. An additional seven days of predicted minute vectors are then derived. The orbit fit in the observed region is accurate to approximately 10 meters. The further into the predicted region the more inaccurate the trajectory becomes.

COMMUNICATION LINK

The present location of the Royal Greenwich Observatory is at Herstmonceux England about 50 miles south of London. The communications link (Fig. 2) used in the experiment was primarily the General Electric commercial time share system. A Post Office (PO) telephone line was arranged between Herstmonceux and London. The GE time share system could be activated by dialing a local London telephone number and nearly immediate access was available to the computer located in Cleveland, Ohio. The only equipment necessary at the RGO site was a Model 35 teletype terminal and acoustical coupler. A similar terminal was available to personnel at NRL.

After the orbit was computed at the Naval Weapons Laboratory the minute vector trajectory date was placed into the NWL time sharing files. It was then transposed by NRL personnel into the GE files in the computer located in Cleveland. By using the terminal at RGO the data could then be retrieved from GE. The cycle could be accomplished in near real time. During the entire experiment absolutely no errors in transmission were experienced on the Cleveland to RGO link.

COMMUNICATION LINK WITH AUSTRALIA

The communications link used between the U. S. and Australia differed greatly from that used between the U. S. and the RGO. For the Australian experiment standard diplomatic circuits were used, augmented by telephone as needed. While this system did not offer the response of the direct link used between the RGO and the U. S. it was adequate once it became familiar to the participants.

EXPERIMENT CONFIGURATION

One TIMATION II receiver was located at the Naval Research Laboratory and used a cesium beam standard as a frequency source for its clock. The cesium beam is referenced to a hydrogen maser also located at NRL. The maser is kept to within a few nanoseconds of the Naval Observatory's standard. Therefore the ground clock at the NRL TIMATION site is ultimately referenced to the time standard from the Naval Observatory.

The complete NRL station configuration consisted of an analog phase receiver, a cesium beam standard and dual circular polarized helices. The receiver is a single band 400 MHz range receiver, which tracks a carrier and tone set. The lowest tone is 100 Hz and 1 MHz is the highest tone. The ratio between adjacent tone frequencies is approximately 3 to 1.

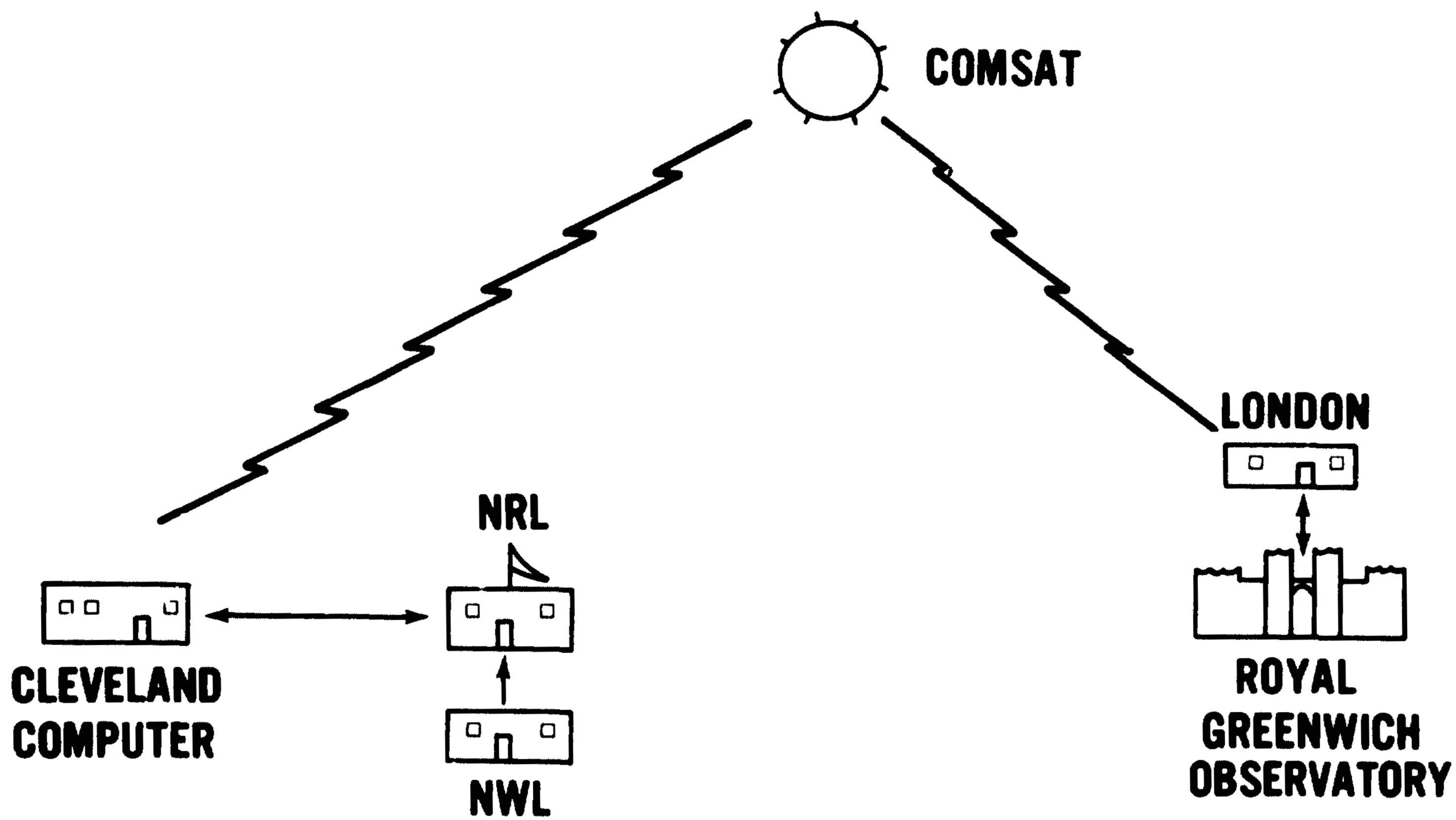

Figure 2. Communication Between RGO, NRL, NWL and the Computer

The site configuration at RGO and Australia consisted of a digital TIMATION II receiver (Fig. 3), a cesium standard supplied by the local station, a digital clock, and dual circular polarized Yagi antennas (Fig. 4). The TIMATION II receiver used automatically combined the range tones and displayed a resolved range (time once a minute when the signal from the satellite was being tracked. Adjacent modulation frequencies had a 10 to 1 ratio as opposed to the 3 to 1 ratio used in the NRL analog receiver. The lowest tone (100 Hz) and the highest tone (1 MHz) were identical to those used at NRL. This larger difference between adjacent tones required a tighter tolerance on signal to noise ratio. Consequently some minutes of data which were correctly resolved at NRL had to be filtered from the RGO system, as will be shown later.

ANALYSIS OF RESULTS OF THE RGO EXPERIMENT

Time difference measurements between the clock in the satellite and the clock at each ground station are taken when the satellite is above the horizon at each ground station. An epoch time transfer can be performed using just one simultaneous measurement from each ground station, however, the precision of the time transfer can be improved by using more observations collected over a large span. For this experiment data were collected for 1 week. The inclusion of data over a 1 week span allowed a determination of the frequency difference between RGO and USNO in addition to the epoch transfer. The repeatability of the time transfer via satellite was demonstrated and the contribution of several error sources was reduced by using redundant measurements.

Time difference measurements at each site were obtained using ranging receivers at 400 MHz. The use of measurements at only one frequency prevented an accurate correction for the group delay to the signal due to the ionosphere. The contribution of the ionospheric effect to the time transfer was minimized by collecting data for the 1 week period, which caused any bias in the time transfer due to this error source to approach zero, however the variance of the time transfers measurements was not reduced.

The observed time difference is given by

$$O_{obs} = t_{prop} + (t_{sat} - t_g) + \Delta t_{iono} + \Delta t_{trop} + K + \epsilon \qquad (1)$$

where

(1) O_{obs} is the measured or observed time difference.

(2) t_{prop} is the free-space propagation delay along the line-of-sight from the satellite to the receiver.

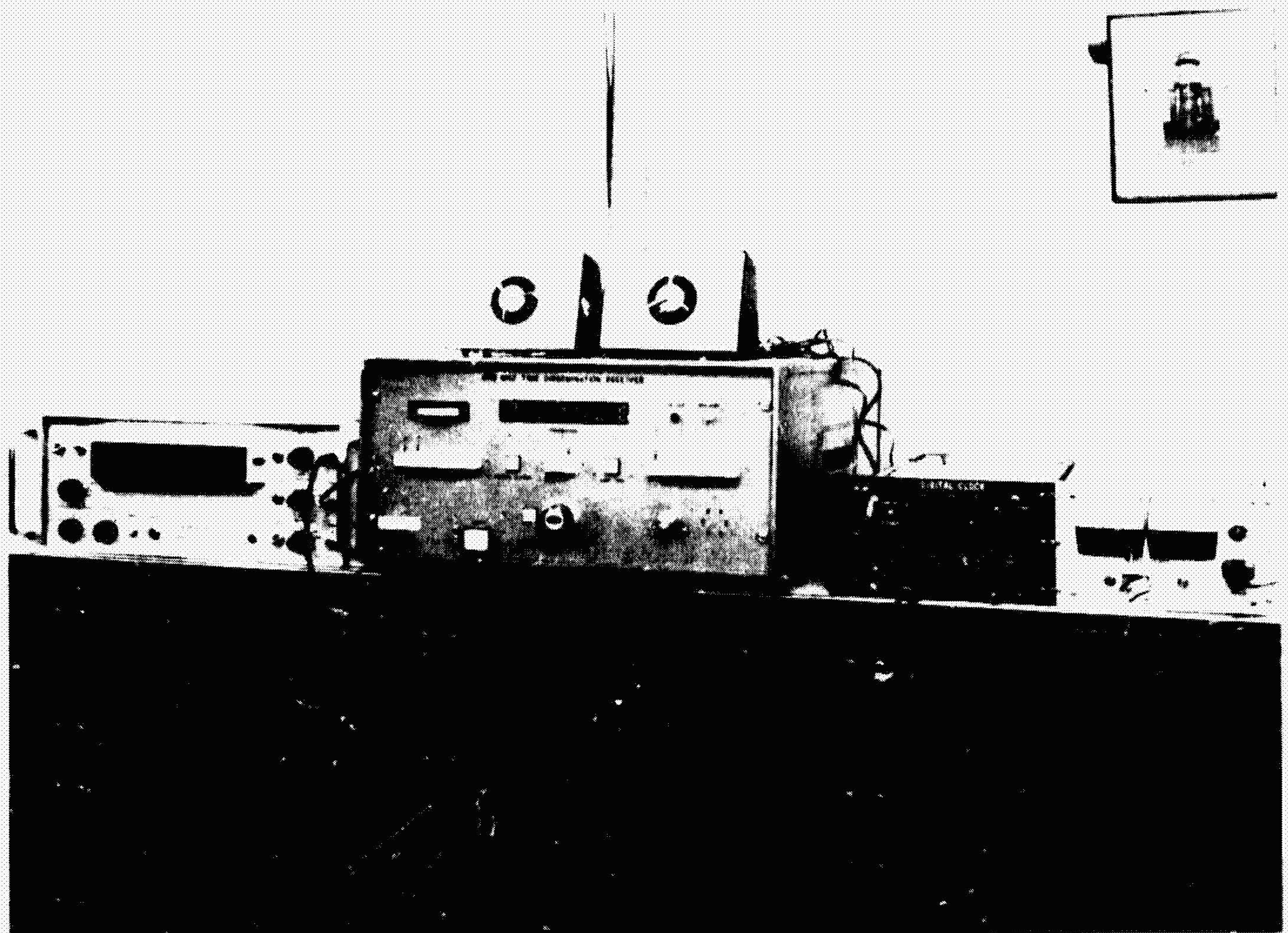

Figure 3. Receiving Equipment Used at RGO and in Australia

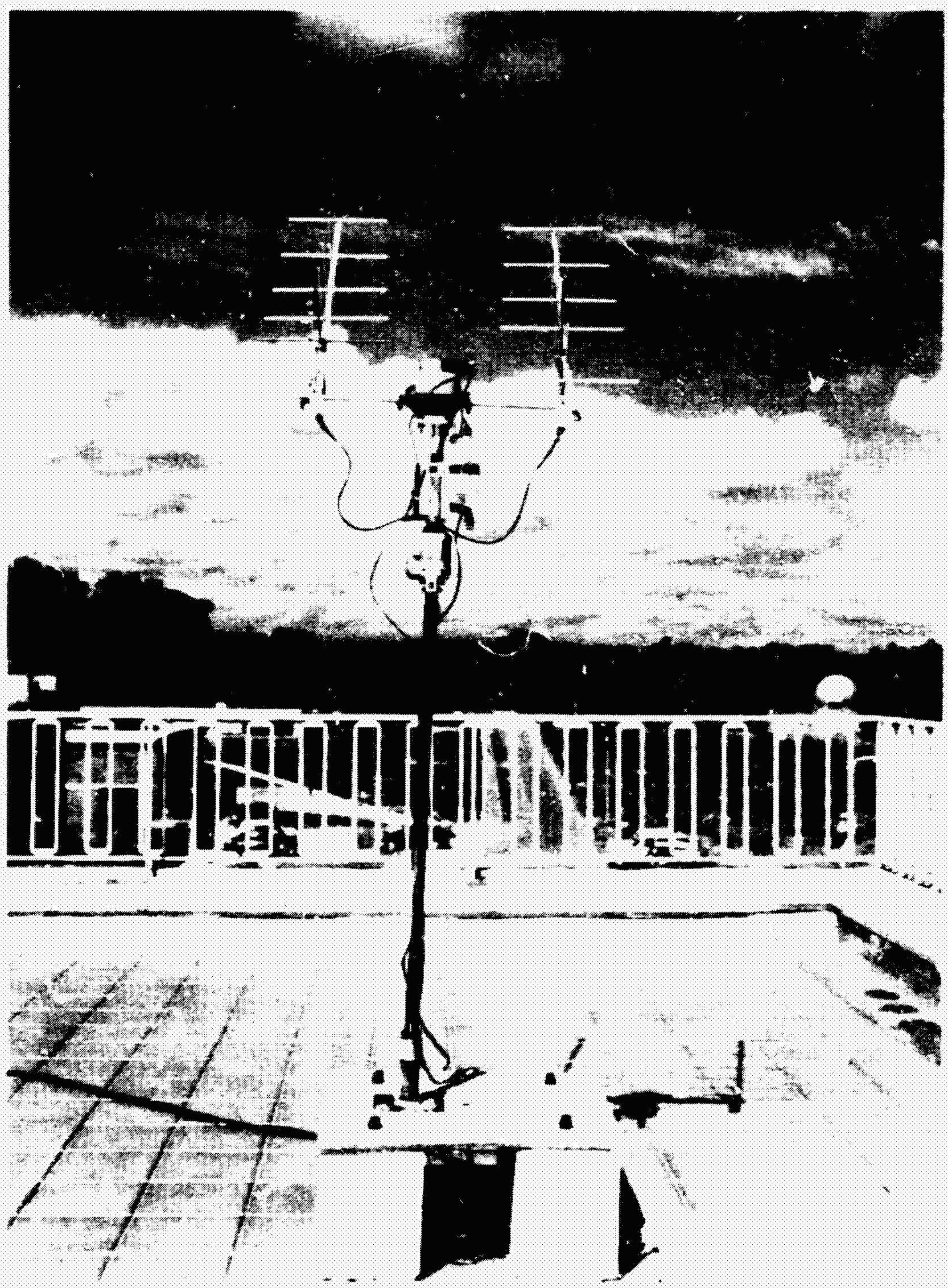

Figure 4. The Antenna Installation at RGO. The same antenna was used in Australia.

(3) $(t_{sat} - t_g)$ is the time difference between the satellite clock and the ground station clock.

(4) Δt_{iono} is the ionospheric group delay at 400 MHz.

(5) Δt_{trop} is the delay through the troposphere.

(6) K is the delay from the antenna through the receiver which is either calibrated to zero or precisely measured.

(7) ϵ is the random and unmodeled error in each observation.

The term t_{prop} is of the form R/c where R is the range from the satellite to the receiver antenna and c the speed of light in vacuum. The calculated value of R is influenced by the accuracy of the satellite ephemerides as well as the knowledge of the observer's geographical position. The largest component of uncertainty in satellite position is along the track of the satellite. The error in t_{prop} due to this component can be minimized by taking the time difference observation when the satellite is near TCA (Time of Closest Approach) to the receiver. At TCA the satellite is a maximum elevation and is therefore moving normal to the line of sight. Since the elevation angle is at a maximum, the contributions due to the troposphere and ionosphere are also minimized.

The satellite ephemeris is used with the receiver antenna position to calculate theoretical values of the time differences denoted by T or T_i for the "i" th point. Then a correction is calculated using the observed time differences which is denoted by (T-O) or (T-O)i. The (T-O)'s may be designated for RGO, NRL or USNO by (T-O)RGO, (T-O)NRL or (T-O)USNO.

The Naval Observatory UTC time, denoted by t_{USNO}, is transferred to NRL by (a) a microwave relay link or (b) a traveling clock. Hence the (T-O)NRL values may be reference to the Naval Observatory by Equation 2.

$$(T\text{-}O)USNO = (T\text{-}O)NRL + (t_{USNO} - t_{NRL}) \quad (2)$$

The NRL clock was corrected before each satellite pass to agree with UTC, hence there is no significant bias between the two clocks, and the second term in Equation 2 approaches zero (to within a few nsec). The two (T-O)'s may be combined to give (T-O)RGO - (T-O)USNO which yields the epoch transfer. The slope of the time transfer curve during the 1 week data span then yields a measure of the frequency difference between the ground station clocks at RGO and USNO.

The TIMATION II satellite clock is driven by stable 5 MHz quartz crystal frequency source and is used to derive the satellite time base which is designated by t_{sat}. The satellite clock is tunable in both frequency and time, however for this experiment no corrections were applied during the data span. The quartz crystal exhibits a low aging rate with respect to the UTC time base, hence t_{sat} may be ultimately related to UTC by Equation 3.

$$t_{sat} = T_0 + f_0 (t_{USNO} - t_0) + 1/2\, a_0 (t_{USNO} - t_0)^2 \qquad (3)$$

The terms T_0, f_0 and a_0 represent the time, frequency and aging rate differences between the satellite clock and the USNO time base at some epoch t_0. If simultaneous observations are taken, then the satellite clock is eliminated when the difference (T-O)RGO - (T-O)USNO is computed using Equation 1. The satellite clock was a factor in this experiment because the TCA's from RGO and NRL were separated by about 15 minutes in time for the same revolution of the satellite.

Figure 5 shows a typical pass taken from the NRL site. The (T-O) values were biased for convenience in producing the computer plots. These (T-O)'s exhibit a slope which is partially due to orbit inaccuracies. Taking the reading of the (T-O) for each pass at the maximum elevation point minimizes the contribution of several error sources.

Figure 6 shows a pass taken from the RGO site. A bias was inserted for convenience in making the RGO computer plots, as is noted in Figure 6. For this pass three points were filtered and two points show a jump of approximately 1 microsecond with respect to the majority of the observations. As mentioned previously, this can occur for the digital receiver used at the RGO site because of the 10 to 1 ratio between adjacent tones. The NRL analog receiver (which used approximately a 3 to 1 tone ratio) and the digital receiver were calibrated at NRL before this experiment to insure that the time differences measured represented the actual time delay.

All passes collected over the 1 week period are presented in Figure 7. The lowermost plot gives the (T-O)USNO values which are obtained from the (T-O)NRL values through the use of Equation 2. The middle plot gives the (T-O)RGO values directly* because their time standard was used to drive the

*A four microsecond offset was inserted for convenience, hence the final values require a four microsecond correction.

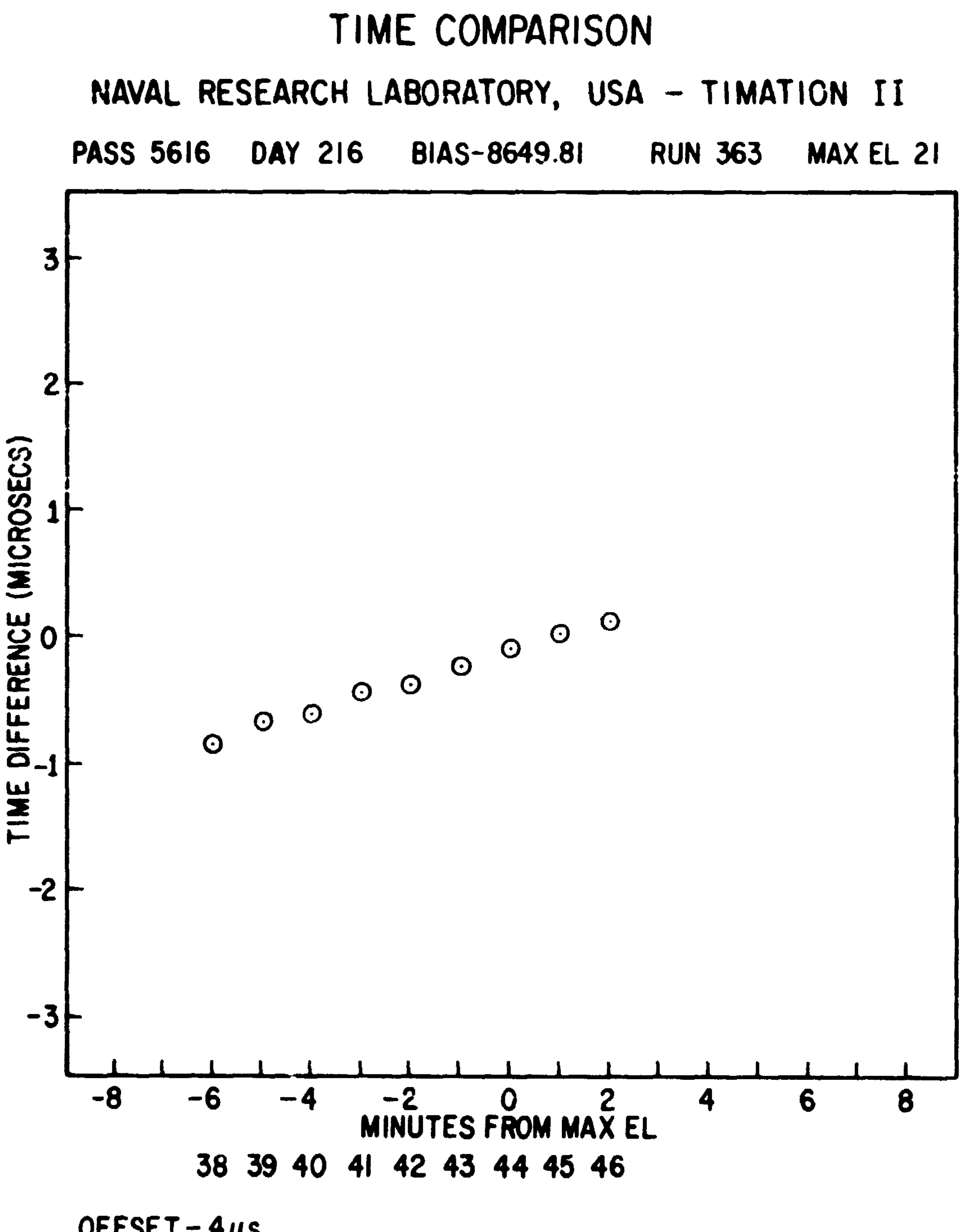

Figure 5. Data From a Typical NRL Pass

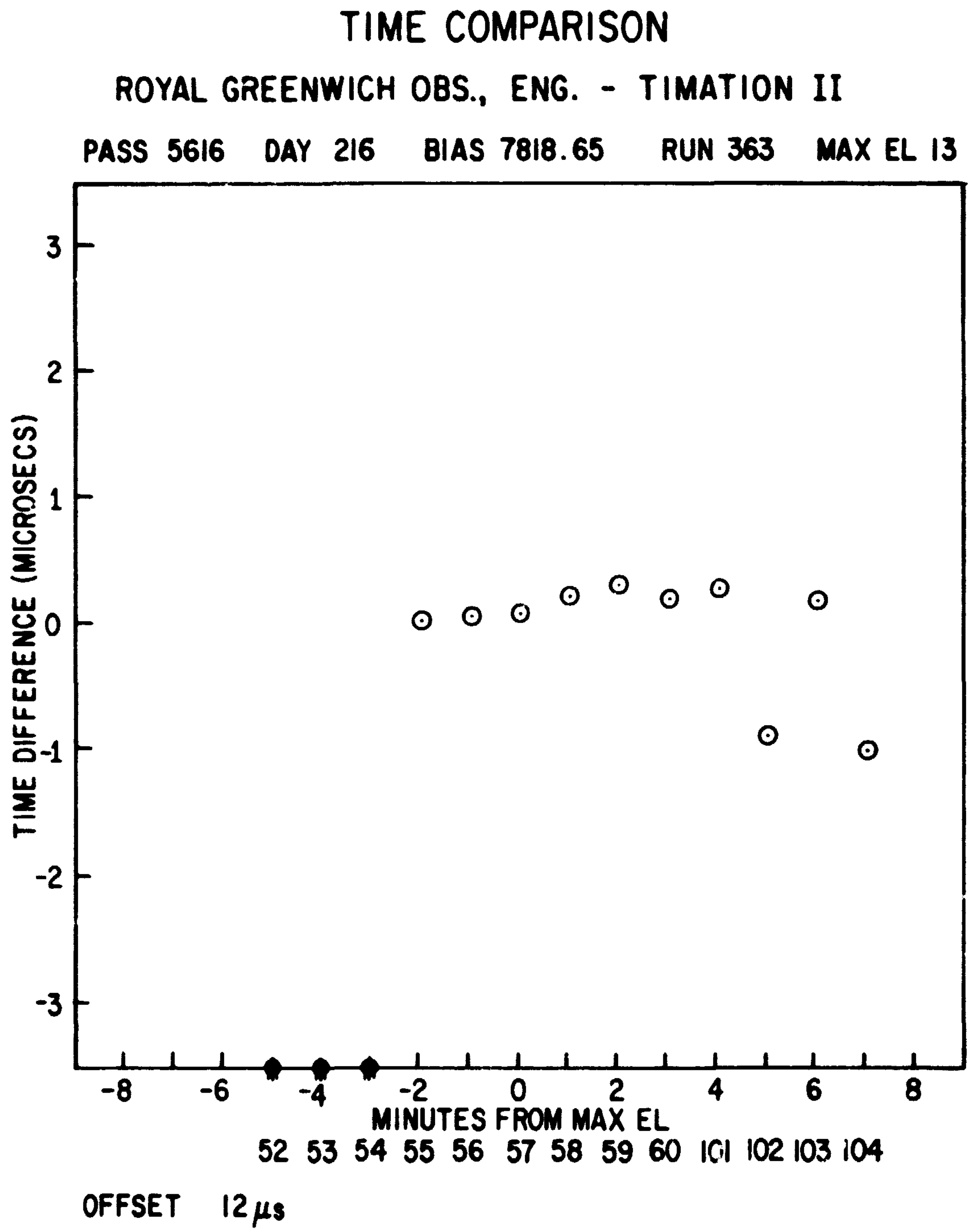

Figure 6. Data From a Typical RGO Pass

TIME TRANSFER - TIMATION II SATELLITE
NAVAL RESEARCH LABORATORY AND ROYAL GREENWICH OBS

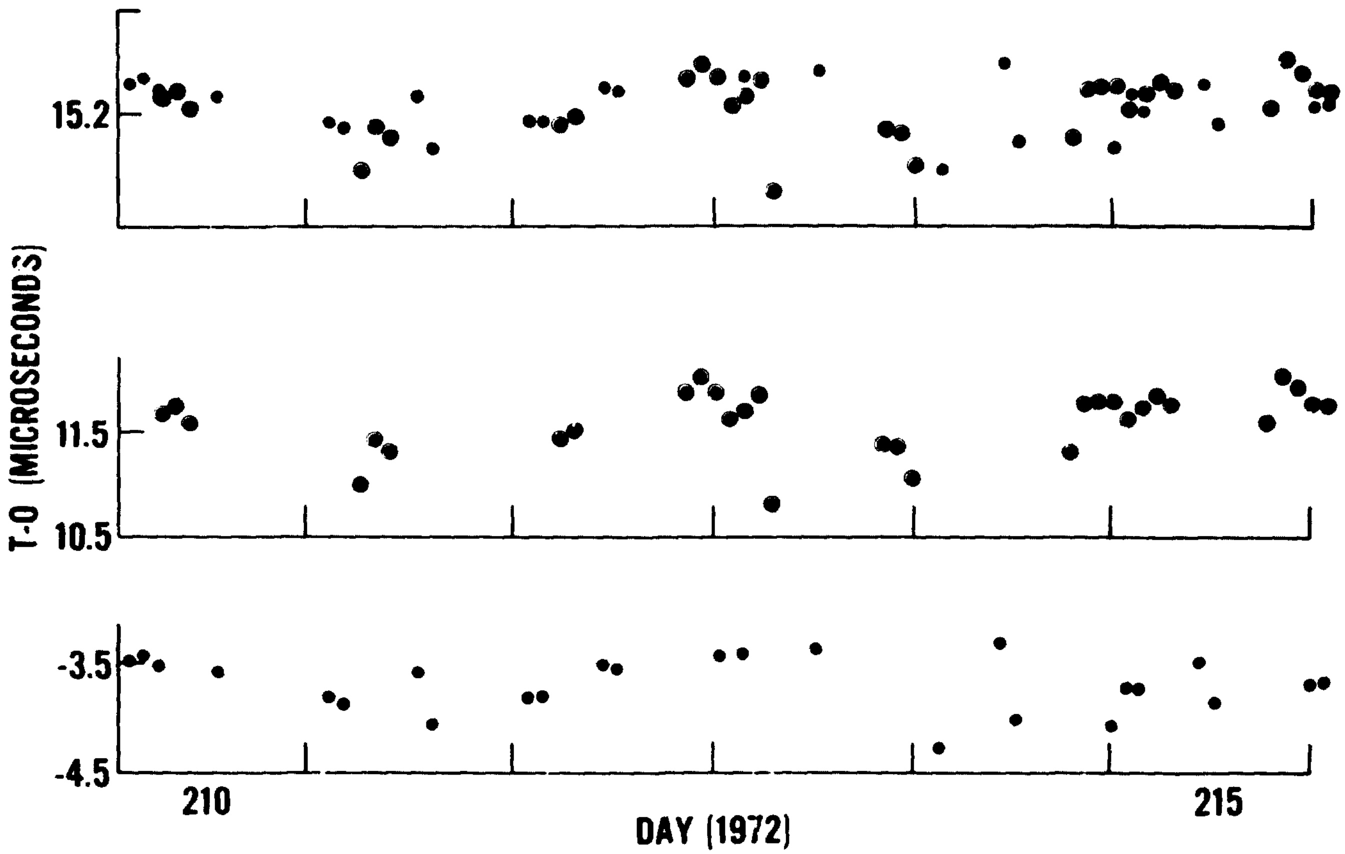

Figure 7. Individual and Combined RGO-NRL Passes Taken Over 6 Days in 1972

digital receiver. The effect of the satellite clock has been removed from Figure 7. The (T-O)'s can be subtrated to produce the final (T-O)RGO - (T-O)USNO plot on the top of Figure 7. This yields the time transfer on a pass to pass basis between RGO and USNO.

CONCLUSIONS

RGO has two different methods of clock synchronization with USNO, firstly the traveling clock experiment which is performed approximately every 6 months and secondly, daily comparison with LORAN-C. Figure 8 shows the traveling clock closure made about 4 months before the TIMATION time transfer experiment and again 3 months after the experiment. It is seen that a constant 1.5 microsecond difference was present between LORAN-C and the traveling clock. Figure 9 compares the results for August 2, 1972 which shows agreement to less than 0.5 microsecond, assuming the same bias for LORAN-C. The frequency difference between RGO and USNO is given by the slope of the (T-O)'s in Figure 13 and yields a value of less than 5×10^{-12}. The RMS noise level was ±0.3 microsecond.

	TRAVELING CLOCK	LORAN C	Δ
4 - 17 - 72	7.9	9.5	1.6
11 - 3 - 72	11.8	13.3	1.5

Figure 8. UTC Differences Made Between RGO and the USNO

THE AUSTRALIAN EXPERIMENT

The Australian experiment was aided by knowledge obtained at RGO. After the completion of the RGO experiment the digital receiver was recalibrated using a large number of satellite passes. The phase adjustments on the several sidetone frequencies were used until the adjustments produced the minimum number of resolution faults. The readings on this receiver were then adjusted to be equal to those obtained on the analog receiver at NRL.

Figure 10 shows the results of the first run at the Australian site. In this case the data shown is a direct comparison of each station with the satellite clock.

8-2-72	
UTC (RGO) - USNO (Loran C)	-11.1
UTC (RGO) - USNO (Traveling Clock)	- 9.6
UTC (RGO) - USNO (TIMATION 11)	- 9.8

Figure 9. RGO - USNO Time Transfer Results

The U. S. station is the solid line and the Australian is dashed. The time difference between the two scales is twenty microseconds. When the difference between the data lines is added to this 20 microseconds the chart shown in Figure 11 is obtained. The chart shows a systematic drift of approximately 0.1 microsecond per day and the data deviation is 0.11 microseconds about this drift line.

Two months after these data were taken the Australian group produced the data shown in Figure 12 and Figure 13. These graphs have RMS deviations approximately three times higher than previously. Presumably this higher value exists because the orbits were made using a single 400 MHz signal in contrast to previous orbits made by means of both 400 and 150 MHz signals.

Figure 14 shows the relationship between the two sets of data. It is seen that the average drift of the two standards is 0.087 microseconds per day. These data were extrapolated further to compare it to the USNO traveling clock measurement made on 6 December. The difference between this extrapolated and the measured value was 0.09 microseconds.

FUTURE MEASUREMENTS

Further measurements are being made in Australia. It is expected that the next satellite of this series will provide improved data for worldwide time transfer.

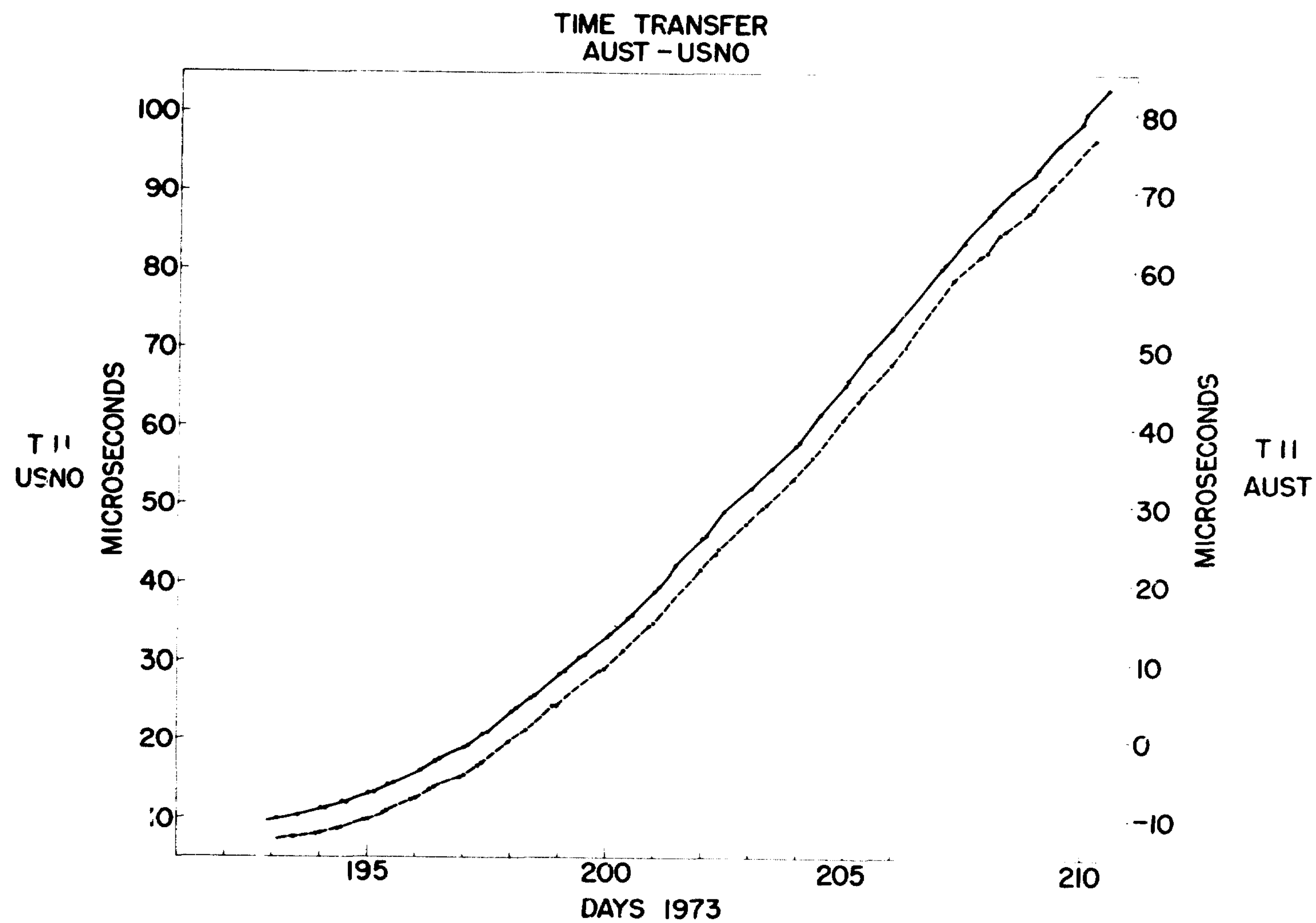

Figure 10. Results of First Australian Run

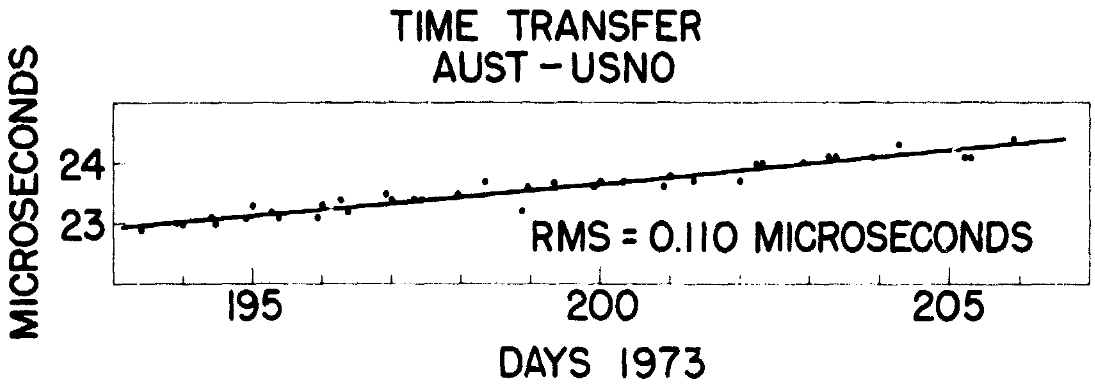

Figure 11. Time Differences Obtained from Figure 10

ACKNOWLEDGEMENTS

Experiments like those described require the help of many people in many organizations. The following list contains a number of those involved.

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Naval Research Laboratory

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Donald Lynch
Thomas McCaskill
Hugh Gardner
Cecelia Burke
Charles Arvey

Johns Hopkins University - Applied Physics Laboratory

P. E. P. White
Henry Frazer
James Wilcox

TRANET - all station personnel

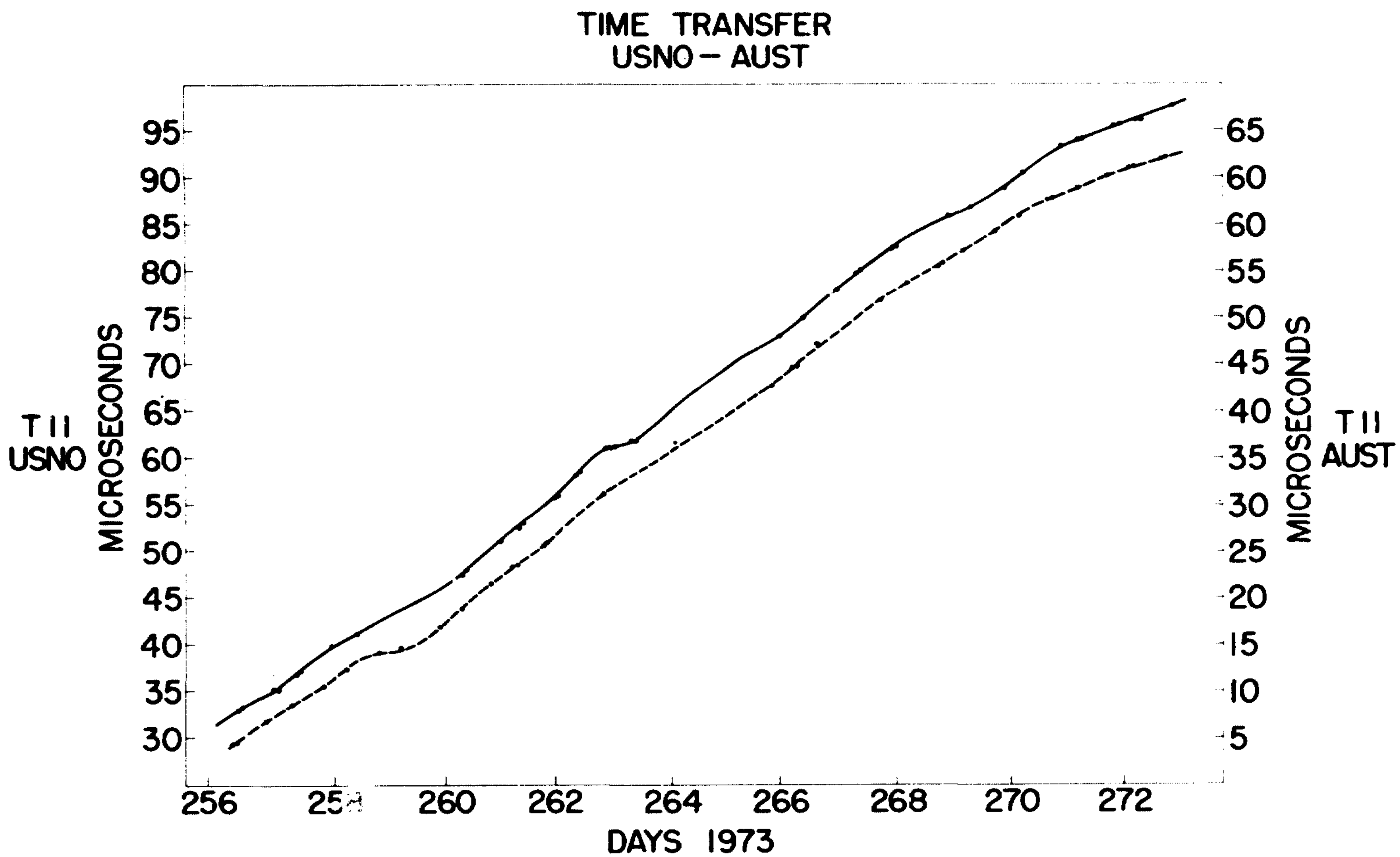

Figure 12. Results of Second Australian Run

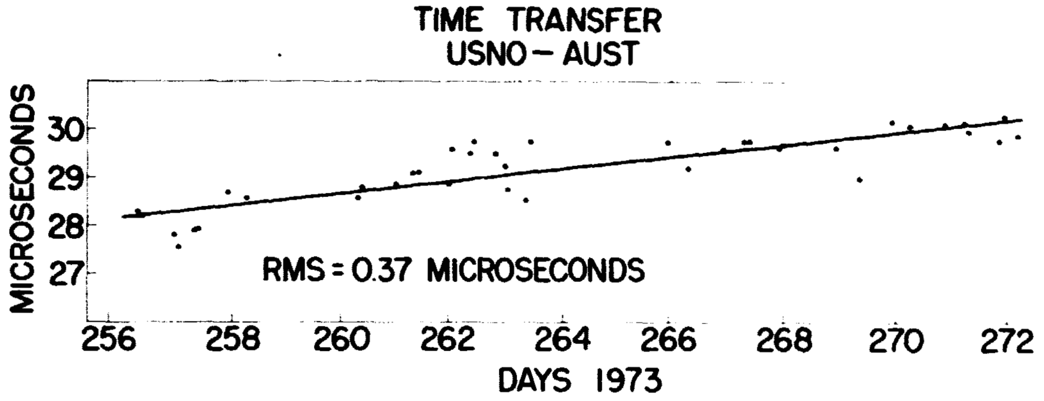

Figure 13. Time Differences Obtained from Figure 12

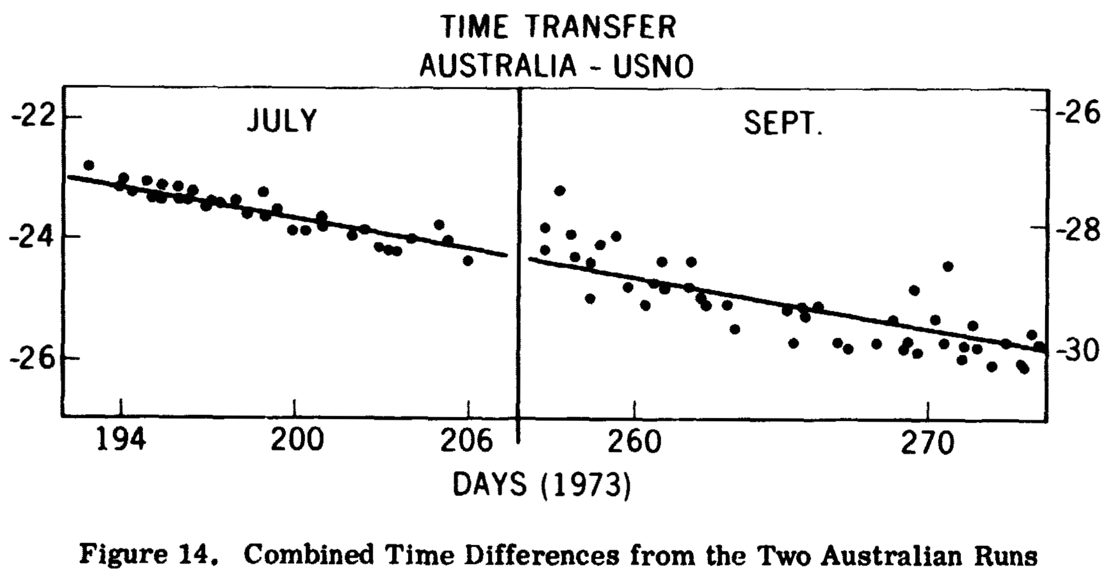

Figure 14. Combined Time Differences from the Two Australian Runs

QUESTION AND ANSWER PERIOD

DR. WINKLER:

Dr. Peter Morgan, from the Australian Time Service, in Canberra is extremely enthusiastic about this direct link which he has now with the rest of the world. Of course, I am also most optimistic that this system, particularly after you are going to have some more satellites in the not too distant future. It will become a most important link to many users, and I may stress that I personally see no competition between, for instance, this system and the SATCOM transfer which is entirely different.

SATCOM is a two-way simultaneous time transfer, using the wide band communications link. It is by its very nature a time transfer which you can compare to a trunk line in telecommunications service; you go to major areas which then are used as local time reference stations.

You cannot put a SATCOM ground station everywhere you need time. It is impossible, the cost and the operational inconvenience would be prohibitive.

But you may be able, and I hope you will be able to use ground timing receivers of considerably less complexity for a NAV-satellite if the receivers are just designed for time recovery rather than the navigation.

I think it may be useful at this planning conference to put something right up into the air and to say that we are planning tentatively to develop ground receivers for the coming — Timation 3 Navigation Technology Satellite.

We ought to know all those requirements for ground receivers which can be anticipated at this moment. It is clear to everyone that they all must be consolidated.

So, I want to encourage you, as of this moment, to get into contact with Mr. Easton or with myself, and hopefully in writing, make your anticipated requirements known.

DR. WINKLER:

Well, no more questions?

(No response.)

DR. WINKLER:

Then thank you very much, Mr. Easton.

INSTRUMENTATION FOR ONE-WAY SATELLITE PTTI APPLICATIONS*

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ABSTRACT

A review of general principles and operational procedures illustrates how the typical passive user and omni receiving antenna can recover PTTI information from a low altitude navigation satellite system for clock calibration and synchronization. The paper presents detailed discussions of concepts and theory of the receiver design. The importance of RF correlation of the received and local PN encoded sequences is emphasized as a means of reducing delay uncertainties of the instrumentation to values compatible with nanosecond to submicrosecond PTTI objectives. Two receiver configurations were fabricated for use in satellite-to-laboratory experiments. In one receiver the delay-locked loop for PN signals synchronization uses a dithered amplitude detection process while the second receiver uses a complex sums phase detection method for measurement of delay error. The necessity for compensation of doppler shift is treated. Differences in theoretical signal acquisition and tracking performance of the design concepts are noted.

INTRODUCTION

Tests are underway in which an experimental satellite in polar orbit at 450 n. mi. altitude having a PN modulation of 3.6 MHz bandwidth and 2^{15} length at a 400 MHz carrier provides the source signals for evaluation of the receiving instrumentation just described and for fundamental demonstrations that reflect the inherent capability of the system for PTTI applications. Included are test results which show the instrumentation noise levels during the period of reception as the satellite passes the laboratory. The differential jitter of the two receivers operating with the same satellite signal gave variations in measured delay at about 10 nanosecond. When the two PN receivers were connected to separate antennas it was possible to discriminate their physical separation to distances of less than 10 feet. These preliminary results infer very accurate global clock synchronization systems of various complexity and cost with ultimate accuracies approaching nanosecond levels. Degradation of synchronization accuracy from the limiting value will be dependent on variations among the radio path(s) between the satellite and widely separated receiving points principally due to refraction effects and also the errors inherent in the navigation process required for estimation of

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the required compensation for delay due to path length. (Experiments in clock synchronization between two remotely located receiving points are planned but have not yet been performed.)

From the work conducted to date we believe the following conclusions to be supported by the preliminary tests: (1) the satellite PN modulation and radiated power levels at the 150/400 MHz channels will be satisfactory for nanosecond to submicrosecond. PTTI applications; (2) progress in correlation receiver design for PN recovery has eliminated the instrumentation delay uncertainties as a major source of PTTI error. Thus the low altitude orbiting clock satellite system is a viable means for clock synchronization of navigating as well as fixed site users.

In contrast to the satellite navigation systems being proposed for high and quasi synchronous altitudes which systems require as many as four satellites in suitable simultaneous view of the navigating user, this low altitude global satellite system can provide the desired PTTI service with a single satellite in orbit with waiting intervals at the users location of 8 to 12 hours. Current schedules suggest than an operational PTTI service, contingent upon demand by users in the national interest, could be available from the improved satellite of the navigation system by 1975.

It is a privilege to report to the PTTI community on evolutionary improvements of the "Operational" Navy Navigation Satellite System. TRANSIT has been and remains dedicated to providing service as a radio navigation aid, however some of the developments in instrumentation are of interest since they provide a means for independent and cooperative users to calibrate and synchronize their clocks. The purpose of this paper is to review the system concept, describe new satellite and user equipment developments, and to present some measured data obtained in exploratory tests with the TRIAD satellite which transmit a new PN synchronizing signal. The tests indicate that the improved TRANSIT system anticipated during CY 1975 will be capable of satisfying many of the submicrosecond timing requirements of navigating as well as fixed site users. The progress in correlation receiver designs has eliminated the PN receiving sets as significant sources of error in submicrosecond PTTI applications.

REVIEW OF GENERAL CONCEPT

Time disciplined signals, broadcast in the VHF/UHF bands from an orbiting satellite clock can be used by any number of remote receiving stations or navigators for timing purposes with essentially the same basic procedures and processes that would be applicable to other one-way radio systems. For example, as illustrated generally in Figure 1, a navigation solution is required to determine range compensations for the distance traveled by the signals from the satellite source to the user. Submicrosecond accuracies require that further compensations be made for ionospheric and atmospheric refraction effects on propagation delay. The instrumentation will introduce errors in the nature of (1) a fixed bias and (2) random variations of the observed satellite timing marks as received. The fixed bias can be corrected by a local delay calibration of the receiving set using a precisely simulated satellite signal, injected effectively at the receiving antenna terminals. The random variations of the data will be smoothed by the statistical processing over a segment of the available satellite pass to determine an average variance and a least squares fit of the mean values to a straight line from which the synchronization "date" error of the user's clock relative to the satellite reference is indicated. A slope of the mean value time indicates error in time interval between the satellite and user's clocks. Generally the processes just described will be performed by a local computer if the user is an independent navigator. If the user is at a fixed site part or all of the computations can be performed at some centralized facility.

Distinctions as to the type of time service that one-way satellite broadcasts may provide should be recognized since there are important implications for both the user and the ground support network of the satellite constellation. First, there is a "date" dissemination mode that permits a fully instrumented independent user, at a fixed site, or on a moving platform, to calibrate and synchronize "date and time interval" of his clock to UTC(USNO) via the satellite, to the full accuracy of the system.

The second type of service can be referred to as a "uniform time interval" broadcast mode. For this service the satellite clock "date" control may be entirely absent or too coarse to qualify for PTTI. This mode permits clock synchronization among two or more cooperative users who transfer their own definition of "date" and "interval" among themselves from a designated master clock to the cooperative slaves. The basis for the clock transfers is the relative comparison(s) of the respective master and slave calibrations to the satellite reference. The best accuracy in transfer is obtained when the satellite reference signals are "co-visible" among the cooperative users.

The UTC(USNO) "date" dissemination mode is the ultimate system objective for it can service all types of users, those that are independent and passive as well as the cooperative users. Indeed the TRANSIT system currently operates in the "date" dissemination mode, however according to USNO reports,[1] improvement in accuracy of about two orders magnitude would now be useful.

The "date" dissemination mode requires accurate maintenance of the satellite clock by a system ground support network of satellite monitors (including a

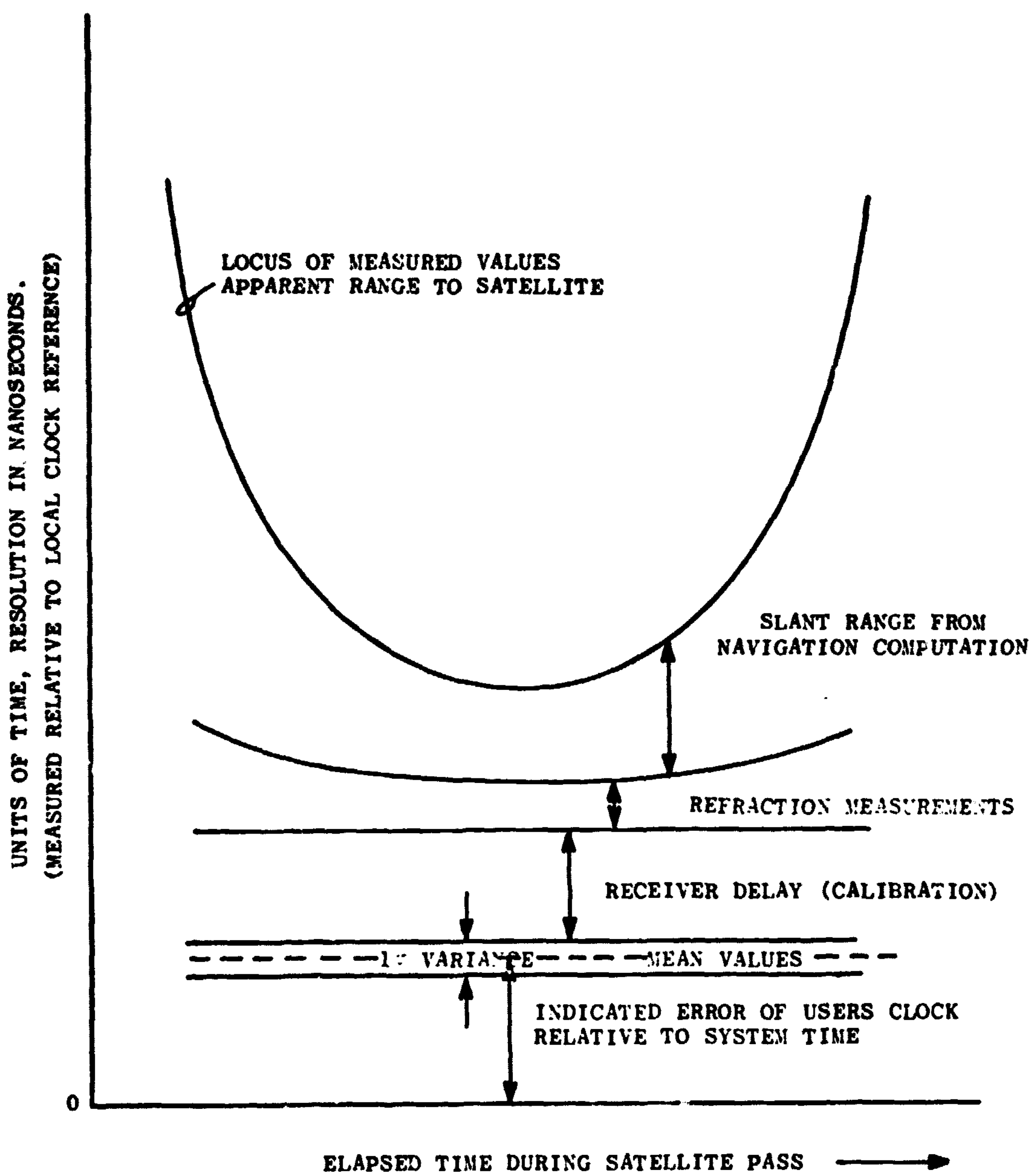

Figure 1. User's Process for Time Calibration of His Local Clock

receiver at USNO—Washington, D. C. or adjacent thereto), orbit tracking stations, computing facilities, and a command transmitting station arranged ideally as in Figure 2. In the ideal network there are four basic timing functions, namely:

1. A cooperative time transfer by satellite direct from UTC(USNO) to the TRANSIT system working clock reference. With a single satellite transfer opportunities occur regularly every eight to twelve hours when co-visible conditions exist.

2. Calibrations of the orbiting satellite clock to UTC. Opportunities to calibrate to UTC (TRANSIT) occur every orbit (110 minutes) and to UTC (USNO) every eight to twelve hours.

3. Adjustment of the orbiting satellite clock to UTC by radio command. Opportunities occur once per 110 minute orbit.

4. Satellite time dissemination by one-way broadcast to users. Availability per satellite will be dependent upon the user's position in latitude, but in no case would it exceed eight to twelve hours.

With this level of ground network support the reliability of the satellite UTC transmissions will be dependent upon the predictability of the satellite oscillator and clock over the calibration and adjustment intervals of only 110 minutes. With a one-in-view continuous satellite coverage it could be possible for any user on earth to effectively obtain periodic clock calibration updates to UTC(USNO) within a lapse of no more than 110 minutes.

The PPTI community must be warned that before this level of satellite UTC service can be expected a tradeoff analysis of timing requirements vs. performance and cost would be needed to support the ground system deployment.

PROGRESS IN IMPROVING BASIC INSTRUMENTATION

A transition period is planned during which improvements will be deployed. All improvements will be designed to avoid incompatibility or obsolescence of the more than 700 military and commercial navigation units now in service. During the transition period a wide variety of user equipment designs can be phased in to satisfy new requirements.

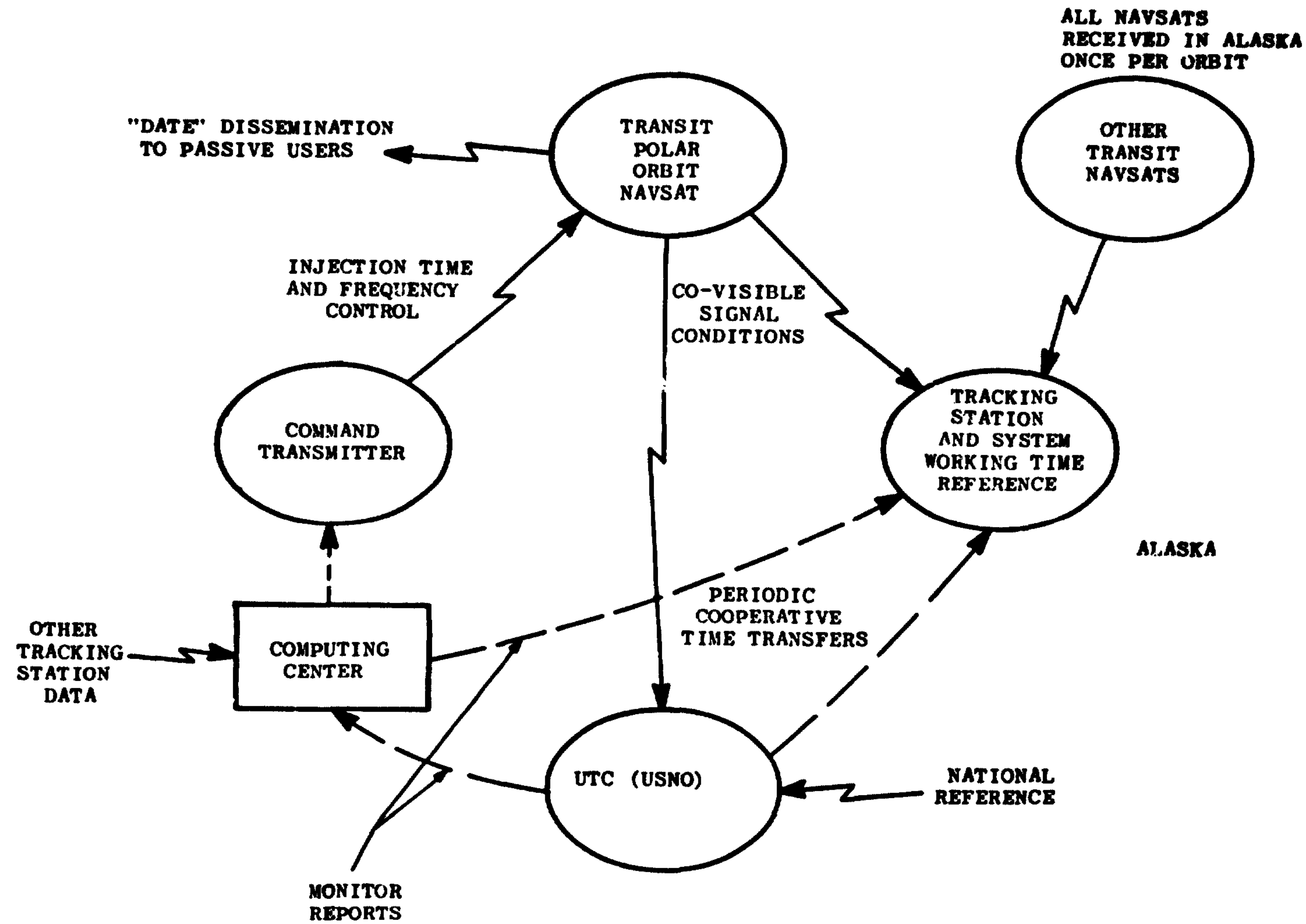

Figure 2. Ground Support to Maintain Satellite Clock for "Date" Disseminations

SATELLITE INSTRUMENTATION

New (TIP) satellite designs include features for improving the dedicated navigation service. Fortunately some developments are significant to PTTI users.

1. A disturbance compensation (DISCOS) and orbit maintenance subsystem will be provided. Its purpose is to eliminate the effects of atmospheric drag and allow a means for control of the orbital trajectory in space so that location of the satellite is more accurately predicted and reported to users; for example, for use in range compensation to timing measurements. TRIAD experiments with DISCOS indicate an uncertainty of three meters for the improved satellite at TRANSIT altitudes, compared to a current uncertainty of ten meters.

2. The RF signals that are broadcast from space will be redesigned to include a partial PN phase modulation with repetitive sequences that are uniquely related to the RF carrier frequencies and the variable message modulation. The PN phase deviation of ±45 degrees allocates half of the radiated RF energy to the PN spectrum, the other half to carrier and message spectra which can therefore be received "in-the-clear" by all now existing equipment.

   The FCC allocations permit a 2^{15} code length with a chip interval of 600 nanoseconds and a PN information bandwidth of 10/3 MHz on the 400 MHz radiating channel. The 150 MHz channel has a 2^{12} code length, chip interval of 4.8 microseconds, and PN information bandwidth of 5/12 MHz. When operational the PN sequences are synchronized and uniformly repeat 6103 times in exactly 120 seconds of UTC with fiducial time coincident at the even two minute UTC dates. The TRIAD satellite can broadcast the PN modulation on the 400 MHz channel.

3. The satellite frequency reference will be supplemented by a digitally programmable synthesizer. This allows delayed adjustments during the orbit of frequency offset with compensation for drift rate so that a uniform clock time scale is maintained. A control strategy can be used to steer "clock date" and indirectly the PN modulation for coincidence to "UTC date" referred to radiations from the satellite antenna. The programmable synthesizer has a fine resolution in the range of 2×10^{-12} to 4×10^{-13}. The effective operating reference frequency is $5(10^6 - 84.48)$ Hz from which all modulation waveforms and carrier frequencies are coherently generated, with the PN and information bit intervals being 120/6103 seconds.

   Currently the TRIAD satellite operates in a free running crystal oscillator mode at a nominal frequency near $5(10^6 - 140)$ Hz which avoids use of the experimental satellite by any navigator. "Date" of the TRIAD clock is not controlled but a uniform interval is broadcast giving 6103 reference pulses in about ($120 + 6.6 \times 10^{-3}$) seconds.

RECEIVING SET INSTRUMENTATION

The 150 and 400 MHz satellite signals available at the terminals of omnidirectional dipole and volute receiving antennas will range between -115 and -140 dbm. It is therefore necessary in the power limited system to recover the PN timing code under negative SNR conditions. The delay-locked PN recovery loop especially designed with correlation at RF allows synchronization and tracking with minimum delay error under the negative SNR conditions.

Two PN receiving equipments have been constructed as modifications to existing AN/BRN-3 and AN/SRN-9A navigation sets. Figures 3 and 4 respectively. Industry sources have completed production design studies for PN capabilities integrated into the SRN-9A and the new AN-WRN-5, Figure 5.

The delay-locked feedback loop performs a cross correlation between the PN encoded information of the received RF signal with noise and a local signal, noise free, appropriately modulated by the same encoded information waveform. The local modulating waveform is delay shifted to bring its sequence into time synchronization with the received code. Under this condition the correlator then produces a signal that can be used as a loop driving force to automatically maintain synchronization. Error correcting feedback is via the voltage controlled clock (VCC), local PN code generator, modulator, and correlator circuits.

The PN receiving set must be wideband up to the correlation circuit if it is to achieve the full accuracy potential of the spread spectrum PN modulation. In the correlation process the convolution of the received and local PN signals, under conditions of synchronized tracking, results in a redistribution of the received PN spectral energy into an enhanced coherent carrier signal which may then be amplified in very narrowband circuits for eventual detection of the synchronization error. In contrast the convolution of the local PN with received noise and non-coherent interfering signals results in a spreading redistribution of the interfering energy across a wide band of frequencies.

RF CORRELATION

A key concept in the design of PN recovery equipment is the combination of the processes of correlation with frequency translation from the RF to the first IF,

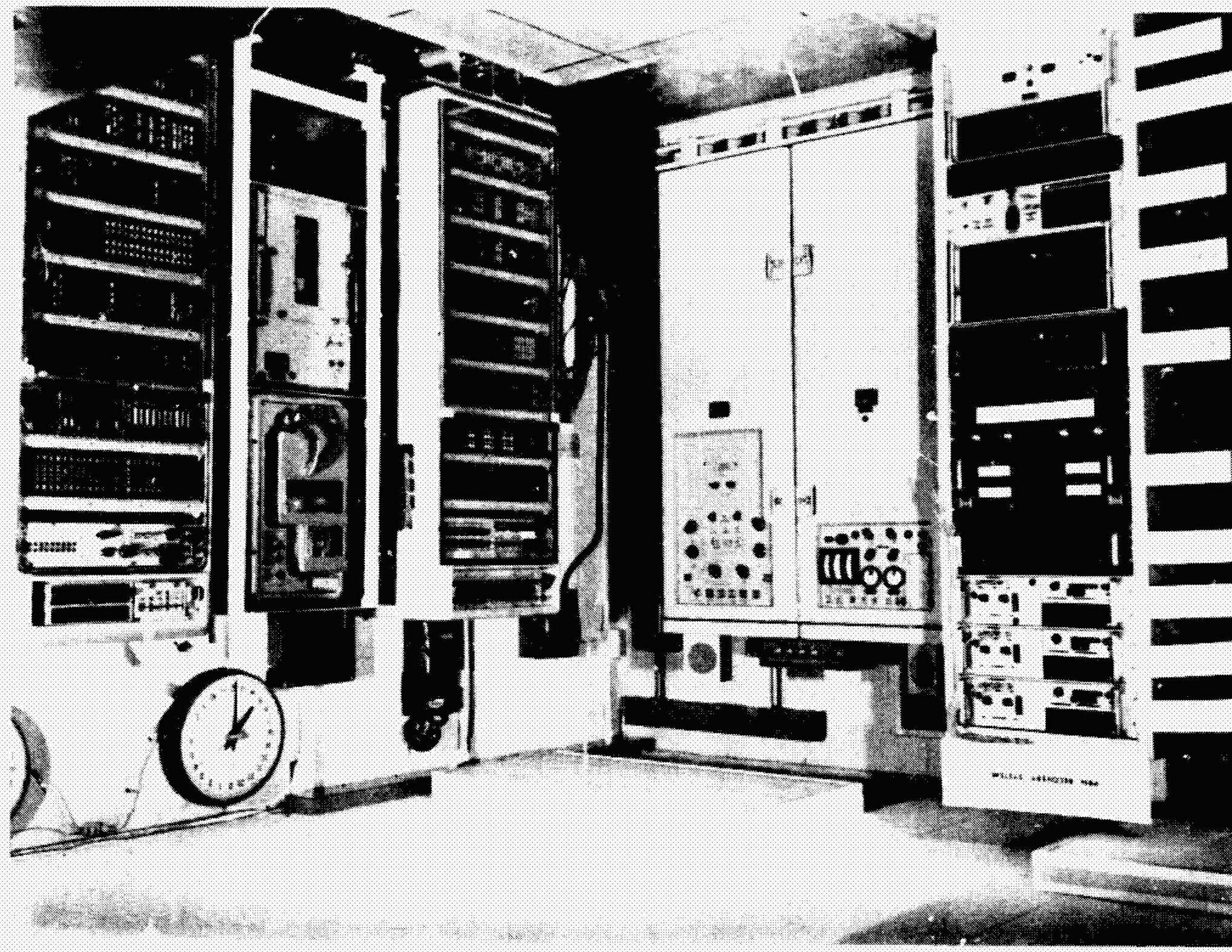

Figure 3. AN/BRN Navigation Set with PRN Modifications

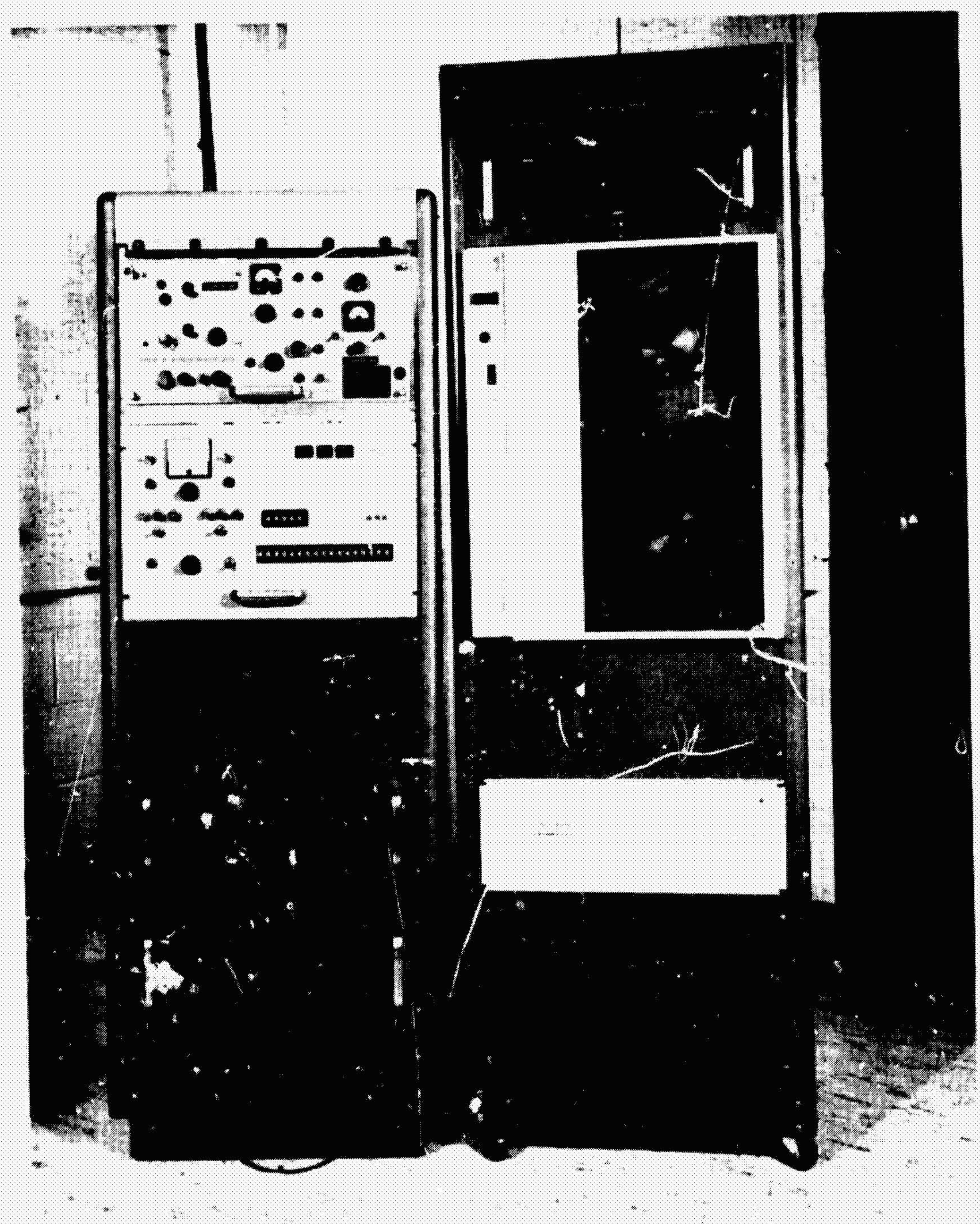

Figure 4. AN/SRN-9A Navigation Set with PRN Modification

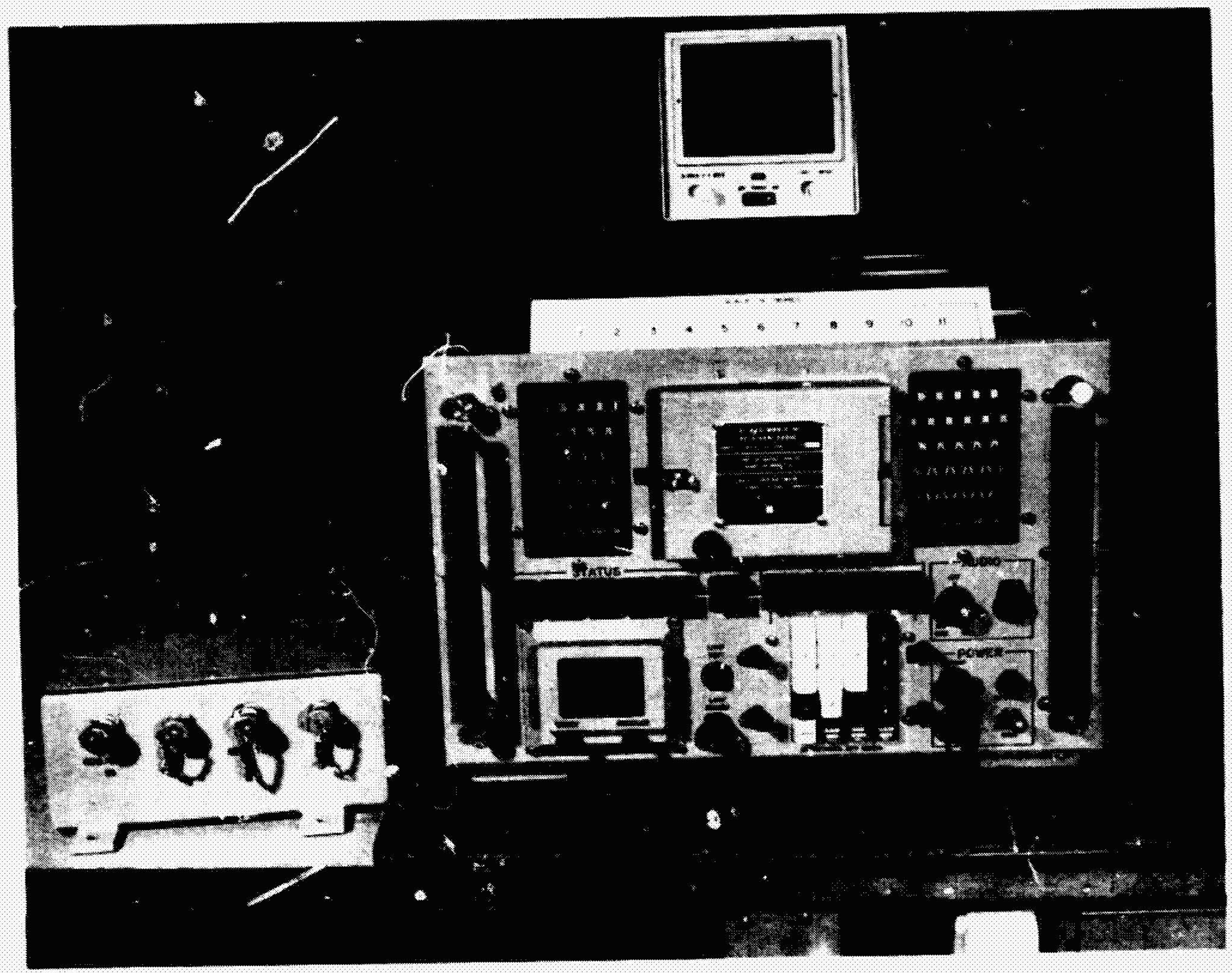

Figure 5. AN/WRN-5 Navigation Set

Figures 6 and 7. The significance of RF correlation lie in performance and cost since it provides:

1. A low and very stable value of receiver time delay which may be determined by calibration and used with confidence. The major delay instabilities of amplifying IF strips are avoided.

2. Frequency spreading, while the total energy remains small, of noncoherent noise and interfering signals into wideband spectra that can be attenuated by filtering relative to the desired information.

3. An optimum distribution of bandwidth, gain, and power dissipation leading to an easy economical design. Most of the signal amplification is in the narrowband IF circuits. Precorrelator RF gain must be sufficient to preserve noise figure.

In the modification of the SRN-9, Figure 6, it was imperative that RF correlation be used as choices of bandwidth and gains had been previously set by the narrowband requirements of coherent carrier tracking and the recovery of the 50 bps information phase modulation used for transmitting definitions of satellite orbits to the user.

DOPPLER COMPENSATION

Another feature of high performance-low cost PN receiver designs, to be used in applications characterized by dynamic motion, is compensation of doppler frequency shift. At TRANSIT altitudes the maximum doppler effect is less than 25 parts in 10^6. The compensation is applied in two ways. First, the frequency of the PN modulated local reference signal to the RF-to-IF frequency converter (also the PN cross correlator) is adjusted for the doppler shift. The converter output is therefore completely stabilized in frequency to a unique carrier allowing a minimum practical IF bandwidth with maximum discrimination against noise power and interference.

The second compensation is applied via a synthesizing network to adjust the clocking frequency input to the local PN code generator. All spectral components of the local PN modulating waveform will therefore match corresponding doppler shifted frequencies of the received PN signal. Basically, this is a form of signal derived aided tracking that relieves the delay-locked loop of the burden of tracking rate variables. Small effective noise bandwidths may therefore be used for PN recovery which results in a very low random jitter of the PN output timing pulses.

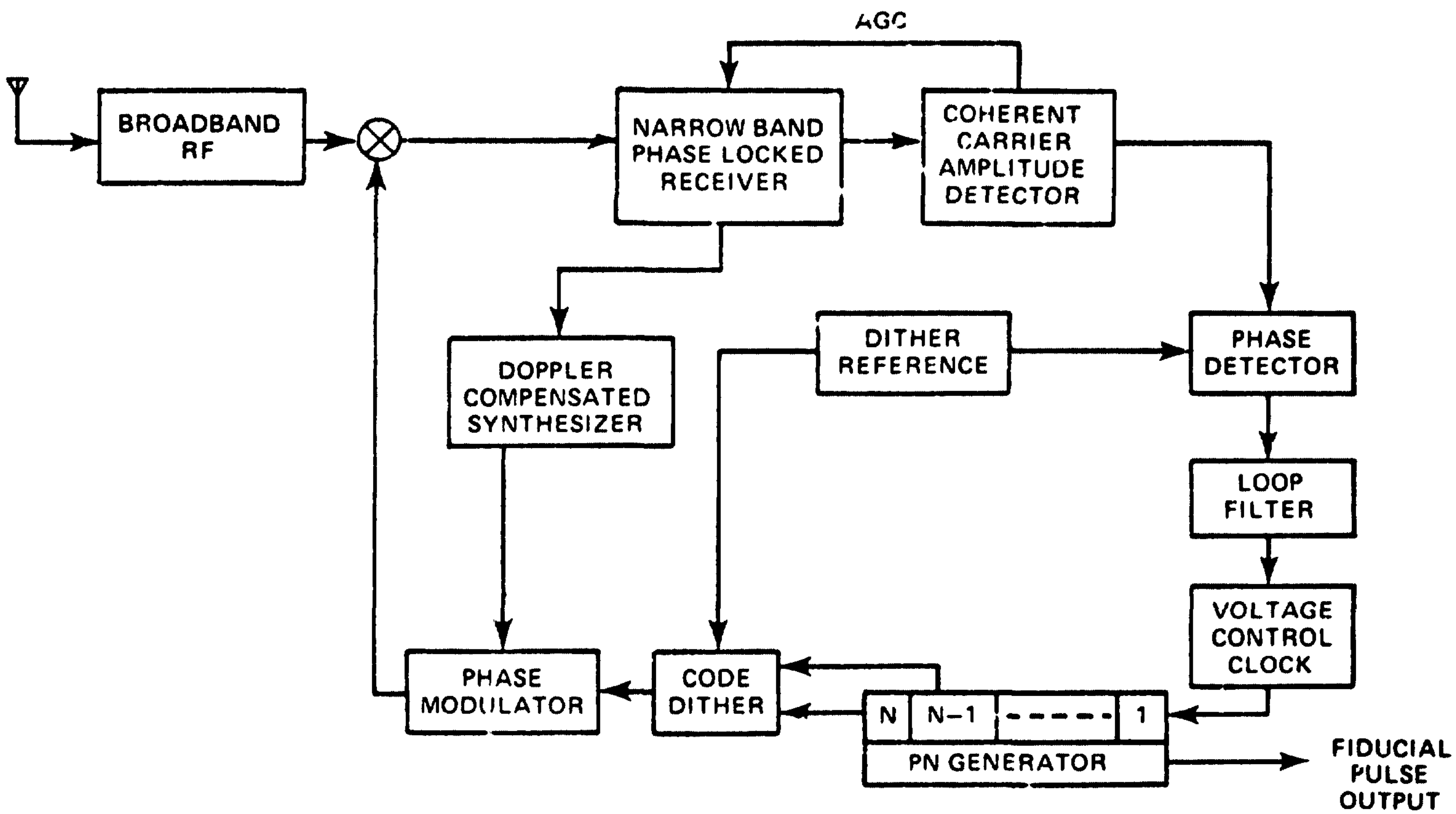

Figure 6. Amplitude Dithered Delay-Locked Receiver for PN Reception

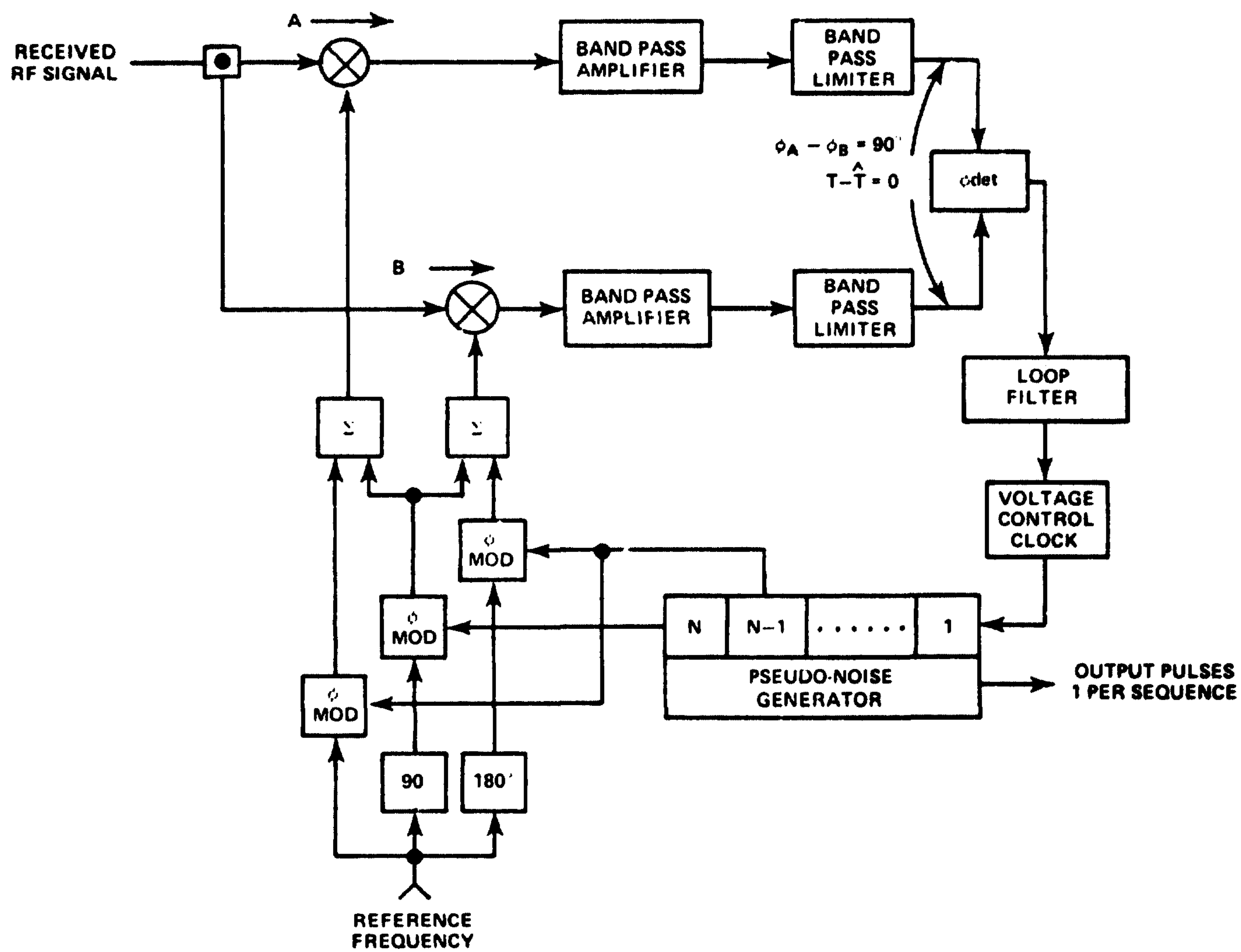

Figure 7. Complex Sums Delay Locked Receiver

PN RECEIVER CONFIGURATIONS AND DETECTION PRINCIPLES

The BRN-3 and SRN-9 PN receivers have important features in common such as correlation at RF, doppler compensation and a common objective of functional isolation and independent PN measurement with no impact on performance in doppler recovery from carrier tracking or in message demodulation. However, detailed requirements peculiar to the mission and environment of the BRN-3 submarine user as contrasted to those of the SRN-9 surface users lead to dramatic differences in design philosophy and circuit configurations. A full discussion is beyond the scope of this report but some comment is useful.

The modified SRN-9, Figure 6, is a common channel receiver. It uses circuits in the receiver for the dual purpose of doppler recovery by phase locked carrier tracking simultaneously with PN recovery by delay tracking the encoded sequences. For PN recovery the synchronization delay error signal for loop control is detected in a 3 step process. First, the RF correlator provides an enhanced output carrier whose amplitude is a function of the delay error. The amplitude will be a maximum when the delay error is zero. In order to obtain a polarity sensitive control the local PN modulating waveform is delay dithered (advanced and retarded equal amounts at a frequency that is fast compared to the code interval). Now the IF carrier with dithered amplitudes indicating delay error and direction is amplified by the IF strip. The 2nd detector is the phase coherent amplitude detector normally used for receiver AGC. The baseband output of this AGC detector contains a signal at the dither frequency whose magnitude and polarity are determined in a 3rd level of synchronous detection to develop the final forcing function that drives the VCC and local PN code generator.

The modified BRN-3, Figure 7, except for antenna and RF preamplification, uses separate receiving circuits for carrier doppler and PN recovery, hence these operations are inherently isolated and independent. The particular PN configuration is called a complex sums phase sensing receiver. The error signal for feedback delay control via VCC and local code generator is developed by a 2 step detection process. First, a special RF correlator produces a resultant carrier phase angle which is indicative of the direction and magnitude of the delay error. The IF carrier is amplified and heavily filtered to obtain a positive SNR. The signal is then limited in level for the 2nd step detection of delay error by phase comparison. Dual channels of RF correlation and IF processing are used so that relative phase comparisons are sufficient for delay error measurement. Theoretical analysis of the complex sums PN receiver is given in Reference 2.

The major points of significance for these recovery techniques are outlined:

1. Common Channel Dithered Amplitude Sensing Receiver (SRN-9A)

   a. A minimum volume, weight, and power consumption is needed for the added PN capability.

   b. Superior performance in ultimate threshold sensitivity is obtained for a specific PN noise bandwidth. From Reference 3, the normalized (rms) noise tracking error is

$$\frac{\sigma T}{\Delta} = \sqrt{\frac{B_n N_o}{2P_s}}, \text{ where}$$

   Δ = the chip interval of the encoded PN waveform
   B_n = the effective loop noise bandwidth
   N_o = the noise spectral power density
   P_s = the received energy in the PN signal

   c. The amplitude enhancement of carrier signals in the common channel by the RF correlation process effectively improves the SNR available for carrier phase locked tracking (+3 db maximum when the PN phase deviation at the satellite is 45 deg), except when large delay dither magnitudes are required for initial acquisition or for automatic reacquisition on loss of lock due to signal fading.

2. Separate Complex Sums Phase Sensing Receiver (BRN-3)

   a. The use of bandpass limiters for IF signal level control provides a delay error detection capability that is insensitive to a wide range of dynamic rates of amplitude fluctuation of the received RF signal that would exceed the regulating limits of coherent AGC. The circuit is independent of and insensitive to phase errors in coherent tracking.

   b. In the complex sums receiver, the normalized (rms) noise error for delay locked tracking is estimated to be in the range:

$$\frac{4}{\pi}\sqrt{\frac{B_n N_o}{2P_s}} \leqslant \frac{\sigma T}{\Delta} \leqslant \sqrt{\frac{B_n N_o}{2P_s}}$$

   where the factor $4/\pi$ is contributed by the IF bandpass limiters operating at threshold SNR conditions. The circuit sacrifices about 1 db in threshold sensitivity in return for accurate error detection in the presence of fast fading and for the inherent simplicity of the limiter design.

   c. The circuit has superior acquisition performance in allowable search velocity (2.7 to 1 compared to best amplitude sensing circuit) and can acquire and track without phase coherent doppler compensation. A programmed frequency synthesis to maintain the carrier signals within the narrow IF passband is adequate.

d. Local phase modulation indices for PN correlation can be arbitrarily set without regard to reconstruction of carrier and message modulation (90 deg is optimum for interference discrimination in the PN receiver). Also, the circuit performs best when the remote PN source totally suppresses the carrier.

EXPLORATORY TESTS WITH SATELLITE SIGNALS

A few tests of limited scope have been performed with the TRIAD experimental satellite to obtain a "quick look" at the instrumentation noise levels and the basic resolution of the PN design for ranging and timing measurements.

The objective of the first test was to determine the relative stability and the jitter of the system (not including the radio propagation medium). This was done by differential measurements between the two PN receiving sets while they simultaneously tracked the TRIAD signal received from space. The test circuit is shown in Figure 8 and resulting measured data is plotted in Figure 9. The standard deviation and the mean values are plotted along with the level of the signal received at the output of the common antenna terminals. Except when the signal level became marginal the differential (rms) jitter of the two sets was in the range of 15 to 25 nanoseconds. Following the test a calibration of the BRN-3/PN was obtained with local test signals with results shown in Figure 10.

The objective of the second test was to check the inherent resolving capability of the PN instrumentation in determining the distance in physical separation of two antennas co-located with a baseline oriented approximately parallel to the satellite N-S orbital subtrack. The general test circuit is shown in Figure 11 where separations of 50, 24.5 and 10 feet were used. Variations in the measured mean delays between the PN outputs of the two receivers over the interval from satellite rise to set should follow a shallow S-curve indicating the antenna distance separations. The peak-to-peak delay variation in nanoseconds will be approximately numerically twice the value of the separations in feet for a direct overhead satellite pass. Figure 12 shows the 50 feet antenna separation rather dramatically even with the 80 to 100 nanosec rms differential noise jitter measused when the BRN-3/PN tracking loop was in wideband position.

The indications for the 24.5 and 10 feet separations are naturally less dramatic. The interesting result to note in Figures 13 and 14 is the substantial improvement

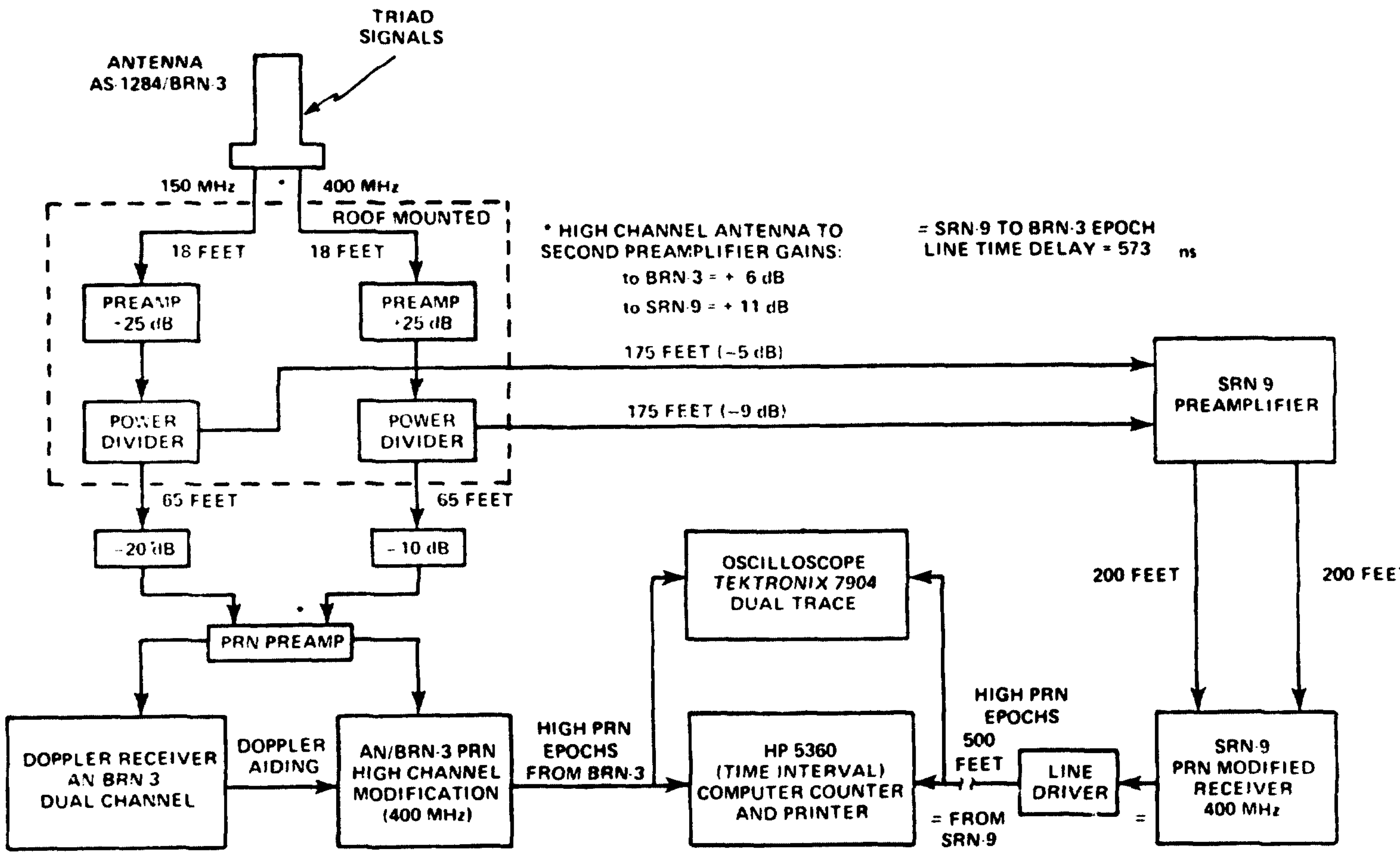

Figure 8. Test Circuit for Measurement of Instrumentation Delay Jitter

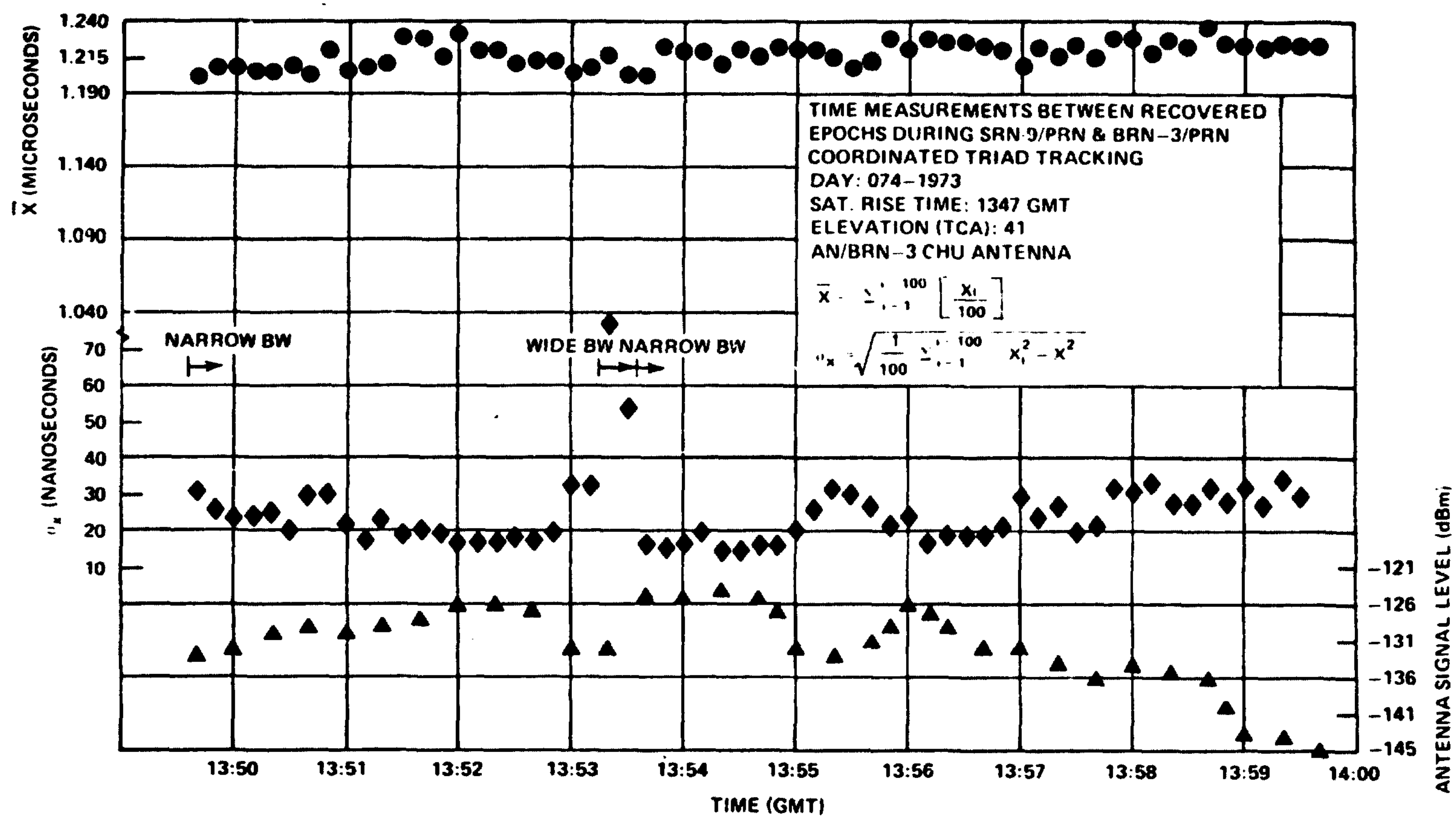

Figure 9. Satellite Data Indicating Receiver Instrumentation Delay Jitter

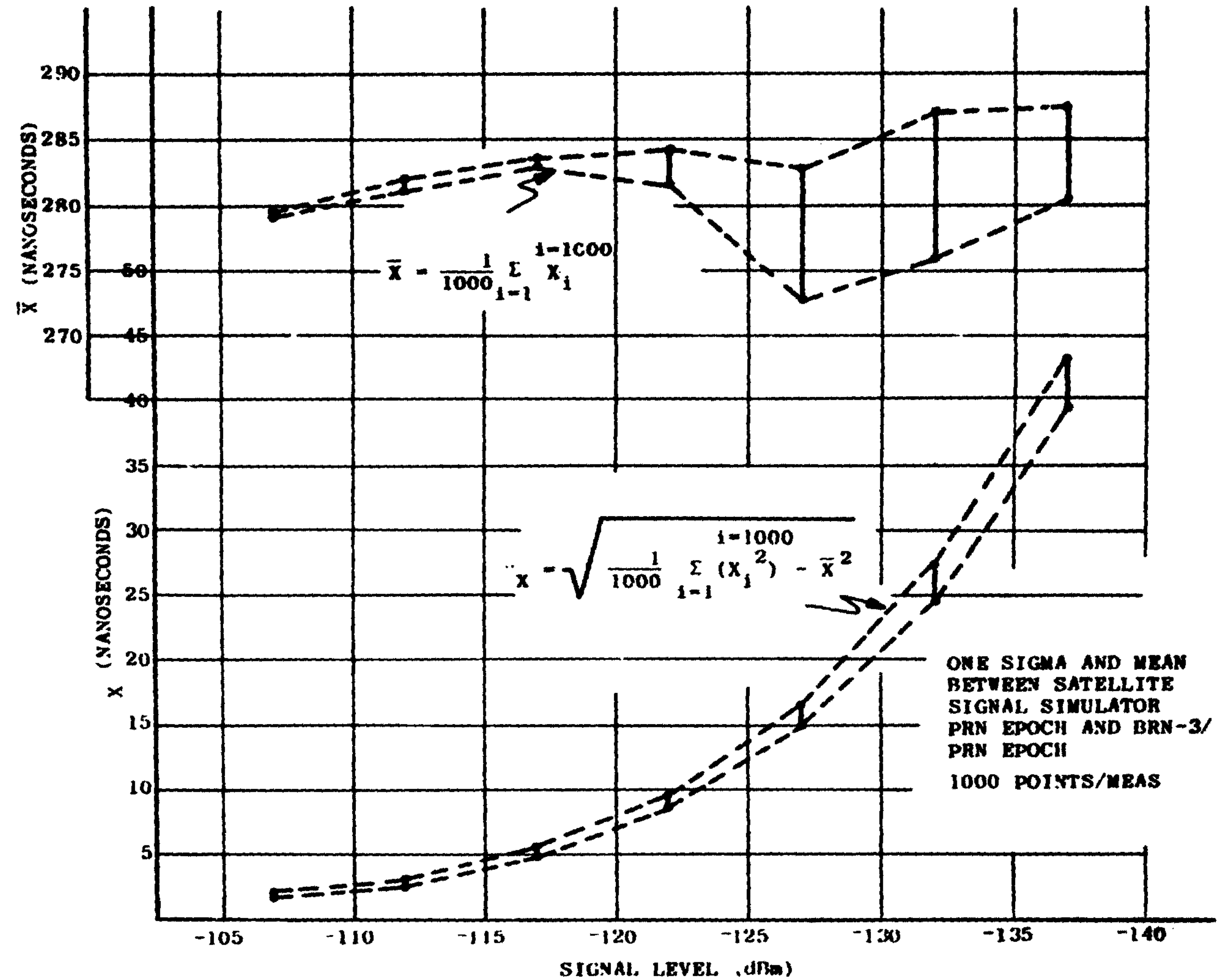
290
285
280
275
270
$\bar{X}$ (NANOSECONDS)
$\bar{X} = \frac{1}{1000} \sum_{i=1}^{i=1000} X_i$
50
45
40
35
30
25
20
15
10
5
σ_X (NANOSECONDS)
$\sigma_X = \sqrt{\frac{1}{1000} \sum_{i=1}^{i=1000} (X_i^2) - \bar{X}^2}$
ONE SIGMA AND MEAN BETWEEN SATELLITE SIGNAL SIMULATOR PRN EPOCH AND BRN-3/PRN EPOCH
1000 POINTS/MEAS
-105
-110
-115
-120
-125
-130
-135
-140
SIGNAL LEVEL (dBm)

Figure 10

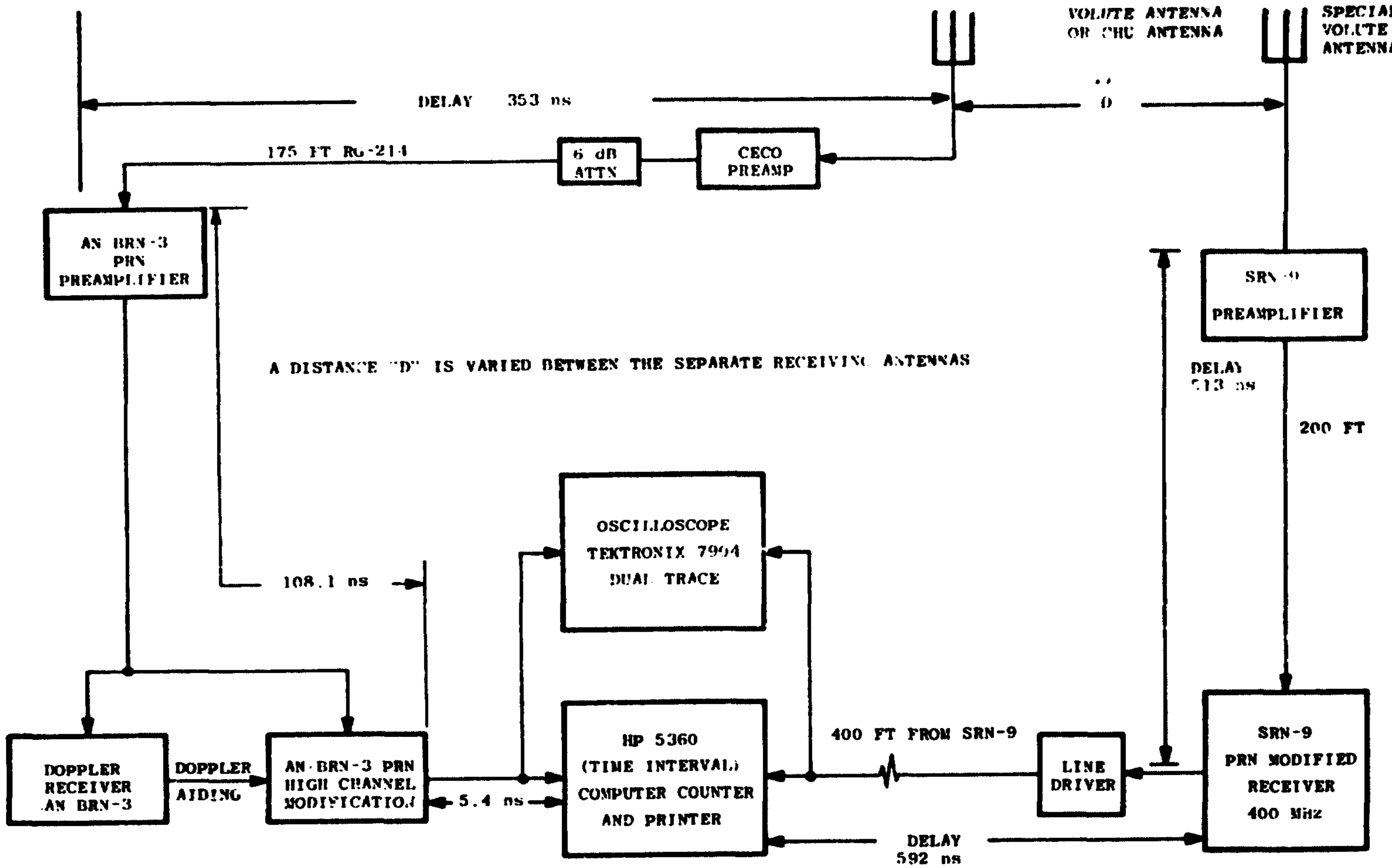

Figure 11. Simplified Block Diagram of PRN Jitter Test Between BRN 3 and SRN-9 Epochs From TRIAD 1 Using Separate Antennas

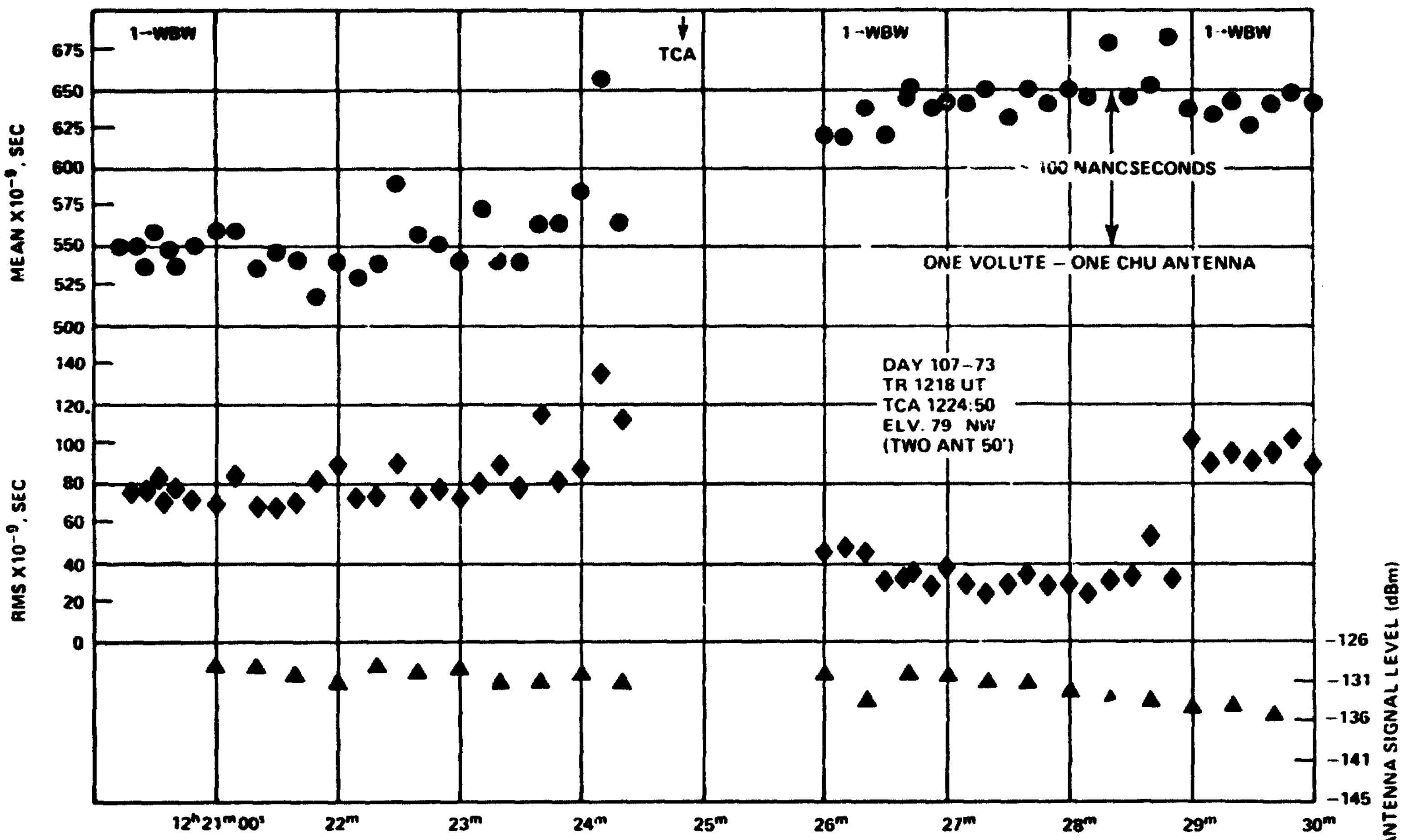

Figure 12. Discrimination of Antenna Separation Distance Using TRIAD Satellite Signals

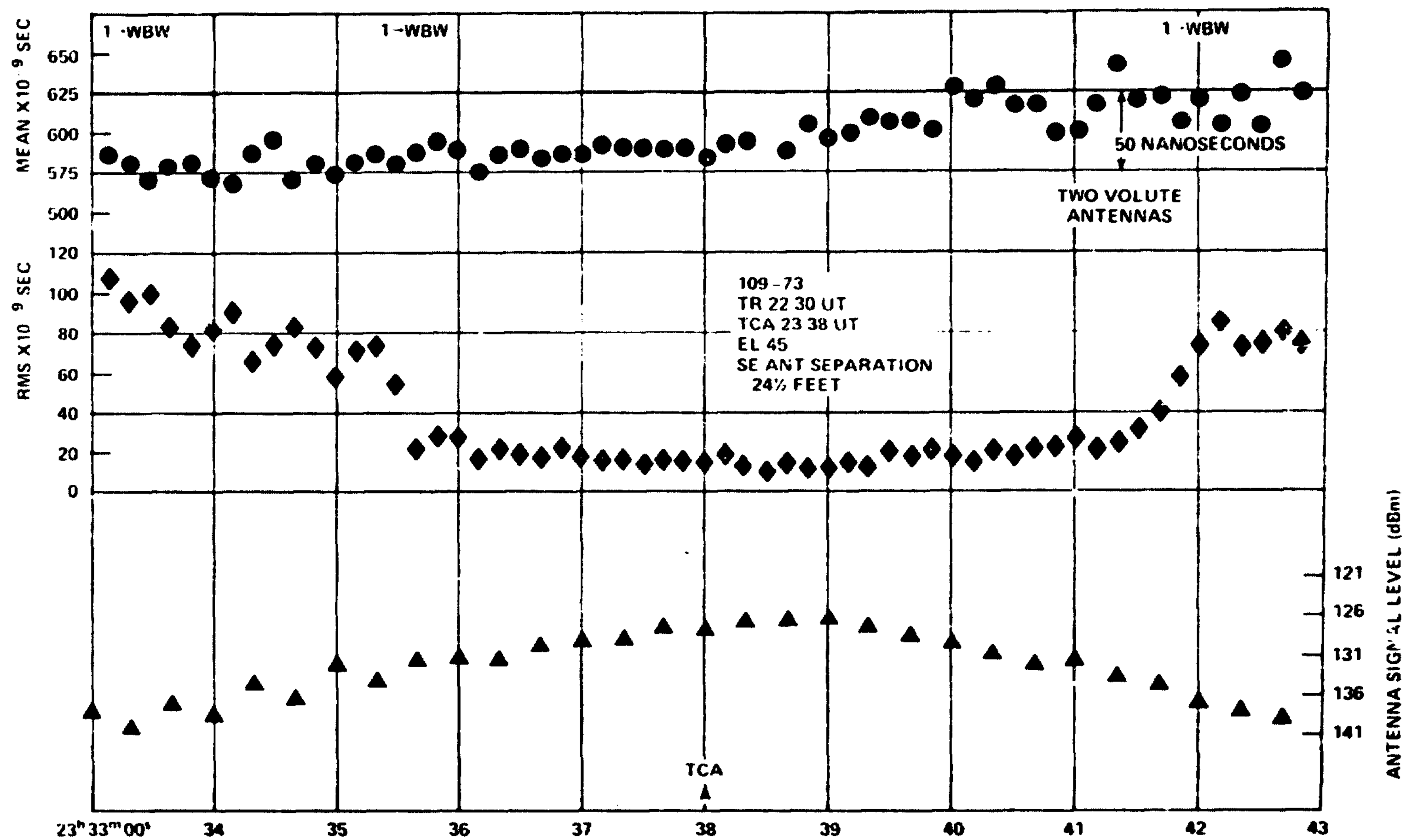

Figure 13. Discrimination of Antenna Separation Distance Using TRIAD Satellite Signals

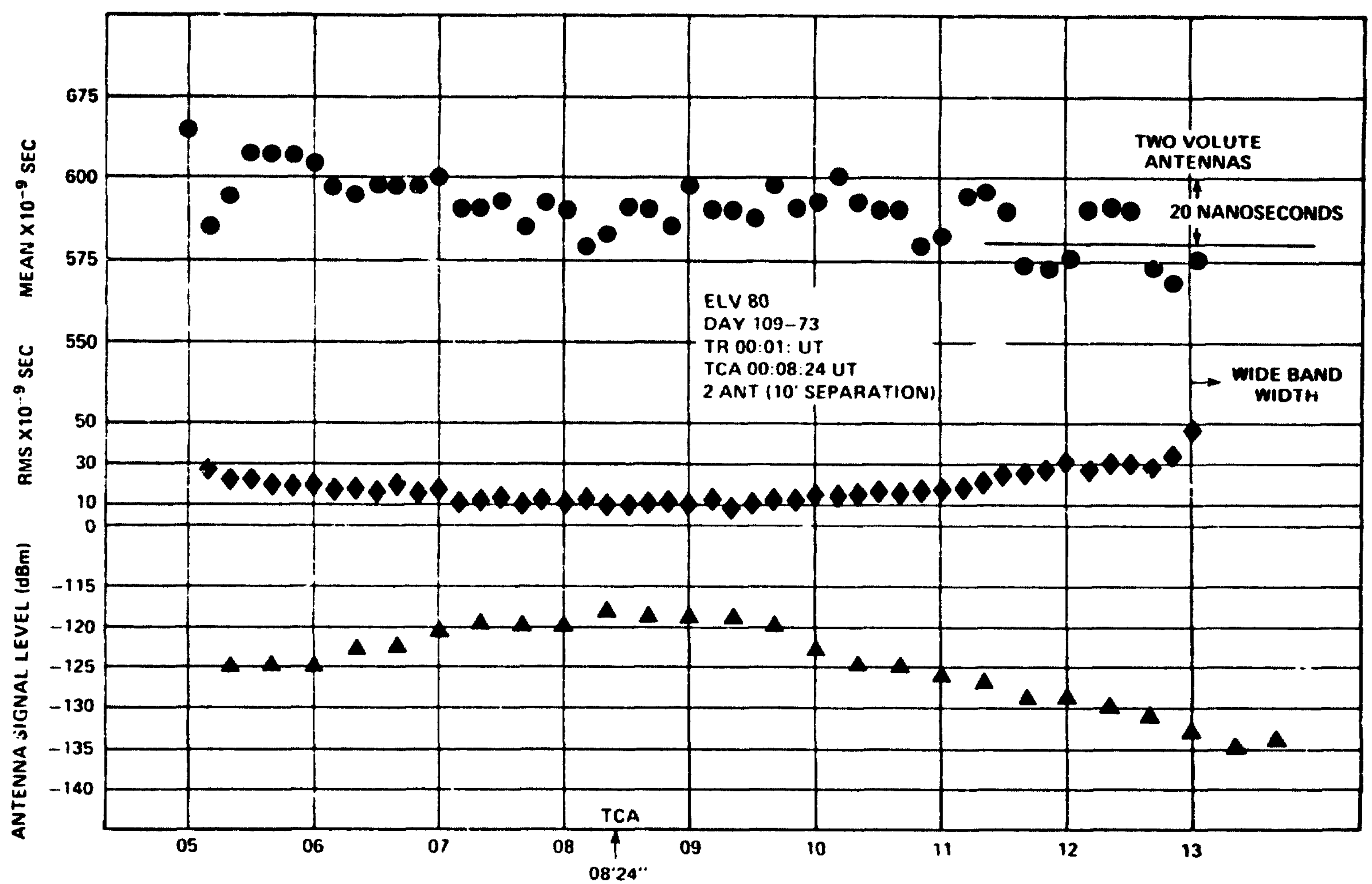

Figure 14. Discrimination of Antenna Separation Distance Using TRIAD Satellite Signals

in the differential rms tracking noise when volute antenna were used for both BRN-3 and SRN-9 receiving sets.

In the third test it was desired to measure the apparent delay to the satellite clock pulses transmitted by PN vs. elapsed time during the satellite pass. For this quasi absolute propagation delay measurement the single BRN-3/PN receiving set was used with volute antenna. The local reference clock time interval scale was adjusted on the basis of previous satellite observations to approximate the -140 PPM offset satellite time interval scale. Data obtained during a short segment of the pass, centered about the time of closest approach (TCA), is plotted in Figure 15. The smoothness of the locus of measured values is of interest since the data includes the refraction uncertainties of the radio propagation path as well as the PN instrumentation errors.

These basic and rather elementary tests constitute only the beginning of the full evaluation of the performance capabilities of the TRANSIT system for applications in local clock calibration and synchronization. In the next 3 to 4 months some additional effort is scheduled. Selected satellite passes will be tracked and measured data will be processed to perform the compensations indicated in Figure 1. The objectives will be to establish more completely the technical feasibility, to analyze the measured data for a definition of the dominating sources of error, and to demonstrate time transfers between master and slave clock systems by monitoring the satellite PN broadcasts.

Even from the fragmentary work performed to date we think the following conclusions can be supported: (1) the satellite PN modulation design and the radiated power levels will be adequate for PTTI applications in the submicrosecond ranges of accuracy, (2) progress in correlation receiving set design for PN recovery has eliminated the receiving set instrumentation delay uncertainties as a significant source of error. The low altitude one-way transmitting satellite provides a viable means for the accurate calibration and synchronization of clocks distributed globally among fixed site and navigating users.

ACKNOWLEDGMENT

The material reported herein is the work product of many persons associated with the TRANSIT Navigation System. Special acknowledgement is due Mr. E. F. Prozeller for the PN subsystems of the improved satellites and the modified AN/SRN-9 receiving set. The test data was collected and plotted by Mr. R. E. Dove and by Dr. R. J. Taylor.

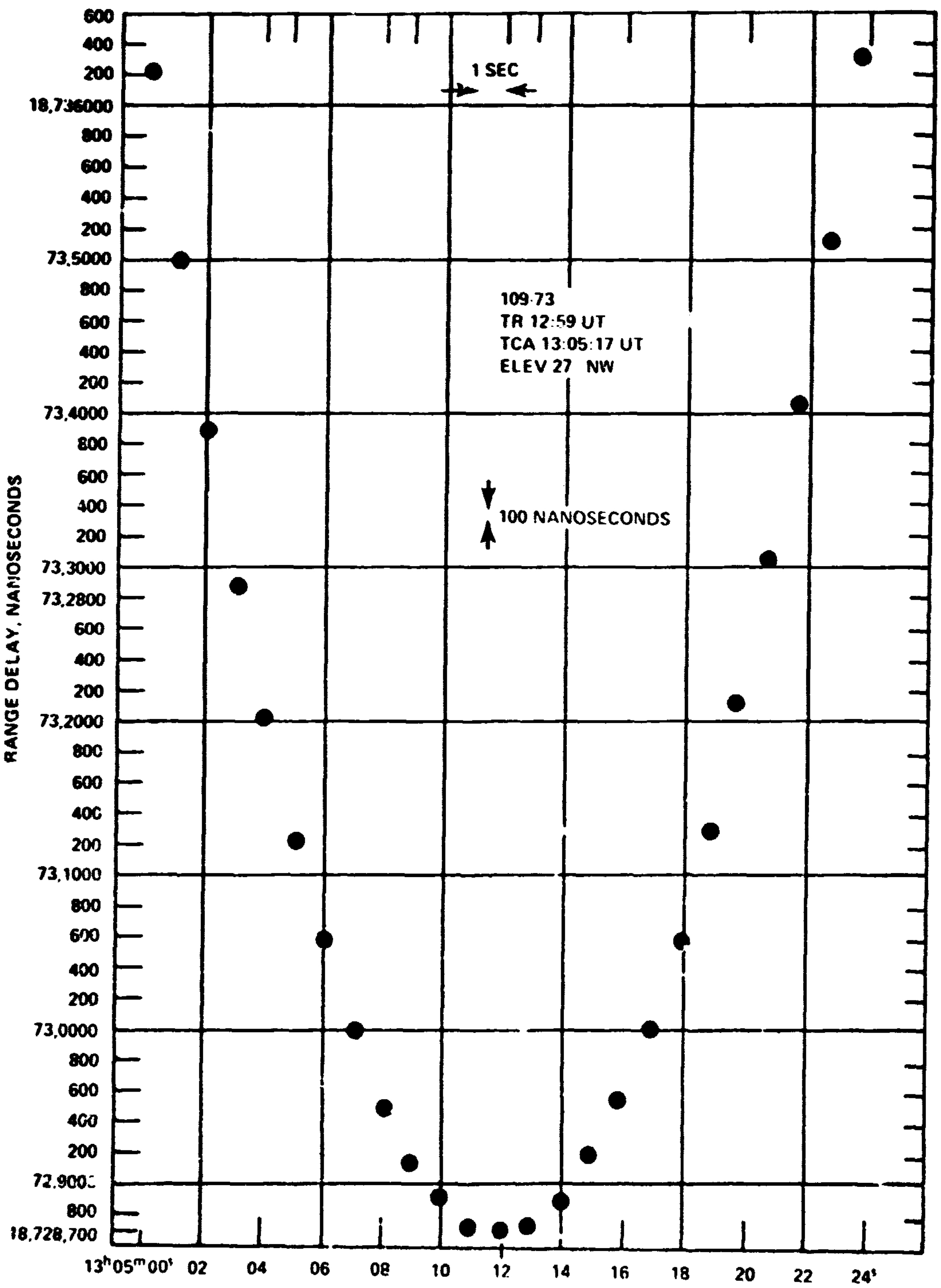

Figure 15. Propagation Del'y During Satellite Pass

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2. E. F. Osborne and T. A. Schonhoff, "Delay-Locked Receivers with Phase Sensing of the Correlation (Error) Function", Conf. Record of the NTC 1973, Atlanta, Ga., paper 26B.

3. W. J. Gill, "A Comparison of Binary Delay-Lock Tracking-Loop Implementations", IEEE TRANS. on Aerospace and Electronic Systems, Vol AES-2, No 4, July 1966, pp 415-424.

QUESTION AND ANSWER PERIOD

DR. WINKLER:

Thank you, Mr. Osborne. Are there any questions?

I, of course, am in complete agreement with you. I think we have a resource here which we have not yet used. We have left that to the French who are using transit satellites for routine time transfers and you will find a report on their experience in the special issue of Time and Frequency, IEEE, May of 1972.

There is one question here.

QUESTION:

It is kind of a compound question. I am not sure just what the Triad satellite is. What I want to know is, will the Triad satellite be able to be used for navigational purposes? Also, can the satellite, the new satellite that just went up, 2016, can that be used in the mode that you are talking about now to provide timing after it is used up as a navigational satellite? And also, can, say, the two satellites, 10 and 18, can they be used in any way as a timing satellite?

DR. OSBORNE:

Yes, the current satellite that went up two weeks ago or thereabouts is one of the traditional designs that does provide a time service, but it does not have the pseudo-random capability. The performance you will get with it would be similar to that of the other four or five that are already in the system.

As to the Triad satellite, it was the first satellite of the experimental improvement program. While it was intended to eventually have an operational role in the system for navigational purposes, there was some unfortunate failure in the equipment, and the satellite is available generally only for experimental purposes. And that does not say that if we had a national catastrophe or something, we might possibly use it; but there are absolutely no plans to use the Triad satellite ever for operational navigation.

DR. WINKLER:

Here is another question.

MR. MAZUR:

Bill Mazur, Goddard.

Do you have any idea of the cost of these pseudo-random code receivers?

DR. OSBORNE:

Well, that is a very difficult thing to get into and I hesitate to talk about costs, especially if you put it in the connotation of low cost, because, you know, low cost is like beauty, it is in the eyes of the beholder.

There have been two units built, and we suspect that adding the pseudo-random code, at least until somebody finds a need for substantial numbers of them, is apt to cost you maybe $30,000 to add that feature to existing equipment.

Now, one should point out, of these some 700 units that I said were in the field, these units are for navigators, and they do an awful lot of things that many, many people interested in time would not require.

So, it is unfair to say that, you know, the cost of one of these devices is unreasonable, because, you know, you fit the device to whatever you need, and don't buy something that you don't need.

SESSION IV

Chairman: Dr. Robert F. C. Vessot
Smithsonian Astrophysical Observatory

N75 11289

PRECISE TIME AND TIME INTERVAL DATA HANDLING AND REDUCTION

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U. S. Naval Observatory

ABSTRACT

In the past year, the increase in PTTI data to be reduced to the U. S. Naval Observatory Master Clock and the requirement for its quick dissemination has necessitated development of more efficient methods of data handling and reduction. An outline of the data involved and of the Time Service computerization of these functions is presented.

INTRODUCTION

During the past several years, the instrumentation and operation of many systems which could be used for world-wide synchronization have been discussed. Among them have been Omega, Loran-C and Loran-D, television comparisons, and the Defense Satellite Communication systems. Implicit in all of these systems used for timing is that someone, somewhere is receiving data and giving some feedback to the participating stations. It is the mechanics of this role of the U. S. Naval Observatory Time Service which I plan to discuss this afternoon.

With the rapid development of timing systems, the increase in data input to the Time Service has been tremendous. However, there has not been a corresponding increase in personnel to process the data manually. Because of this fact, in March 1973 it was decided to inauguarate automatic data processing for Precise Time and Time Interval data as much as possible.

As all data from the Defense Satellite Communication terminals were already being received in machine-readable form, i.e., paper tape via TWX, this system was used as the nucleus for the design and implementation of a program to store, calculate and disseminate all PTTI data.

FORMAT

As the first step in this program, a standard format for TWX transmissions was devised. What was desired, at the minimum, was a format which the IBM 1800 Automatic Data Acquisition System could use to distinguish PTTI data from all other incoming TWX messages and yet which would be flexible.

Additional requirements were the Day, Month, and Year; the local reference or Cesium number; the identification of the monitored systems; the time comparison; a check number; and the date/time of the comparison (Fig. 1).

The addition of 'NOTES' gave flexibility to the format in that any comments and/or questions could be transmitted, in any form, in the same message.

From inception, the computer processing was envisioned as handling all incoming PTTI data. The next figure is of two messages received from the Camp Roberts, California and Futenma, Okinawa Satellite Communication (SATCOM) terminals. They have transmitted a time transfer via satellite, a direct time comparison, and readings of Loran-D and Loran-C, respectively (Fig. 2).

To identify the TWX message as PTTI data, four Y's followed by the location and activity, must be on line 1. Line 2 is for the date, line 3 is the local cesiums and the following lines contain the monitored systems. In the message from Camp Roberts, each of the Cesiums were used: Cs 576 for Loran-D and Cs 550 for a time transfer with Kwajalein, Marshall Islands. Cs 576 is also used in time transfers with Ft. Dix, New Jersey and Brandywine, Maryland.

In addition to the SATCOM terminals which are transmitting data in this format, are such stations as Nasa/Guam; Detachment "Charlie" of the Naval Astronautics Group in Hawaii; and Elmendorf Air Force Base in Alaska (Fig. 3).

```
YYYY LOCATION/REPORTING ACTIVITY
DAY MONTH YEAR
LOCAL REFERENCE/CLOCK
  SYSTEM IDENTIFICATION  READING  CHECK  DATE/TIME
  .
  .
  .
LOCAL REFERENCE/CLOCK
  SYSTEM IDENTIFICATION  READING  CHECK  DATE/TIME
  .
  .
  .
NOTES
  1.  CS _____  TIME DELAY SETTING ______ ______.
  2.  (Any additional information, comments, questions, etc.)
```

Figure 1. Basic PTTI Teletype Format

```
.
.
.
BT
UNCLAS
YYYY CP RBTS SATCOM
31 OCT 73
CS576
  S7-47         1916.5    3833.0    312200Z
  RDIX            -1.0      -2.0    300150Z
  CS550            2.0       4.0    312200Z
CS550
  KWAJ            10.6      21.2    310900Z
NOTES
  CS576 TIME DELAY SETTING 999980  1999960.
  CS550 TIME DELAY SETTING 999960  1999920.
BT
```

```
.
.
.
BT
UNCLAS
YYYY OKINAWA SATCOM
15 OCT 73
CS447
  HHON         4.0     8.0    152318Z
  CS558        3.5     7.0    152233Z
  SS3/7761    31.23   62.46   152233Z
  SS3/7764    31.05   62.10   152234Z
NOTES
  1.  CS 447 TIME DELAY SETTINGS 265219  530438.
  2.  CS 558 TIME DELAY SETTINGS 316526  633052.
  3.  REF YOUR MSG 111953Z OCT 73. REFER TO TEXAS INST
MAN NO. 83202-970I DRAWING NO 161904 DETAIL A. WE NEED
A 16 TOOTH PINION GEAR AND A 24 TOOTH GEAR MESHING WITH
IT. PART NO. 161903-1 or 161623-1 AND 169791-1 OF DRAWING
NO. 161905. WE ALSO NEED TAKE UP MOTOR NO. 175148-0001/
115 VAC/ 60 HZ/ 20 RPM
BT
```

Figure 2

```
.
.
.
BT
UNCLAS FM STADIR.
YYYY GUAM STADIR
09 OCT 73
CS136
  SS3Z      43.1      86.2    0000Z
  CS107     -5.5     -11.0    0420Z
BT
```

```
.
.
.
BT
UNCLAS //N02400//
YYYY HONO DET C
18 NOV 73
CS118
  SIX/1        16896.7     33793.4
  NWC/2           95.0       190.0   0100Z
  NWC/1           61.1       122.2   0100Z
  NLK/2            6.2        12.4
  CS060           -9.6       -19.2
  CS060/P        47.775      95.550
CS060
  SIX/2       16916.3      33834.6
NOTES
  NLK/1       INOPERATIVE.
  NDT         SCHEDULED MAINTENANCE 172300Z to 180700Z
NOV 73.
BT
```

Figure 3

Each morning, the complete reel of TWX paper tape is scanned by the Time Service Data Acquisition System and all PTTI data (identified by the 4 Y's) are listed on an IBM 1816 typewriter and punched onto cards for later use in the U. S. Naval Observatory IBM 360/40 general purpose computer. The data punched are the civil date, the computed Modified Julian Date, "Local Reference or Cesium Number", and the time comparison. The check number, which is twice the time comparison, is automatically verified. Any discrepancy is noted on the typewriter as an error.

STORAGE AND REDUCTION

The punched cards are then used as input to the IBM 360/40. All permanent storage and all calculations are done here because of the greater capacity and flexibility in data manipulation. Since only SATCOM time transfers, direct comparisons and some television comparisons are used in this system currently (although expansion is being planned) only the data used are stored on the disk pack. The calculations to reduce all the data to the difference U.S. Naval Observatory Master Clock (USNO MC)—Local Reference or Monitored system are then made.

In Figure 4, we can see not only the links or series of additions necessary to reduce the data to USNO MC but also the worldwide precise time synchronization possible through the SATCOM terminals.

The connecting link between all terminals and the USNO MC is the terminal at Brandywine, Maryland (coded MBWE). To ensure that its relationship to USNO MC is well known, portable clock visits are scheduled, at a minimum, bimonthly. Additional data are provided by a microwave link which is read Monday through Friday.

Timing access to the Pacific is possible through the Honolulu terminal (HHON/HHEL) (Fig. 4). Through this path, precise time reference stations have been established at Guam and Okinawa. After modifications to the equipment at Thailand (SSEA) are completed, a precise time reference station will also be possible there. If a station can be established at either Northwest Cape (ACAP) or Woomera (WOOM), Australia an important link will have been established for the control of the Naval Communication Station, NWC.

As seen in Figure 4, the Northwest Pacific Loran-C chain (SS3) is monitored by Okinawa, Nasa/Guam, and SATCOM/Guam. Such redundancy can provide great reliability to the reported values of SS3.

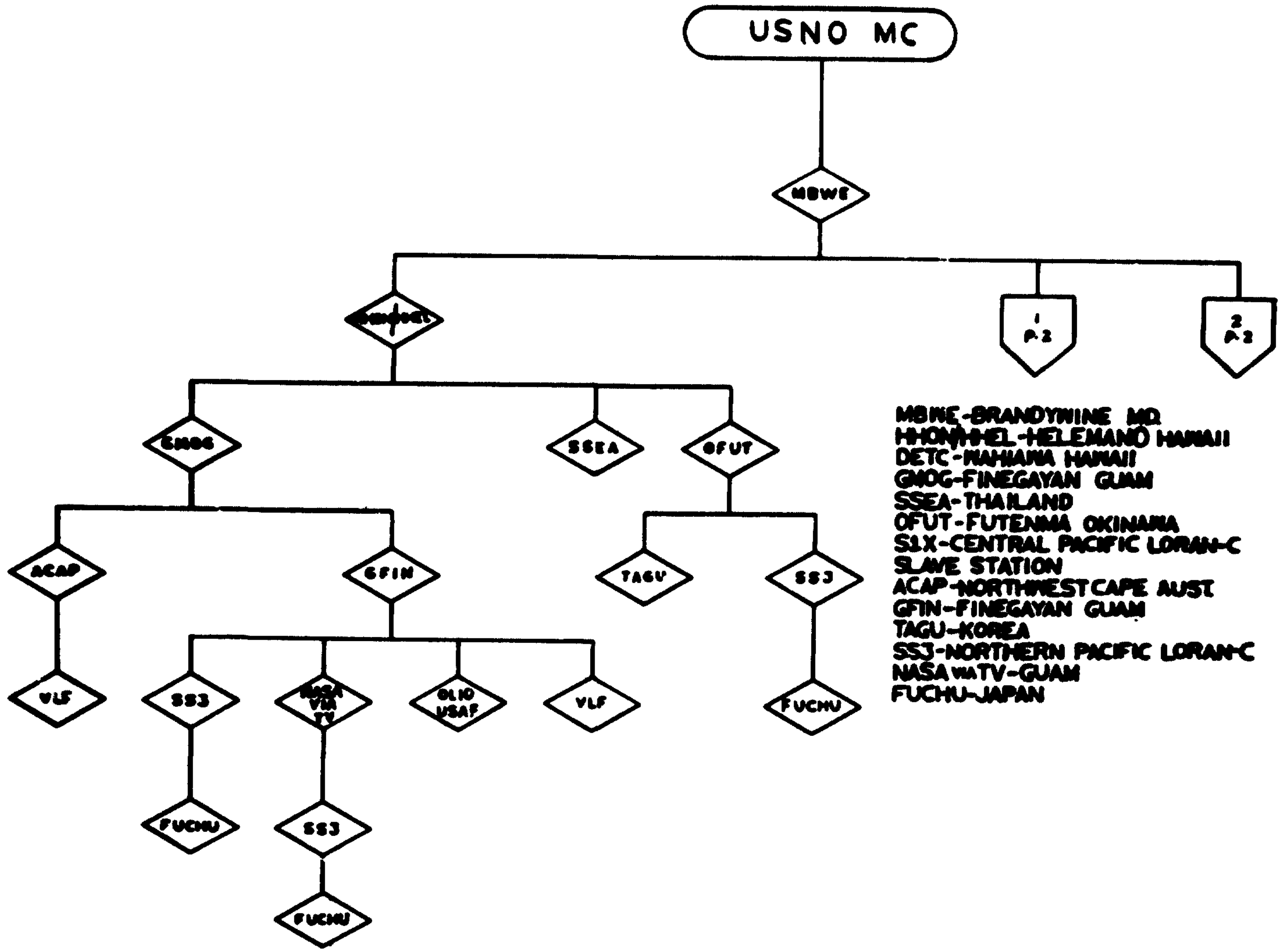

USNO MC
MBWE
GNOG
SSEA
OFUT
ACAP
GFIN
TAGU
SS3
VLF
SS3
NASA VIA TV
OLIO USAF
VLF
FUCHU
FUCHU
SS3
FUCHU
1 P.2
2 P.2
MBWE-BRANDYWINE MD.
HHON/HHEL-HELEMANO HAWAII
DETC-WAHIAWA HAWAII
GNOG-FINEGAYAN GUAM
SSEA-THAILAND
OFUT-FUTENMA OKINAWA
S1X-CENTRAL PACIFIC LORAN-C
SLAVE STATION
ACAP-NORTHWEST CAPE AUST.
GFIN-FINEGAYAN GUAM
TAGU-KOREA
SSJ-NORTHERN PACIFIC LORAN-C
NASA via TV-GUAM
FUCHU-JAPAN

Figure 4

Through the Camp Roberts terminal (CRBT) (Fig. 5), links to Kwajalein, Marshall Islands; tentatively to Woomera, Australia; and to Shemya, Alaska are possible. With a link to Shemya and by portable clock visits to Elmendorf Air Force Base, the Northern Pacific Loran-C chain (SH7) which is monitored by Elmendorf, can be related to USNO MC.

In the East, synchronization to USNO MC is also provided by the SATCOM terminals: going from Brandywine through Ft. Dix, New Jersey to Norfolk, Virginia and then to Guantanamo Bay, Cuba. Another path is through Ft. Dix to Naples, Italy or to Landstuhl, Germany where equipment modifications are now being made.

The method and equipment used in time transfers between SATCOM terminals have been discussed at past PTTI meetings (PTTI Planning Meetings, 1971 and 1972).

OUTPUT: LISTINGS AND GRAPHS

The daily output of this program are six pages of computer listings. The first two are a summary of the data reduced to USNO MC. While beginning and ending dates are variable, the usual list is for the current month with about an eight-day over-lap. The remainder of the listings contain all the raw data received. Using the lists (Fig. 6), discontinuities and/or discrepancies are located and problems resolved when possible. If necessary, clarification from the terminals is requested. The problem most often encountered is the transmission of the wrong sign.

On the summary sheets (Fig. 7), the difference of USNO MC—Local Reference or Monitored System is given as well as the calculated rate of change in parts in 10^{13} in respect to USNO MC.

Our goal is to keep the cesiums within ±10 microseconds and also with a rate of change of less than ±12.0 parts in 10^{13} in respect to USNO MC. From the following plots, using data stored on disk, the steps made in controlling the cesiums at the SATCOM terminals may be seen.

In the graph of Norfolk, Virginia/Cs 351 (Fig. 8), the measurements obtained in late July and early August gave a time difference USNO MC-VNOR/CS 351 first of -9.8 microseconds and then of -12.0 microseconds. A control message, based on these time differences, was sent requesting a 15 microsecond retard. Immediately after the step, frequent data were received which gave a rate of -15.9×10^{-13} for Cs 351 in respect to the USNO MC. Therefore, a second control message to decrease the frequency was sent. Since then (September 10), Cs 351 has remained within 1 microsecond of USNO MC.

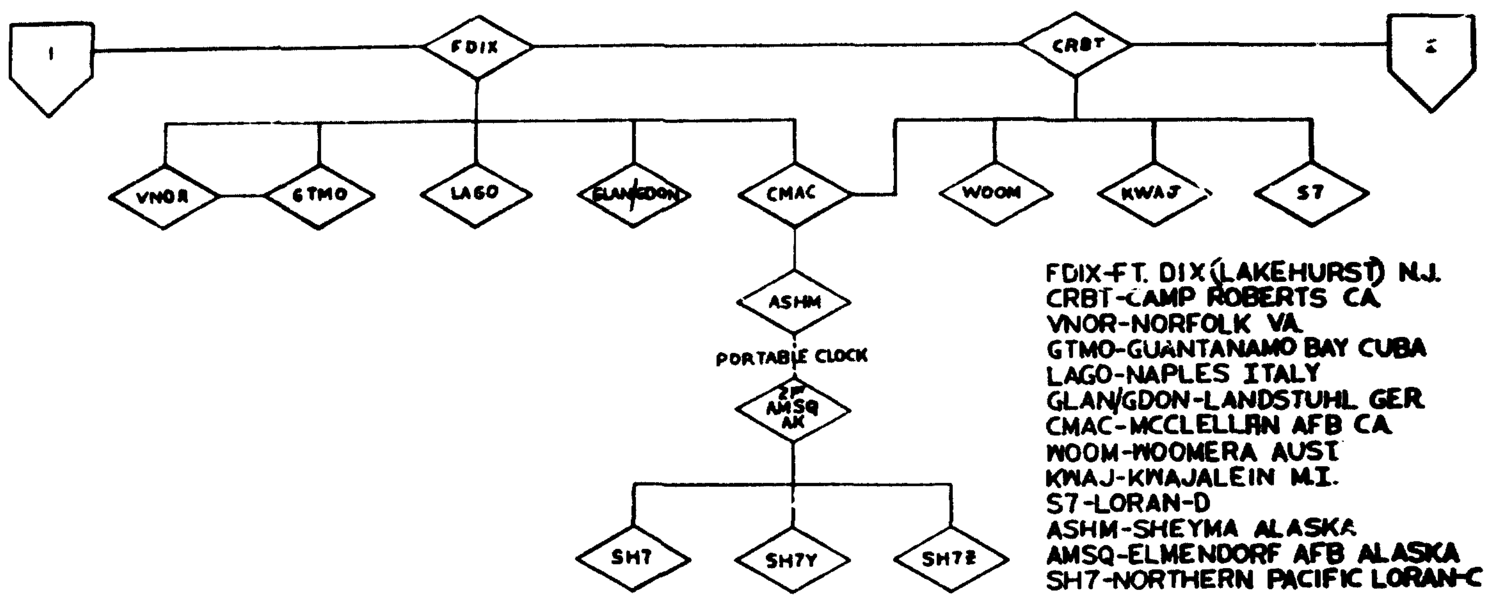

1
FDIX
CRBT
2
VNOR
GTMO
LAGO
GLAN/GDON
CMAC
WOOM
KWAJ
S7
ASHM
PORTABLE CLOCK
2F
AMSQ
AK
SH7
SH7Y
SH7Z
FDIX-FT. DIX (LAKEHURST) N.J.
CRBT-CAMP ROBERTS CA
VNOR-NORFOLK VA
GTMO-GUANTANAMO BAY CUBA
LAGO-NAPLES ITALY
GLAN/GDON-LANDSTUHL GER
CMAC-MCCLELLAN AFB CA
WOOM-WOOMERA AUST
KWAJ-KWAJALEIN M.I.
S7-LORAN-D
ASHM-SHEYMA ALASKA
AMSQ-ELMENDORF AFB ALASKA
SH7-NORTHERN PACIFIC LORAN-C

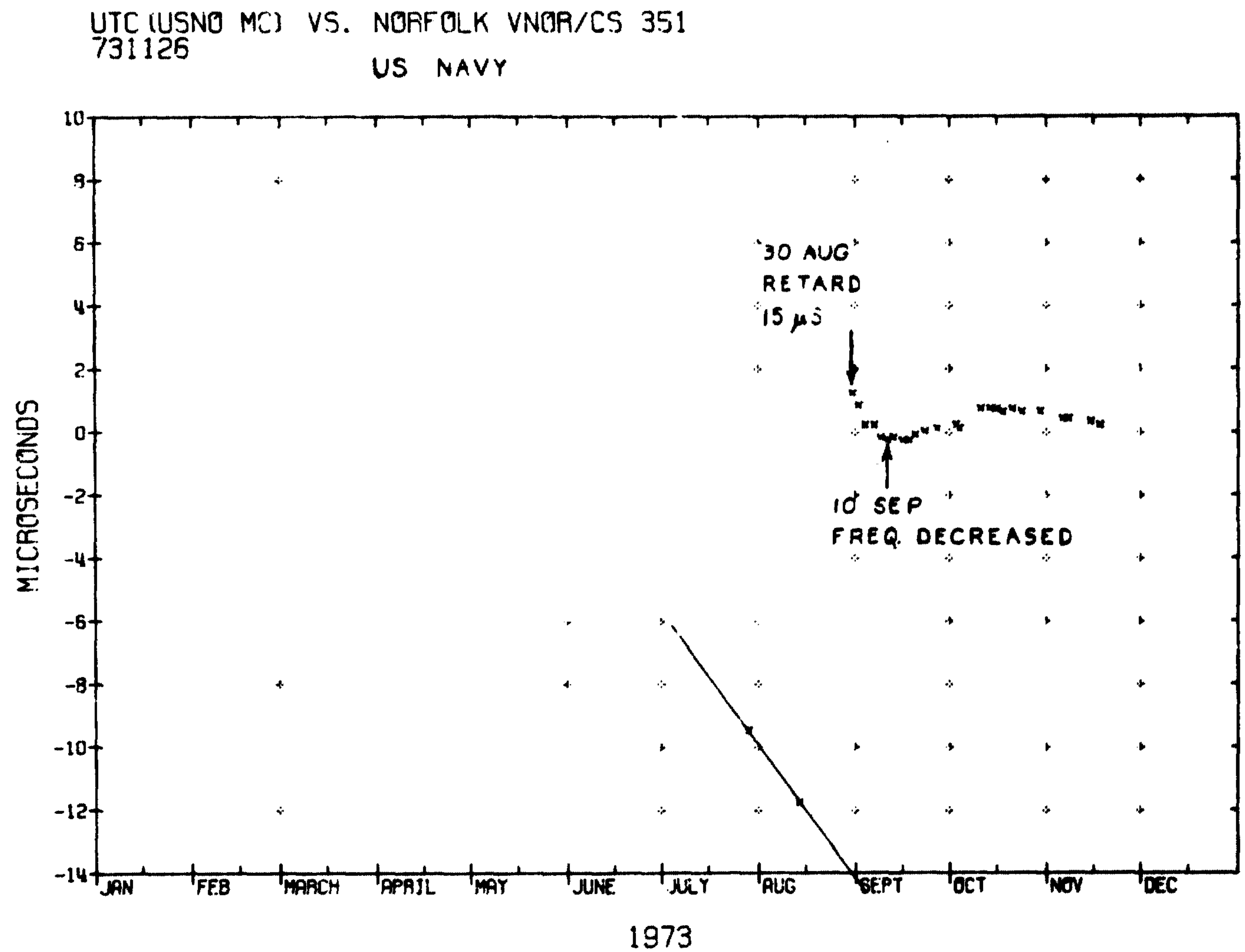
Figure 5

740107 DATE		5 USNOMC -LAKEHURST	42 FDIX -VNOR	51 VNOR -FDIX	43 FDIX -GTMO	70 VNOR -GTMO	71 GTMO -VNOR	66 LAGO -FDIX	56 FDIX -LAGO	82 USNOMC -VNOR	44 USNOMC -GTMO	60 USNOMC -LAGO
731023	41978											
731024	41979											
731025	41980		7.3	-7.2						0.4		
731026	41981											
731027	41982											
731028	41983											
731029	41984		7.2	-7.2		-6.4	6.4				-6.0	
731030	41985											
731031	41986	-6.8	7.2	-7.2						0.4		
7311 1	41987											
7311 2	41988	-6.7										
7311 3	41989											
7311 4	41990	-6.6										
7311 5	41991											
7311 6	41992							-2.4	2.4			-4.1
7311 7	41993	-6.5	6.7	-6.7						0.2		
7311 8	41994											
7311 9	41995	-6.4	6.6	-6.6						0.2		
731110	41996											
731111	41997											
731112	41998											
731113	41999											
731114	42000											
731115	42001											
731116	42002	-4.1	6.2	-6.2						0.1		
731117	42003											
731118	42004							-1.5	1.5			-4.5
731119	42005	-6.0	6.0	-6.0				-1.3	1.4	0.0		-4.7
731120	42006											
731121	42007											
731122	42008		6.0	-6.0						0.0		
731123	42009	-5.9	6.0	-6.0						0.1		
731124	42010											
731125	42011											
731126	42012											
731127	42013											
731128	42014		6.0	-6.0						0.1		
731129	42015											
731130	42016		5.9	-5.9						0.0		

Figure 6

740107 DATE		1 USNOMC -BRANDYWINE	2 USNOMC -HONOLULU	32 USNOMC -PC112	3 USNOMC -CP ROBERT	22 USNOMC -CS550	4 USNOMC -GUAM	17 USNOMC -GMOG	5 USNOMC -LAKEHURST	6 USNOMC -LANDSTUHL	7 USNOMC -OKINAWA
731023	41978	1.5		0.4			6.3				
731024	41979	1.6									
731025	41980	1.6	13.9								0.2
731026	41981	1.6		0.7	-5.7	-4.3					
731027	41982	1.6	-4.1				6.2				
731028	41983										
731029	41984	0.3									
731030	41985	0.3					6.1				
731031	41986	0.3	-4.1						-6.8		
7311 1	41987	0.3									
7311 2	41988	0.4	-4.1	1.0	-6.4	-4.2			-6.7		
7311 3	41989	0.4									
7311 4	41990	0.4	-3.9						-6.6		
7311 5	41991	0.4					6.0				
7311 6	41992	0.4		1.2							
7311 7	41993	0.4	-3.6						-6.5		
7311 8	41994	0.5									
7311 9	41995	0.5	-3.1	1.4					-6.4		
731110	41996	0.5					6.1				
731111	41997	0.5									
731112	41998	0.5	-2.8	1.5							
731113	41999	0.5					6.0	-0.5			
731114	42000	0.6									
731115	42001	0.6									
731116	42002	0.6	-2.3		-7.4	-3.8			-6.1		
731117	42003	0.6									
731118	42004	0.6									
731119	42005	0.6	-2.2						-6.0		
731120	42006	0.7									
731121	42007	0.7									
731122	42008	0.7									
731123	42009	0.8	-1.9		-8.0	-3.6			-5.9		
731124	42010	0.8									
731125	42011	0.8									
731126	42012	0.9									
731127	42013	1.0					1.0	-0.8			
731128	42014	1.0	-1.1	2.4			1.2				
731129	42015	1.0									
731130	42016	1.1	-0.8	2.5							
RATE OF CHANGE PARTS IN 10^{13}			**+9.0 27 days**	**+5.7 24 days**	**-9.0 147 days**	**+2.6 36 days**	**+2.0 34 days**	**-2.5 55 days**	**+4.9 93 days**		**-2.9 234 days**

Figure 7



UTC (USNO MC) VS. NORFOLK VNOR/CS 351
731126
US NAVY
MICROSECONDS
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
JAN
FEB
MARCH
APRIL
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1973
30 AUG
RETARD
15 μS
10 SEP
FREQ. DECREASED

Figure 8

At this point, I'd like to present the Control Messages which were sent to Norfolk (Figs. 9 and 10). The first message initiated the step. To do this, it was necessary to change the thumbwheel settings which control the amount of delay in the system. Since USNO MC-Cs 351 was negative, we wished to retard it or, in other words, to increase the delay in increasing the thumbwheel settings. In each Control Message sent, the USNO gives the current thumbwheel setting and then the new setting we desire. Each unit change is equivalent to 1 microsecond. After the change is made, an acknowledgement is sent by the SATCOM terminal, giving the old setting, the new one, and the date/time of the change.

In like manner, a change in frequency is introduced. Here, the change is accomplished by adjusting the C-field setting of the cesium beam. Since the rate of change in USNO MC-Cs 351 was negative, we knew that the frequency of Cs 351 was high in respect to USNO MC. We therefore decreased the C-field setting, each unit change in the setting being approximately equal to a change in frequency of 5.0 parts in 10^{13}.

In contrast to the ease in which Cs 351 was controlled, the graph of USNO MC-GMOG/Cs 529 (Fig. 11), shows the worst case in that a number of corrections were necessary to bring Cs 529 (located in Guam) into the tolerances desired.

The first time comparison was made by portable clock visit in April 1973. The difference was better than 40 microseconds and the frequency was quite low as indicated by subsequent data from time transfers made with the Honolulu terminal. The frequency rate of change with respect to the USNO MC was $+45.7 \times 10^{-13}$.

A Control Message to advance by 50 microseconds and to increase the frequency by a number of major divisions was sent. No C-field setting was specified as it was not known at that time. Unfortunately, the frequency was changed by too great an amount. Additional messages were sent and since September 1, the difference USNO MC-GMOG/Cs 529 has been less than 1 microsecond.

As an example of the best case is the plot of USNO MC-OFUT/Cs 447 at Okinawa (Fig. 12). After an unexplained jump of approximately 6.0 microseconds in mid-February, Cs 447 has been very stable. Its rate of change in respect to the USNO MC, over 234 days, has been -2.9 parts in 10^{13}. The two portable clock measures made in April and October gave rise to an unexplained discrepancy of approximately +0.4 microseconds in the sense SATCOM time transfer-Portable Clock measurement. This difference, appearing also in the comparison of measurements made at Guam and Thailand, has not however appeared in any other comparisons of SATCOM time transfers and portable clock measurements. The discrepancy is still being discussed and will be investigated further.

TIME

TO: REFERENCE STATION

```
.
.
.
TO NAVCOMMSTA NORFOLK VA
BT
UNCLASS  //N02400//
ADJUSTMENT OF VNOR/CS 351
1.  INCREASE THUMBWHEEL SETTING FM 920 383
CK 1 840 766 TO 920 398 CK 1 840 796.
2.  REQ DATE/TIME ADJUSTMENT PERFORMED.
BT
```

FROM: REFERENCE STATION

```
.
.
.
TO RUEBPAA/NAVOBSY WASHINGTON DC
BT
UNCLAS //N02300//
1. 301538Z AUG 73
CS 351 THUMBWHEEL SETTING CHANGED FM 920 393 CK
1 840 766 TO 920 398 CK 1 840 796.
BT
```

Figure 9. Control Messages

FREQUENCY

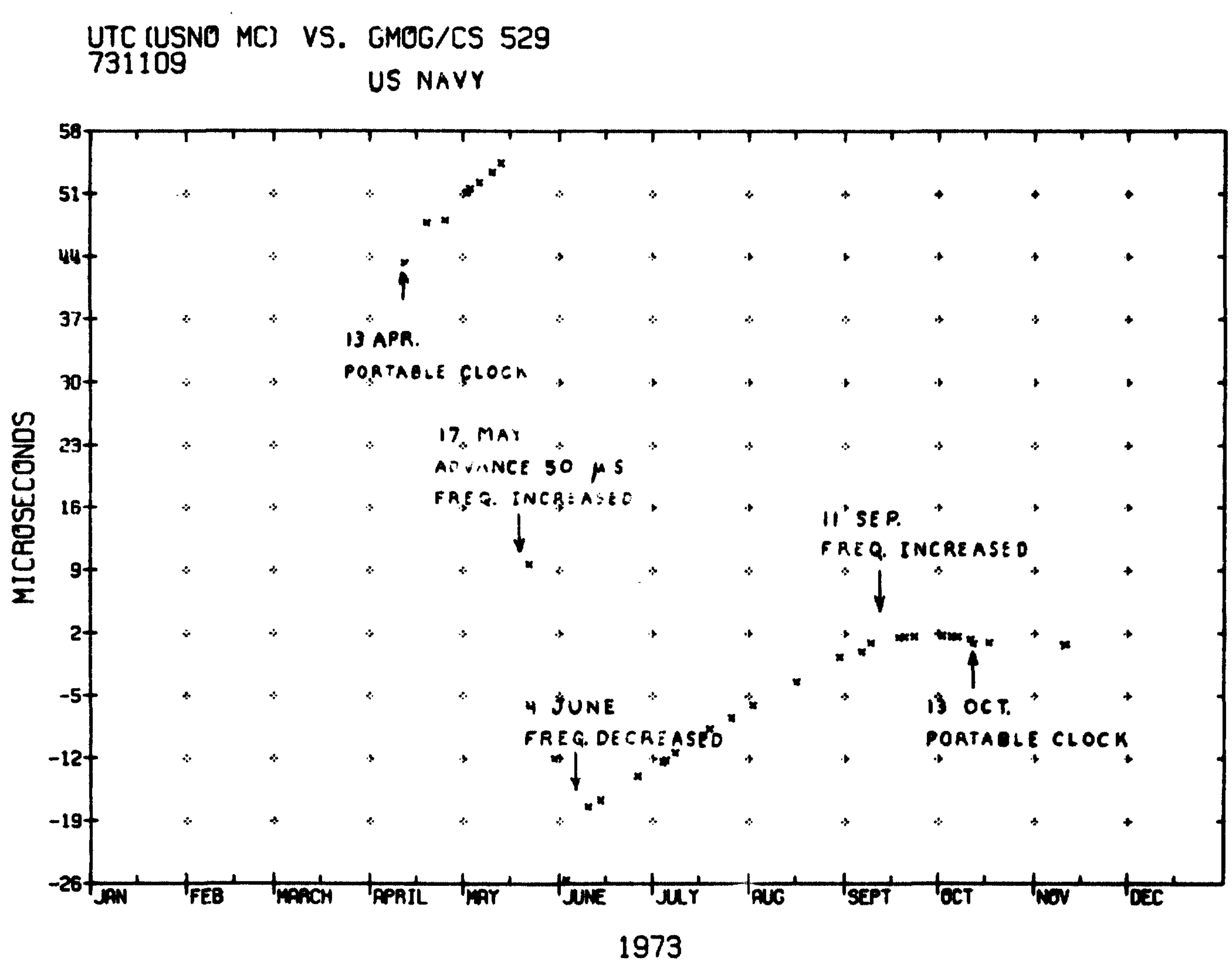
TO: REFERENCE STATION

```
.
.
.
TO NAVCOMMSTA NORFOLK VA
BT
UNCLASS //N02400//
ADJUSTMENT OF VNOR/CS 351
1.  DECREASE C-FIELD SETTING FM 700 CK 1400
TO 696 CK 1392.
2.  REQ DATE/TIME ADJUSTMENT PERFORMED.
BT
```

FROM: REFERENCE STATION

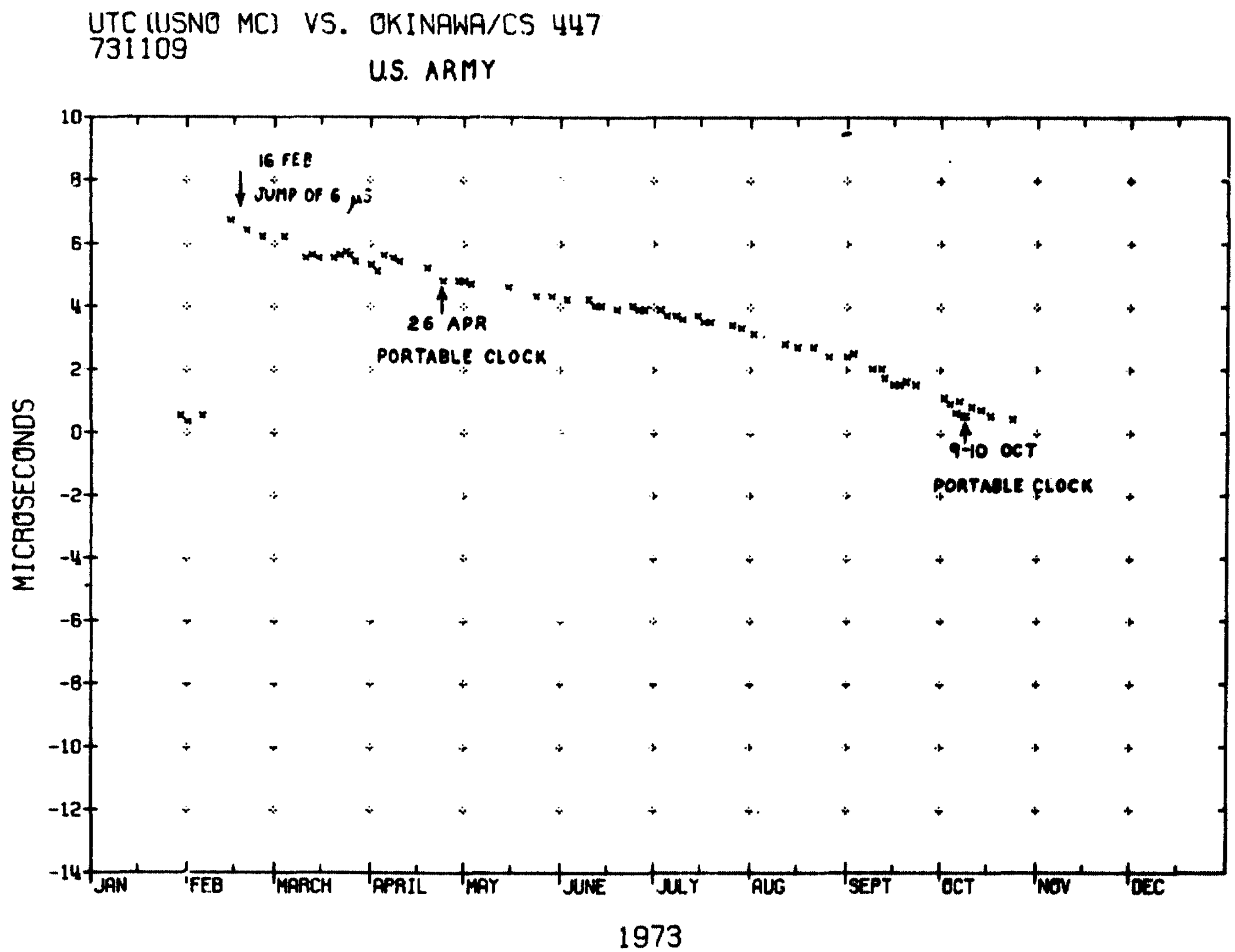
```
.
.
.
TO RUEBPAA/NAVOBSY WASHINGTON DC
BT
UNCLAS //N02300//
1. 101712Z SEP
CS 351 C-FIELD CHANGE FROM 700 CK 1400 TO
696 CK 1392.
BT
```

Figure 10. Control Messages



UTC (USNO MC) VS. GMOG/CS 529
731109
US NAVY
MICROSECONDS
58
51
44
37
30
23
16
9
2
-5
-12
-19
-26
JAN
FEB
MARCH
APRIL
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1973
13 APR.
PORTABLE CLOCK
17 MAY
ADVANCE 50 μS
FREQ. INCREASED
4 JUNE
FREQ. DECREASED
11 SEP.
FREQ. INCREASED
13 OCT.
PORTABLE CLOCK

Figure 11



UTC (USNO MC) VS. OKINAWA/CS 447
731109
U.S. ARMY
16 FEB
JUMP OF 6 μS
26 APR
PORTABLE CLOCK
9-10 OCT
PORTABLE CLOCK
MICROSECONDS
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
JAN
FEB
MARCH
APRIL
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
1973

Figure 12

As of 1 November, time transfers between Okinawa and Honolulu have been temporarily suspended to permit equipment modification at Okinawa. However, Loran-C (SS3) data as well as time comparisons between the cesiums at Okinawa are still being received. Although not reduceable to USNO MC, the data will indicate if any jumps occur in either the LORAN-C station or in the Okinawa cesiums numbered 447 or 558.

Eventually, cesiums will be installed at approximately 28 SATCOM terminals, each of which will be a precise time reference station.

DISSEMINATION

The final output of the automatic processing is the Time Service Announcement Series 16, issued every 10 days. The last figure (Fig. 13) is of the last issue. While Series 16, which is prepared by the IBM 360/40, began solely as a Satellite Communication Time Transfer Report, it has developed into a report of all timing information received from the terminals (with the exception of Loran-C and Loran-D) and is distributed to more than 65 organizations. The data reported include direct comparisons made between cesiums at the terminals, television measurements and microwave measurements. This report, as well as the other Announcements of the Time Service, are available upon request.

CONCLUSION

As the need for greater world-wide synchronization and more Precise Time Reference stations increase, so will the requirements for faster data handling, reduction and dissemination of PTTI data. To fulfill those requirements, the USNO has begun using automatic data processing in this field. The program for which the Defense Satellite Communication system served as the nucleus, is currently being expanded and soon will be able to process all data received, including VLF and Loran-C and Loran-D.

ACKNOWLEDGEMENT

Credit is due to Mr. P. E. Lloyd who operates the IBM 1800 and IBM 360 for these programs and to Mr. L. T. Tillery who did the lettering for the figures.

U.S. NAVAL OBSERVATORY
WASHINGTON, D.C. 20390

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THE REPORT LISTS UTC(USNO MC) - UTC(REFERENCE CLOCK) REFERRED TO 0000 UTC.
UNIT IS ONE MICROSECOND. ESTIMATED ACCURACY IS ± 0.3 MICROSECOND.

MBWE	BRANDYWINE, MARYLAND	HHEL/HHON	HELEMANO, HAWAII
P.C.	HELEMANO, HAWAII	DETC	WAHIAWA, HAWAII
CRBT	CAMP ROBERTS, CALIFORNIA	A	CAMP ROBERTS, CALIFORNIA
GFIN	FINEGAYAN, GUAM	GMOG	FINEGAYAN, GUAM
NASA	GUAM	FDIX	FT. DIX (LAKEHURST), NEW JERSEY
OFUT	FUTENMA, OKINAWA	B	FUTENMA, OKINAWA
VNOR	NORFOLK, VIRGINIA	KWAJ	KWAJALEIN, MARIANA IS.
LAGO	NAPLES, ITALY	GTMO	GUANTANAMO BAY, CUBA

DATE 1973	MJD	MBWE CS 531	HHEL/ HHON CS 561	P.C. (3) CS 112	DETC (3) CS 118	CRBT CS 576	A (3) CS 530	GFIN (3) CS 107	GMOG CS 529
NOV. 11	41997	0.5	....	....	....	....	....	....	....
12	41998	0.5	-2.8	1.5	3.3	....	....	....	....
13	41999	0.5	....	....	....	....	....	6.0	-0.5
14	42000	0.6	....	....	....	....	....	....	....
15	42001	0.6	....	.... (5)	....	....	....	....	....
16	42002	0.6	-2.3	....	3.4	-7.4	-3.8	....	....
17	42003	0.6	....	....	....	....	....	....	....
18	42004	0.6	....	....	....	....	....	.... (7)	....
19	42005	0.6	-2.2	....	3.5	....	....	....	....
20	42006	0.7 (2)	....	....	....	....	....	....	....
21	42007	0.7	....	....	....	....	....	....	....
22	42008	0.7	....	....	....	....	....	....	....
23	42009	0.7	-2.0	....	3.4	-8.1	-1.7	....	....
24	42010	0.7	....	....	....	....	....	....	....
25	42011	0.7	....	....	....	....	....	....	....

Figure 13

QUESTION AND ANSWER PERIOD

DR. WINKLER:

Thank you, Ms. Fisher.

Questions for the paper, please?

ENS WHITE:

Is the observatory's current position to assume the kind of clock control that you demonstrated for the SATCOM terminals and to extend it to other organizations? Say, control over a cesium that we might have at one of our sites? Are you in a position to assume the control of that in terms of adjustments and one thing and another.

MS. FISHER:

I would defer that to Dr. Winkler.

DR. WINKLER:

I cannot commit ourselves without knowing exactly the situation, and I would like to invite you for a discussion on that. The possibility exists, technically, because the system is designed as developed by Ms. Fisher to handle 30 messages a day or 100 messages a day. It doesn't make any difference in that regard.

The greatest problems which exist are in training; sign convention, for instance, is a major headache for us. It does require a considerable amount of training. I think we have to at least initially take into account the human interface. That is why we appreciate having so many actually operating people here in the audience, so we can get into some direct contact.

I think after that has been established, after we have collected considerable experience, we will have a very smoothly running system.

There is another question.

MS. FISHER:

I would also like to mention that any kind of analysis of error on any of these transfers is not gone into yet. We are only establishing the system. It has only been started since March of 1973, and it is just now being done by the computer.

Right now, we are just trying to get a data set, something to work with. I think in the three graphs that you did see, the time transfers do indicate a great deal of consistency, and you can extrapolate and predict these values for some time ahead.

Question, please?

MR. MITCHELL:

Tom Mitchell, Kwajalein Missile Range.

In regard to the sign convention which Dr. Winkler mentioned, when we first started out we weren't sure of our sign convention, and possibly we had some errors.

My primary question here concerns the first reading that I sent in. This was 73 microseconds, which we disagreed with, and we did not change. Now, to this date we have not been able to determine where the 73 microsecond reading came in. However, it was a consistent reading, but because of the magnitude we were able to determine that it was a bad reading.

Should the reading be of a lower magnitude, and we get consistent readings like that, how would we determine whether we have had a jump in our clock, or whether there is a mistake in the reading that we are getting.

MS. FISHER:

Well, the procedure we would like to follow is to contact the terminal itself and ask for another time transfer just to confirm it. In your case, we did not have any readings at all from Kwajalein before that first one. It was so far off, that we sent a control message right away.

Now, again, here, if I recall, you immediately made another time transfer with Camp Roberts that showed that the first reading was in error. Why that would occur, I don't know. Perhaps somebody more involved in the equipment, involved in time transfers could tell you that.

DR. WINKLER:

Again, let me remind you also that the quickest way to find out is to look at another time source, e.g. Loran or send a portable clock, and we are left again to our main means to calibrate the validity of the overall procedure. We cannot be entirely without it.

MS. FISHER:

I think there is going to be another paper later on about the Defense Satellite Communications scheduling, in precise time transfers. The system will be very good, world wide, but we do have the problems of scheduling, and the precise time transfers are very low priority, unfortunately.

DR. WINKLER:

There is another comment that I want to interject here, and that is, at the present time there are roughly 28 satellite ground stations which are or will be available. Out of these 28, DCA, and the services have approved 10 designated stations to serve, in addition to their regular use as precise time reference stations.

Some of these 10 designated stations are Camp Roberts, Hawaii, Okinawa, Guam, and there will be others.

However, since it is an operational system which utilizes in a piggy-back way a communications system, a gigantic communication system, we must preserve the utmost flexibility.

But we will be in a position to serve, to provide time service wherever the action is, because that is where the terminal is going to be.

MS. FISHER:

Any more questions?

MR. MITCHELL:

Yes.

In the remote location that Kwajalein is in, and our mail service is rather poor out there --

DR. WINKLER:

It is poor here, too.

(Laughter.)

MR. MITCHELL:

Well, due to the combination of it being poor here and worse out there, we are receiving the bulletins rather late.

Has any consideration been given to having a teletype feedback on the data, rather than having to wait for the service bulletin to come out?

MS. FISHER:

As far as I know, you are the first one who has brought this up. I don't know whether it would be feasible or not.

DR. WINKLER:

I think it would be. As in everything else we do, we need requirements, we need documented requirements. I would encourage you to get it into your channels. I think the possibility exists, but we need requirements. We used to, three or four years ago, have our Series 4 daily phase values, on composite broadcast transmitted twice daily over some 35 frequencies, worldwide. Now, that was instituted based on the requirement which we got at that time, and our evaluation of these. We think that it was a very good idea.

But after a half year, when we had to document how many people were still using it, we could not justify the continuation of that service.

So, it is always a question of documenting your requirements, and I would only encourage everyone who feels that our service should be improved to let us know in writing, please.

MS. FISHER:

I might also mention one more thing to the gentlemen from Kwajalein. It was due to your suggestion, that we incorporated in the reports some of the other cesiums at SATCOM terminals. For example, I think you asked, since you were transferring with 550, if we would report the time difference between master clock and 550. As you saw on the last slide, we just started. I think maybe two or three issues ago, we started to include, for example, detachment Charley, the two cesiums at Okinawa, and the two cesiums at Camp Roberts.

We do appreciate any comments from anyone who is using the data, and any suggestions that you might have.

DR. WINKLER:

I think we will have to move on. Thank you, Ms. Fisher.

I would like to call now on Mr. Robert Easton, to give us his paper on Submicrosecond Time Transfer between the United States, United Kingdom, and Australia via Satellite.

Mr. Easton, please.

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STATISTICAL PROPERTIES OF HIGH PERFORMANCE CESIUM STANDARDS

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ABSTRACT

The intermediate term frequency stability of a group of new high-performance cesium beam tubes (Hewlett-Packard Model 5061A Option 004) at the U. S. Naval Observatory is analyzed from two viewpoints: (1) by comparison of the high-performance standards to the MEAN(USNO) time scale and (2) by intercomparisons among the standards themselves. For sampling times up to 5 days, the frequency stability of the high-performance units shows significant improvement over older commercial cesium beam standards.

INTRODUCTION

In the last year, the Hewlett-Packard Company has begun production of a new high performance beam tube for its commercial cesium beam frequency standard, the HP 5061A. Denoted as 5061A Option 004, this new beam tube may be included in newly purchased HP 5061A's or may be fitted as a replacement for a standard beam tube in older HP 5061A's or HP 5060A's. Some of the modifications incorporated in the new beam tube include: increased microwave cavity length, reduction in cavity phase-shift, and improvement in the C-field homogeneity, all of which relate to the accuracy of the frequency produced by the beam tube; increased cesium beam flux, which should improve the frequency stability; and better magnetic shielding, which should reduce frequency changes due to external magnetic field changes. Other modifications to the new beam tube, including the new dual beam design, were made to improve the performance of the cesium beam standard when used as a portable clock and when used in field applications.[1]

The U. S. Naval Observatory, currently has eleven cesium standards with the new high performance beam tube. One of these standards has been in operation for over a year; five others have operated for five months or more. From forty days to three months worth of data for three more units is also available. The purpose of this report is to discuss the precision and frequency stability of the new high performance beam tube for averaging times from one hour to five days, with some tentative results for averaging times up to twenty days.

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For PTTI applications the additional cost of the new beam tube would be justified if a requirement exists for increased frequency stability in sampling times greater than one hour. In this regard, there is a preliminary word of warning about the frequency stability values reported here. All of the frequency standards at the U.S. Naval Observatory have good operating environments. In the clock vaults, temperature varies typically by no more than one or two degrees Centigrade for periods of months. Reasonable care is taken to insure that the frequency standards are undisturbed by other electronic instruments, power outages, and operators. For poorer environments the frequency stability of the high performance beam tube will decrease significantly. The results reported here are valid only for cesium beam standards operating in good environments.

All of the data presented here were collected by the Time Service automatic data acquisition system.[2] Once per hour, an HP 5360 Computing Counter measures the five MHz phase difference at the positive going zero crossover between all of the frequency standards and three reference standards, which currently are two of the high performance cesium standards and the U.S. Naval Observatory hydrogen maser. Typically, the counter requires less than one minute to measure the phase difference between all of the frequency standards and one of the reference standards. Since both the high performance cesium standards and the hydrogen maser have excellent stability for averaging times less than one minute, and since for this paper the interest is in averaging times much greater than one minute, one may regard all the phase difference data as having been collected simultaneously. The noise contributed to the phase difference values by the measurement system itself is estimated by comparing a five MHz signal from a reference standard against itself through a cable loop. For all averaging times considered here, the measurement noise is at least one order of magnitude smaller than the best results obtained for frequency stability. To a very good approximation the measurement noise may be regarded as zero in all the computations.

One final question prior to the analysis of the data is that of independence of the frequency standards. Care is taken to insure that all of the frequency standards at the Observatory operate independently of each other. The frequency standards are separated electrically and spatially as much as is practically possible. There are currently seven different locations at the Observatory where conventional cesium standards and the new high performance standards are placed. There is no reason to believe that there is any correlation of frequency variations between any of the frequency standards at the Observatory. In addition, all of the cesium beam frequency standards have been aligned and adjusted according to manufacturer's specified procedure to produce the best possible value for the frequency of cesium from each unit.

DATA ANALYSIS

For a detailed look at the precision and frequency stability of the new high performance standards, the forty day period from 16 August, 1973 to 25 September, 1973 (MJD 41910 to MJD 41950) will also be considered, when nine high performance standards were in operation continuously at the Observatory. In this same time period, 21 conventional HP 5061A's operated continuously. We may estimate the precision in frequency of both of these groups of cesium standards by calculating for each group the average frequency with respect to MEAN(USNO) over the entire 40 day period and the standard deviation in frequency of each group. The results of these calculations are given in Figure 1. While the average frequency of each group is quite close (differing by little more than 1 part in 10^{13}), the standard deviation for the high performance units is somewhat lower than that for the conventional standards. Thus, the high performance standards were a more precise group of frequency standards than the group of conventional cesium standards. Both of these groups of cesium standards indicate that MEAN(USNO), the internal time scale generated by the U. S. Naval Observatory, is high in frequency by 5 or 6 parts in 10^{13}.

$\bar{X}$ = AVERAGE FREQUENCY OF ENSEMBLE WITH RESPECT TO MEAN (USNO)

S = STANDARD DEVIATION OF ENSEMBLE

N = NUMBER OF FREQUENCY STANDARDS IN ENSEMBLE

HIGH PERFORMANCE CESIUM STANDARDS	CONVENTIONAL H.P. 5061A CESIUM STANDARDS
N = 9	N = 21
$\bar{X} = -4.7 \times 10^{-13}$	$\bar{X} = -5.9 \times 10^{-13}$
$S = 13.5 \times 10^{-13}$	$S = 23.4 \times 10^{-13}$

Figure 1. Precision of High Performance Cesium Beam Tube

For estimates of frequency stability, the square root of the Allan variance is used extensively.[3] For the case where two consecutive frequency measurements are made with no dead time between measurements, the Allan variance may be estimated by the following:

$$\sigma_{ij}^2(\tau) \cong \frac{1}{2n} \sum_{\ell=1}^{n} (\bar{Y}_{\ell+1} - \bar{Y}_\ell)^2 \tag{1}$$

In this formula, $\overline{Y}_\ell$ is the average frequency of standard i versus standard j in the ℓth interval of duration τ. All $n + 1$ intervals are consecutive and non-overlapping. This estimate of frequency stability is based upon the frequency variation from one time interval of length τ to the next interval. The average frequency for standard i versus standard j in any time interval is estimated by differencing the phase to phase measurements between the two standards taken at the beginning and the end of the time interval and dividing by a scaling factor.

The following equation is also important:

$$\sigma_{ij}^2 (\tau) = \sigma_i^2 (\tau) + \sigma_j^2 (\tau) \tag{2}$$

This equation states that, if standard i and standard j are statistically independent, then the variance of standard i compared to standard j equals simply the variance of standard i alone plus the variance of standard j alone.

For the forty day period under consideration, frequency stabilities for the high performance frequency standards may be derived in three different, though not entirely independent, ways: by comparison of the high performance units, first, against MEAN(USNO), the internal time scale of the U.S. Naval Observatory; second, against XMO5(USNO), a specially constructed experimental time scale; and third, against each other.

In the first method, MEAN(USNO) is used to estimate the frequency stability of each of the nine high performance standards. In Equations 1 and 2, standard i would be a high performance unit, while standard j would be the MEAN(USNO) time scale. For this discussion, a brief review of the salient features of the MEAN(USNO) time scale is helpful. Basically, out of all the cesium standards available at the Observatory, the best 14 to 20 of these are selected to generate MEAN(USNO). Each standard included in MEAN(USNO) is given a weight of one, so that the time scale will not depend on the behaviour of two or three seemingly well-behaved standards.[4] In the forty day period under consideration, MEAN(USNO) was generated by eighteen cesium standards, of which fourteen were conventional standards and four of which were high performance standards. In using MEAN(USNO) to evaluate the high performance standards, there is some difficulty, since four of the nine high performance units were contributors to MEAN(USNO). Theoretically, frequency stability measures for these four units would be too optimistic. In practice, however, since each standard constituted a little less than 6% of MEAN(USNO), to a reasonable first approximation, any one of the contributing standards may be considered as being independent of MEAN(USNO). A more serious problem is the following: in Equation 2, a stability estimate is derived for the left hand side of the equation, the variance of standard i versus MEAN(USNO). To estimate the variance of standard i alone, an estimate of the variance of MEAN(USNO) is required. For averaging times less than 2 days, good estimates of this variance may be derived, but for longer averaging times, good estimates are generally not available. However, if it is assumed that the variance of MEAN(USNO) is equated to the variance of standard i alone, then an upper bound for the variance of standard i alone is produced.

The second method used to evaluate the frequency stability of the high performance units involves an experimental time scale, denoted as XM05(USNO). Preliminary analysis of the frequency stability of the high performance beam tube indicated that the high performance units were about five times more stable than conventional cesium standards for averaging times of the order of one or two days. As an experiment, for the forty day period under consideration, the XM05(USNO) time scale was derived by giving the four high performance standards in the MEAN(USNO) time scale of weight of five each and the fourteen conventional cesium standards a weight of one each. Unbiased estimates may be derived for the frequency stability of the remaining five high performance units against this experimental time scale. Since the four high performance units in XM05(USNO) each constitute about 15% of this experimental time scale, frequency stability estimates for these units would be somewhat too optimistic.

The third and final method for estimating frequency stability involves intercomparisons of the high performance units themselves. The following equation is utilized:

$$\sigma_i^2(\tau) = 1/2\,(\sigma_{ij}^2(\tau) + \sigma_{ik}^2(\tau) - \sigma_{jk}^2(\tau)) \tag{3}$$

By intercomparing three frequency standards the variance of each standard alone may be estimated. By intercomparing the nine high performance standards, one obtains 28 different, though not independent, estimates of the variance of each standard alone. These may be averaged to produce a single estimate for each clock. This method, known as the three corner hat method, has one serious problem when comparing standards with approximately the same frequency stabilities. If the estimates of the variances on the right hand side of Equation 3 have large uncertainties (which will be true when n in Equation 1 is small), then the estimate for the variance alone might turn out to be negative. For n equal to seven (which is the case for five day averaging periods when the data sample length is forty days), an average of three of the 28 estimates for eight of the nine high performance units was negative; for the ninth standard, seventeen of the 28 estimates were negative. For sampling times less than or equal to two days, where n is greater than or equal to nineteen, very few of the individual estimates for the variance turned out to be negative. In practice, any estimate less than zero was dropped before the final averaging.[5]

Figure 2 shows the results of the three types of frequency stability analysis for the high performance standard denoted as Cs 660/1S. Here the square root of the Allan variance is plotted as a function of the sampling time. Cs 660/1S was not a member of MEAN(USNO) or consequently of XM05(USNO) during the forty day period under consideration. The high performance beam tube in Cs 660/1S is the original beam tube for the unit. Cs 660/1S was in operation for approximately two months before the forty day period analyzed here. All three cuves follow approximately the $\tau^{-1/2}$ behaviour typical for cesium beam standards. As is to be expected, the three corner hat estimates for the frequency stability are smaller than the upper bound estimates produced by comparing Cs 660/1S to MEAN(USNO) and XM05(USNO). For shorter sampling times, the three corner hat estimates are considerably below the other two estimates. Both time scales are limited in these sampling regions by white noise. For longer sampling times, the three estimates begin to converge as the stabilities of both MEAN(USNO) and XM05(USNO) are improving faster than the stability of Cs 660/1S alone. For τ equal to five days, all three estimates differ by less than 2×10^{-14}. The most believable estimates over the entire range of sampling times are the unbiased three corner hat estimates.

The stability curves for Cs 660/1S given in Figure 2 are typical of the results obtained for eight of the nine high performance units. The results for the ninth unit, Cs 733/1S, are shown in Figure 3. At intervals varying from one to three days during the forty day period under consideration, Cs 783/1S was physically inverted 180° and left in its new position until the next inversion. While this procedure is not a definitive test of how the high performance beam tube will perform under non-laboratory conditions, it does indicate that disturbances to a high performance unit decrease its frequency stability significantly. The standard deviation for Cs 783/1S for averaging times of five days was a factor of four poorer than that for the undisturbed Cs 660/1S.

To supplement this statistical analysis, we would like to know how much confidence to attach to the estimates of the square root of the Allan variance. For the MEAN(USNO) method and the XM05(USNO) method, the variance of the Allan variance may be estimated using the methods discussed by Lesage and Audoin.[6] For the three corner hat method, however, it is not clear how to produce a confidence interval for the estimate of the variance of a single standard alone. To check the three corner hat method roughly, consider the following procedure. Estimates have been produced both of the variance of each high performance unit versus MEAN(USNO) and of the variance of each high performance unit alone using the three corner method. Combining these results for each high performance standard (except for Cs 783/1S, the unit which was being inverted) produces eight different estimates for the variance of MEAN(USNO) alone. The results for these computations for τ equal to two days are shown in Figure 4. Since the standard deviation of the standard

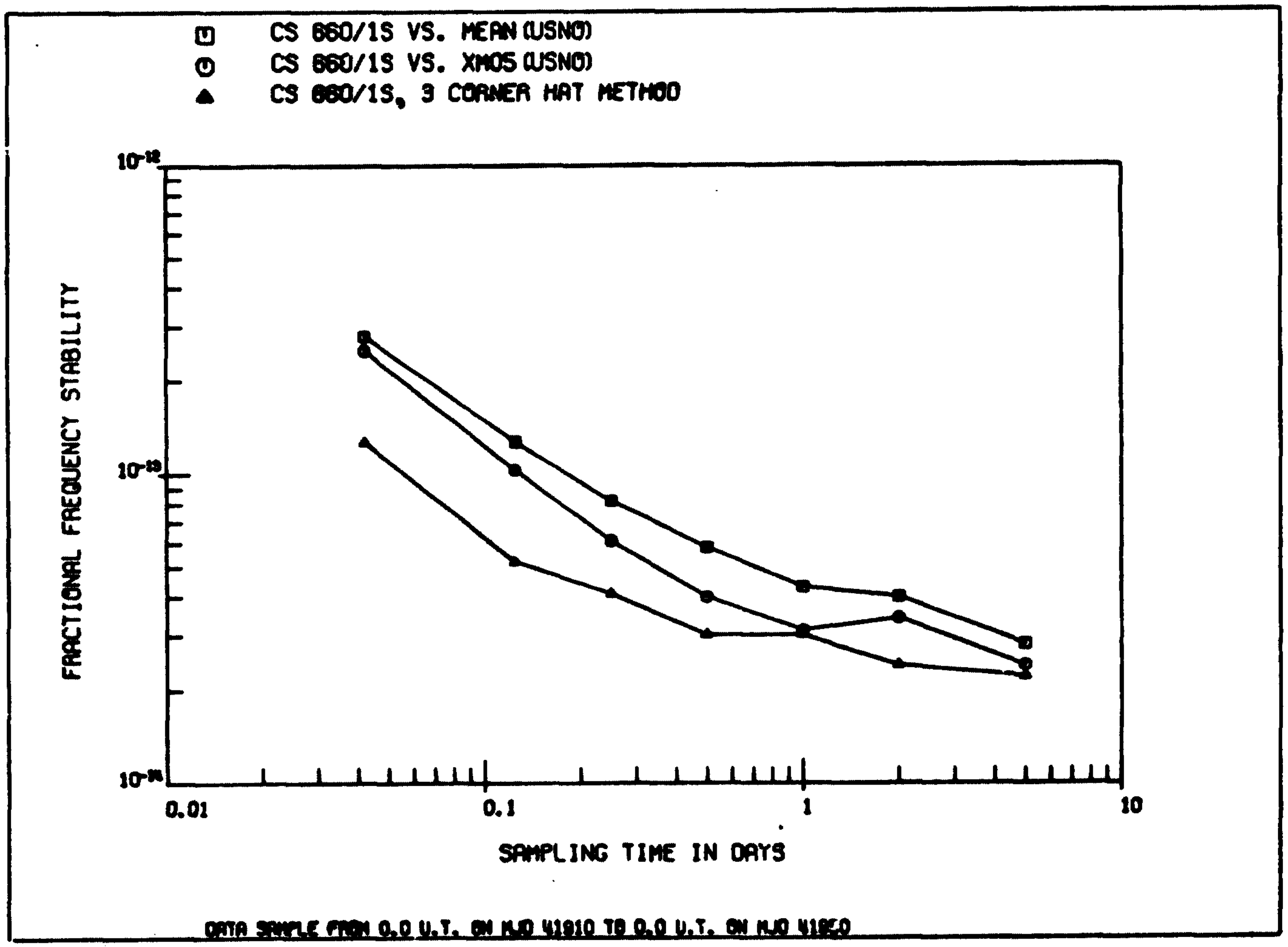
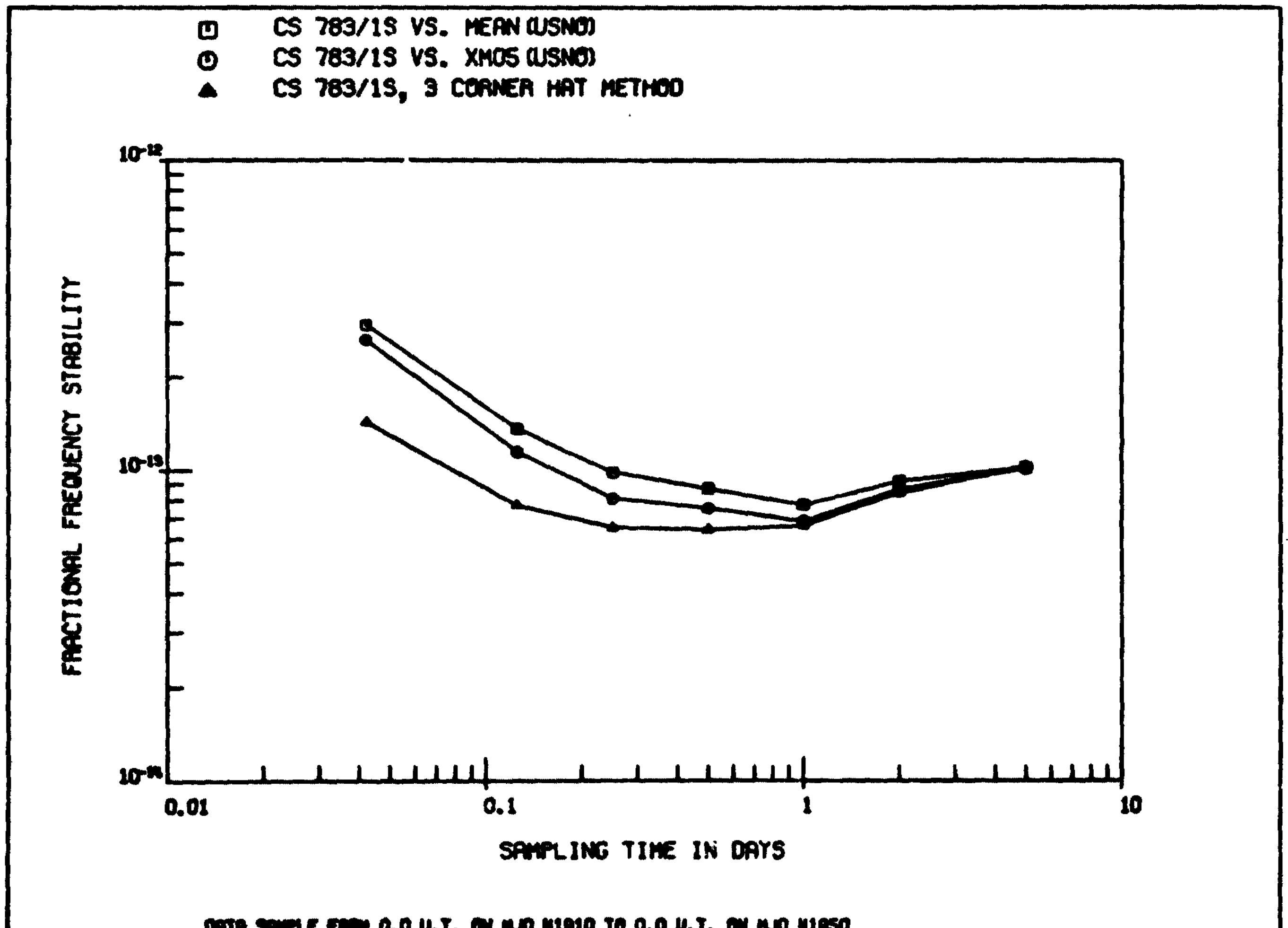

CS 860/1S VS. MEAN (USNO)
CS 860/1S VS. XMOS (USNO)
CS 860/1S, 3 CORNER HAT METHOD
FRACTIONAL FREQUENCY STABILITY
10^{-12}
10^{-13}
10^{-14}
0.01
0.1
1
10
SAMPLING TIME IN DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41910 TO 0.0 U.T. ON MJD 41950

Figure 2



CS 783/1S VS. MEAN (USNO)
CS 783/1S VS. XMOS (USNO)
CS 783/1S, 3 CORNER HAT METHOD
FRACTIONAL FREQUENCY STABILITY
10^{-12}
10^{-13}
10^{-14}
0.01
0.1
1
10
SAMPLING TIME IN DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41910 TO 0.0 U.T. ON MJD 41950

Figure 3

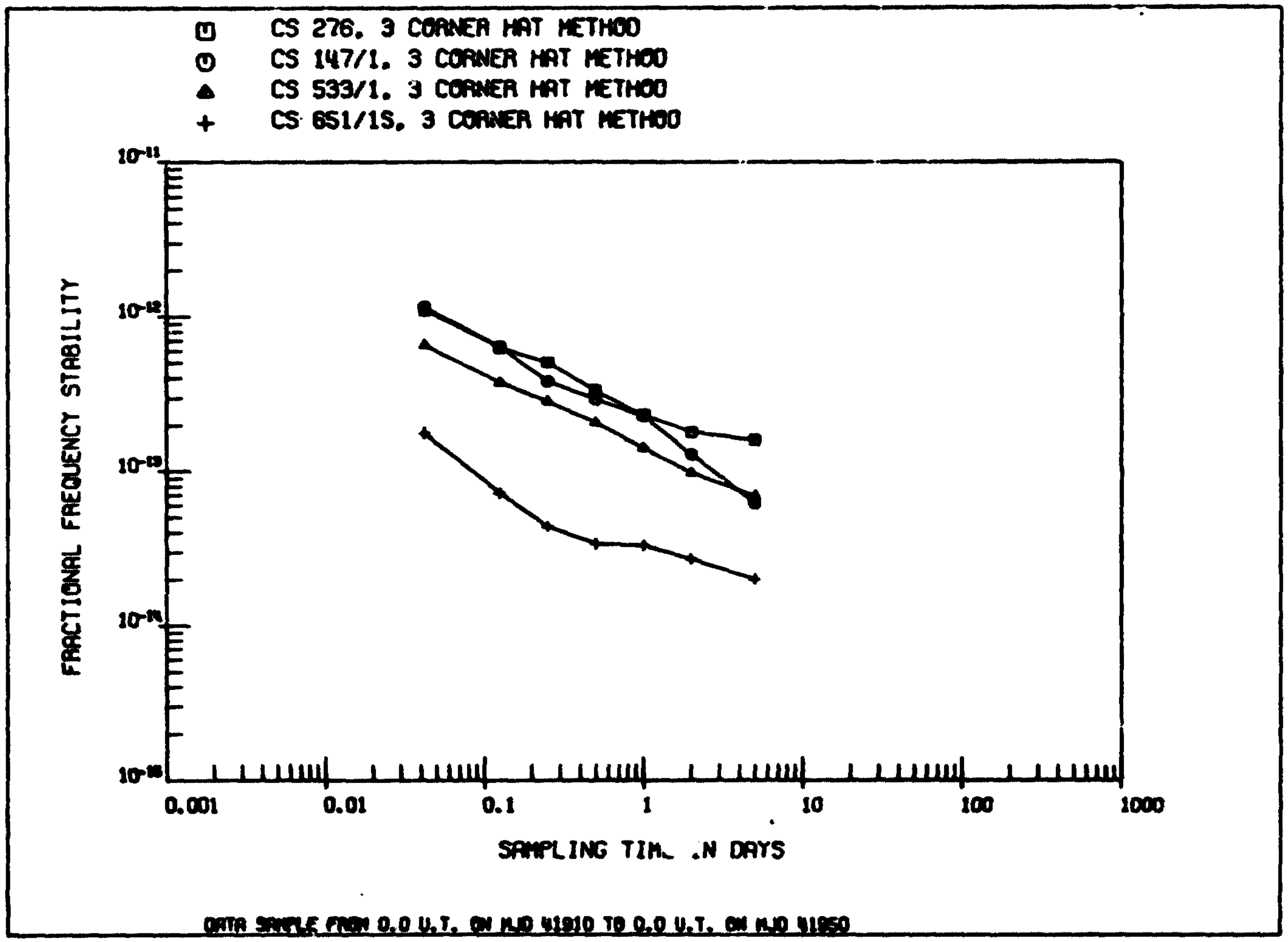
CLOCK	σ CLOCK, MEAN	σ CLOCK	σ MEAN
653/1S	0.32×10^{-13}	0.25×10^{-13}	0.20×10^{-13}
660/1S	0.40	0.24	0.32
431/1S	0.44	0.39	0.20
761/1S	0.35	0.27	0.22
571/1S	0.28	0.17	0.22
656/1S	0.45	0.38	0.24
654/1S	0.40	0.30	0.26
651/1S	0.36	0.27	0.24
			$\bar{X}$ = 0.24
			S = 0.04

Figure 4. For τ = 2 Days

deviation of MEAN(USNO) is quite small (5×10^{-15}), one may conclude that the estimates produced by the three corner hat method are reasonably good. For sampling times less than two days, the results are similar. For τ equal to five days, there are some problems with negative variance again, but if these values are disregarded, the results look fairly good.

For the purpose of comparison, one may estimate the variance of several conventional cesium standards over the same forty day period by using the three corner hat method. Here a conventional cesium standard is compared against all possible combinations of two of the eight undisturbed high performance units. Since two standards with small variances are used to estimate the variance of a third standard with a larger variance, we should get good estimates for the frequency stability of a conventional cesium standard. Figure 5 shows frequency stability plots for three conventional cesium standards (Cs 276, Cs 147/1, and Cs 533/1) and one high performance unit (Cs 651/1S) for comparison. Cs 276 is a HP 5060A which has been in operation since October 1967. Cs 147/1 is an early HP 5061A which has operated since December 1968. Cs 533/1 is a more recent HP 5061A which has been in operation since May 1972. All four stability curves in Figure 5 show the $\tau^{-1/2}$ behaviour characteristic of cesium standards. Cs 651/1S, the high performance unit, was at least three times more stable than any of the conventional cesium standards.

Enough data have been collected to produce preliminary estimates of the frequency stability of the high performance beam tube for averaging times up to twenty days. For these longer averaging times, the three corner hat method is not applicable due to insufficient overlap of available data. Stability estimates for these averaging times are derived by comparing the high performance units against MEAN(USNO).



CS 276, 3 CORNER HAT METHOD
CS 147/1, 3 CORNER HAT METHOD
CS 533/1, 3 CORNER HAT METHOD
CS 651/1S, 3 CORNER HAT METHOD
FRACTIONAL FREQUENCY STABILITY
10^-11
10^-12
10^-13
10^-14
10^-15
0.001
0.01
0.1
1
10
100
1000
SAMPLING TIM. .N DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41910 TO 0.0 U.T. ON MJD 41950

Figure 5

Before producing the standard sigma versus tau plots, it is useful to examine a few frequency versus time plots. These plots contain some information which is lost when conversion is made to the sigma versus tau representation. For the purpose of comparison, Figure 6 shows the five day average frequencies (computed in one day increments) over a 360 day period for a three year old conventional HP 5061A, Cs 497/1, against MEAN(USNO). This cesium standard is one of the better conventional HP 5061A's at the U. S. Naval Observatory. It was a contributor to MEAN(USNO) over the entire period shown in Figure 6. The peak-to-peak variation in frequency of Cs 497/1 versus MEAN(USNO) over this 360 day period was about 6×10^{-13}.

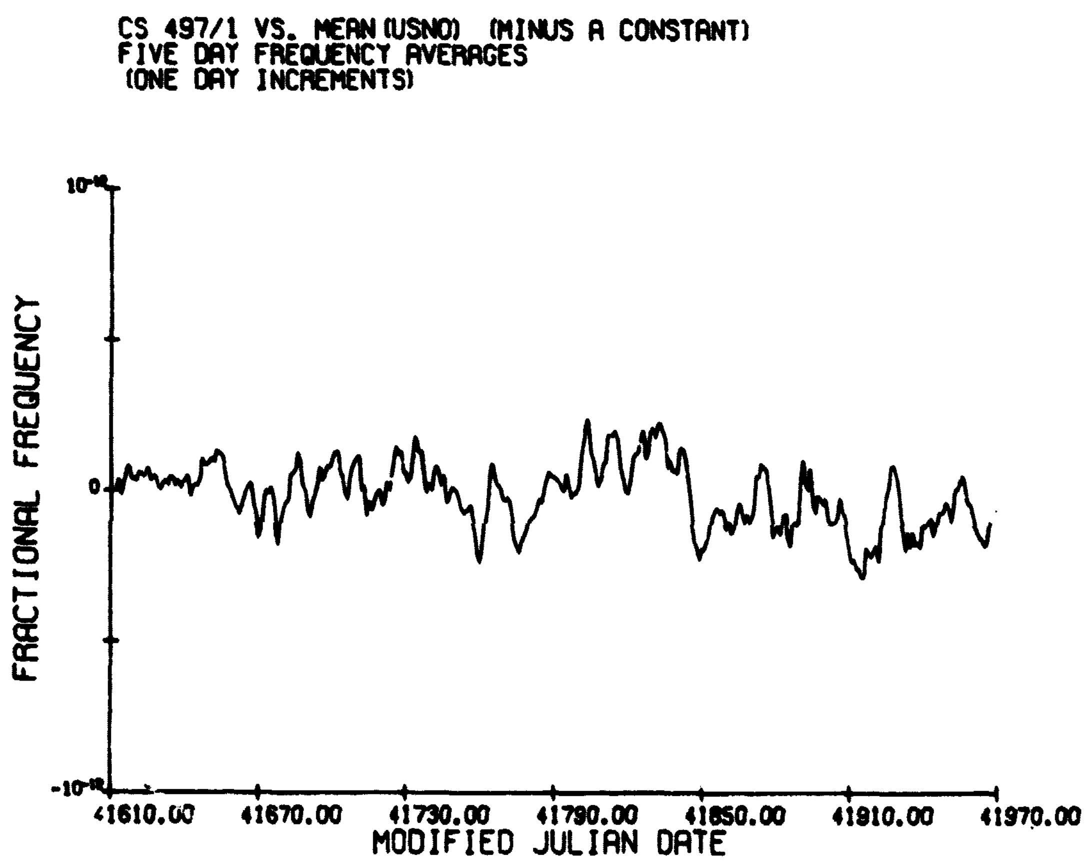


Figure 6

Figure 7 shows the frequency variations of Cs 571/1S versus MEAN(USNO) over the same 360 day period. Cs 571/1S is the one high performance unit which has been in operation for over a year. For the first 120 days shown in the plot, Cs 571/1S was not a contributor to MEAN(USNO), but after that period it was

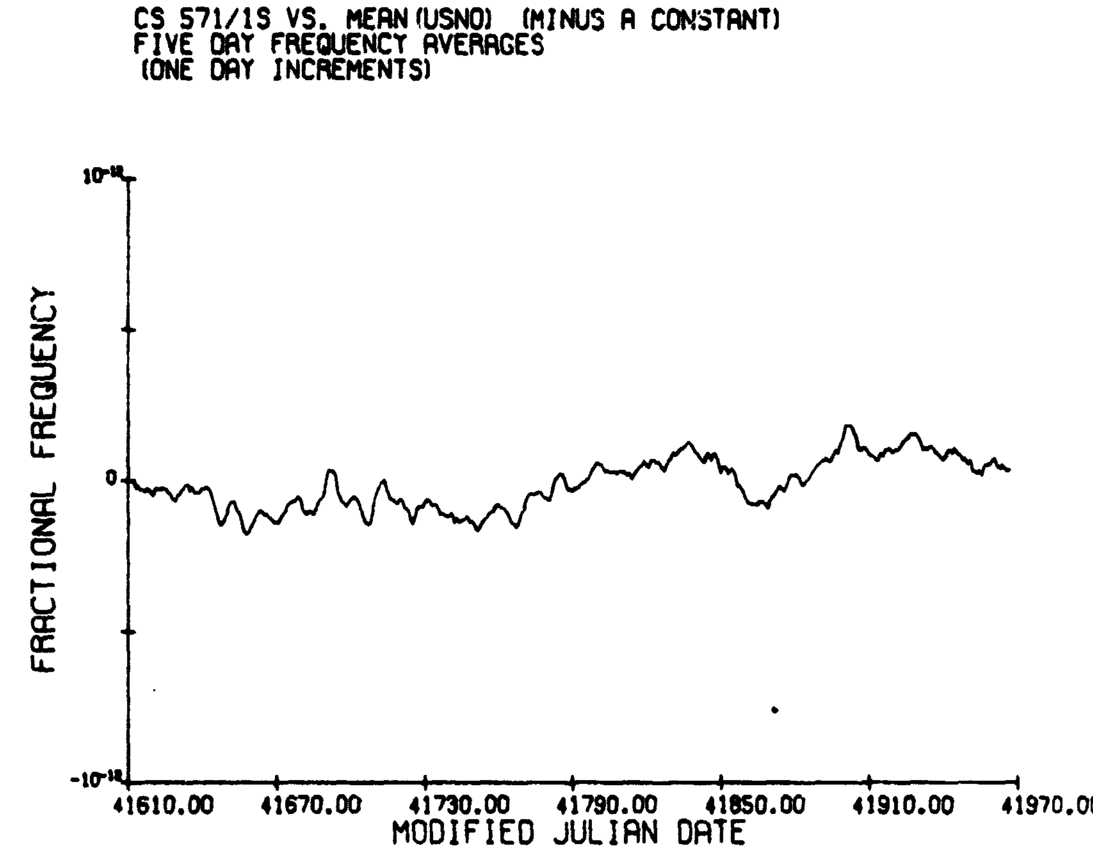


Figure 7

included in the time scale. The peak-to-peak variation in frequency with respect to MEAN(USNO) over the entire 360 day period was about 3×10^{-13}. There was no significant drift in the frequency of Cs 571/1S over this period. This performance was typical for the high performance units with two exceptions. One high performance standard exhibited a drift in frequency with respect to MEAN(USNO) of 3×10^{-13} for the 180 day period it was in operation. The frequency variations of the second exception, Cs 431/1S, are shown in Figure 8. Cs 431/1S is an HP 5061A with a high performance beam tube as a replacement for its original conventional beam tube. The high performance beam tube in Cs 431/1S was one of the first made by Hewlett-Packard. Generally this standard performed well, but it exhibited some large frequency excursions. In particular, there was one frequency excursion of 7×10^{-13} and another excursion of 4×10^{-13} in the opposite direction. After both of these excursions, the frequency of the standard returned approximately to its previous frequency. This anomalous behaviour has not been observed in any other high performance unit. There are

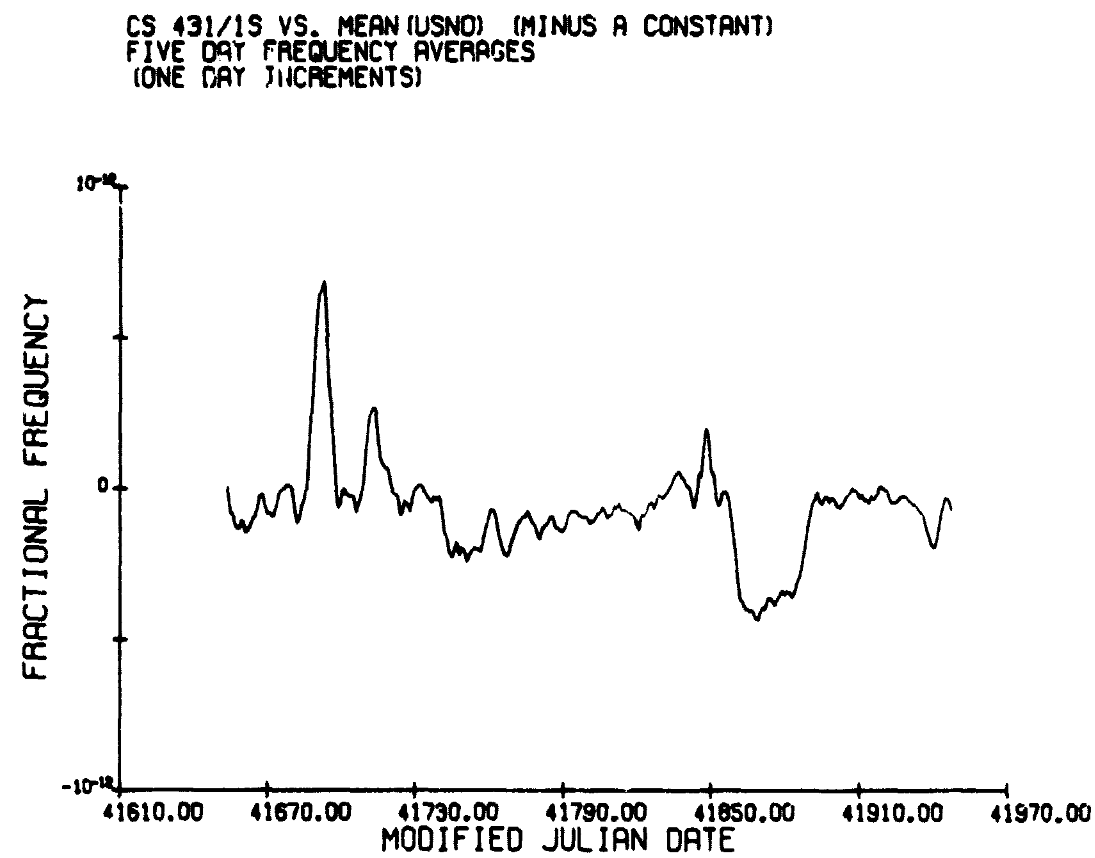


Figure 8

no obvious explanations for these frequency excursions. For the forty day period discussed earlier in this paper, this standard performed as well as any of the other high performance units.

Figure 9 shows the sigma versus tau plot for Cs 571/1S versus MEAN(USNO) for the same 360 day interval shown in Figure 7. The error bars are based on the uncertainty in the characterization of frequency stability for f^{-1} noise, as derived by Lesage and Audoin.[6] For averaging times longer than five days, it is questionable whether the high performance beam tube is more stable than some of the better conventional beam tubes. For the other high performance units (except for Cs 431/1S), the stability estimates for sampling times greater than five days were about the same.

Figure 10 summarizes the frequency stability results presented in this paper. For averaging times less than five days, the typical standard deviation listed in

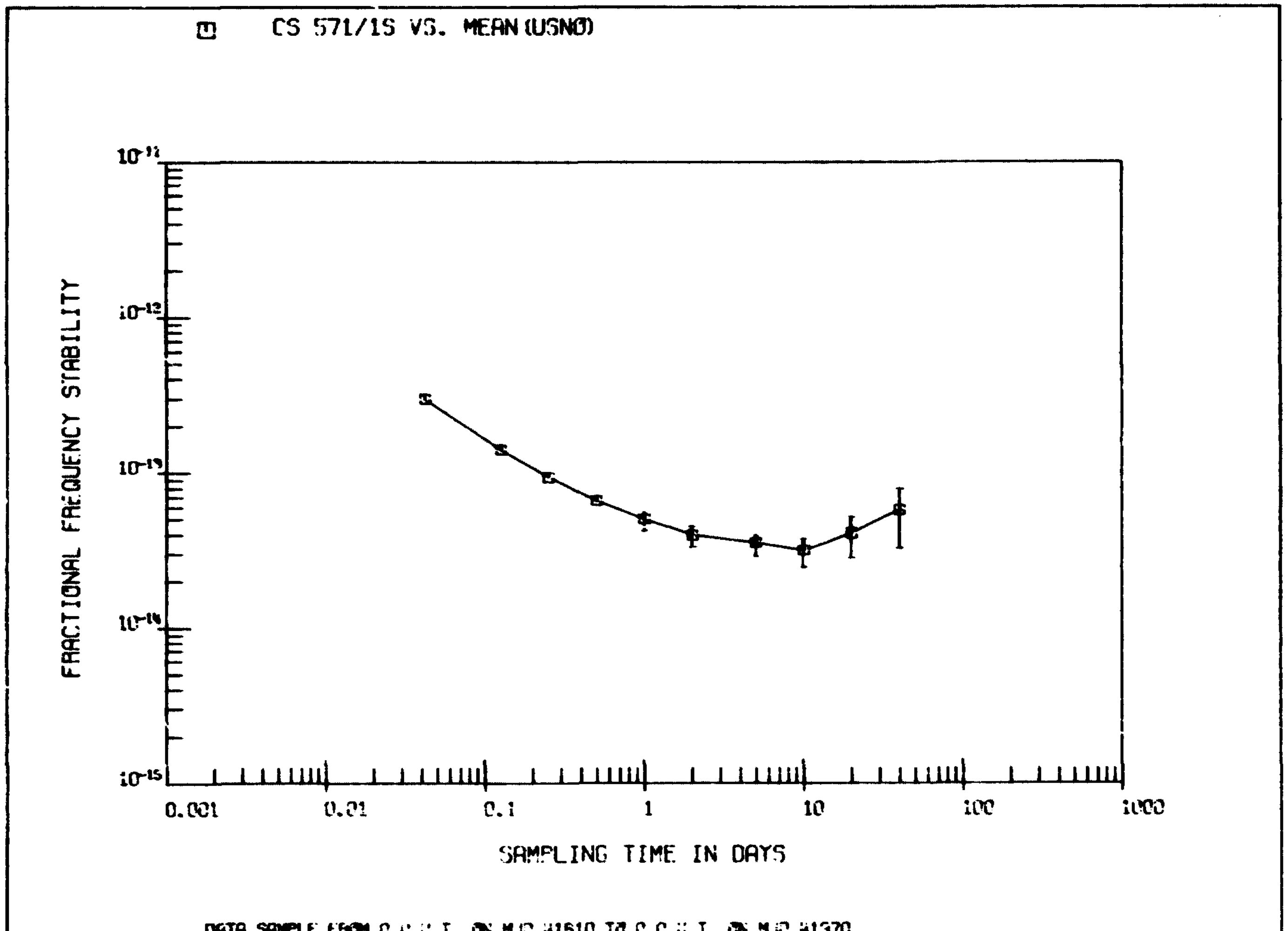

CS 571/1S VS. MEAN (USNO)
FRACTIONAL FREQUENCY STABILITY
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹⁵
0.001
0.01
0.1
1
10
100
1000
SAMPLING TIME IN DAYS
DATA SAMPLE FROM 0.0 U.T. ON MJD 41610 TO 0.0 U.T. ON MJD 41970

Figure 9

τ	TYPICAL $\sigma(\tau)$	UNCERTAINTY
1 HR	1.5×10^{-13}	0.2×10^{-13}
12 HR	0.4	0.1
1 DAY	0.3	0.1
5 DAY	0.3	0.1
10 DAY	0.4	0.2
20 DAY	0.4	0.3

Figure 10. Summary of High Performance Beam Tube Behaviour

Figure 10 is based upon the three corner hat method. For five day averaging times frequency stability, estimates from the three corner hat method and the MEAN(USNO) method were combined to produce the typical standard deviation. For averaging times greater than five days, the MEAN(USNO) method alone was used to derive the typical standard deviation. The values for the uncertainty include both the variations in frequency stability found among the high performance units and the uncertainty in the estimates themselves.

ACKNOWLEDGEMENTS

I would like to thank Dr. G. M. R. Winkler, Dr. R. G. Hall, and my other colleagues at the U.S. Naval Observatory for their helpful discussions and comments, and Mr. D. W. Allan of the National Bureau of Standards for a very helpful discussion on the three corner hat method.

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QUESTION AND ANSWER PERIOD

DR. VESSOT:

Are there any questions?

QUESTION:

I was struck by your remark that you said you used the manufacturer's recommended procedure to calibrate the clocks, and you just put the Zeeman signal into the clock, and then turning the C-field until you get it?

MR. PERCIVAL:

Yes.

QUESTION:

We have found that the flying clocks which were being banged around by the laborers riding on the back of a pickup truck in the rain, or getting tossled around in aircraft and so forth and so on, needed re-setting of the C-field quite frequently, and we have come across a method that seemed to get a little better accuracy than the factory procedure. I would like to discuss it with you afterwards.

MR. PERCIVAL:

Okay.

DR. VESSOT:

You probably subjected the tube to more environmental tests than just traveling with this thing.

QUESTION:

Yes, they were banged around quite a bit.

DR. VESSOT:

Any other questions?

DR. REDER:

Your peak to peak variations show a very pronounced oscillating behaviors. Do you have any explanation for this?

DR. VESSOT:

Fritz, it is a mood cycle. It is every 30 days, I noticed this, and then some of the others had a 90 day mood cycle.

MR. PERCIVAL:

If you look at a lot of time series data just eye balling it, I have an idea that your mind picks out periods that don't actually exist. What you are looking at and what you think are periods, are not really found if you made a time series analysis of these things and tried to dig out the frequencies.

DR. VESSOT:

Dr. Reder and I have used our own eyeball spectrum analyzers and seen this, and I thought I was the only one.

MR. PERCIVAL:

Yes, it would be something to follow up, and I agree, they do look rather suspicious.

DR. BARNES:

Jim Barnes of the Bureau of Standards.

I would commend you on a very fine paper. I enjoyed it.

I would make one comment only, in that people commonly use non-overlapping estimates for estimating the Allen variance, and if you do that, the paper gives you a very good means of estimating confidence intervals.

If you are willing to give up that method of estimating confidence intervals, you can use overlapping estimates and get improved confidence. You don't always know what it is, but you know it is at least as good as the last you have run.

MR. PERCIVAL:

Yes, but I was using the m equal 2 case here, in which case there is no real difference. You would only get that if you are using m equal 4 to shift along and get the thing.

DR. BARNES:

If your sample is displaced, if your one sample time, tau, is displaced a small increment or small fraction of tau for your next estimate --

MR. PERCIVAL:

Oh, I see. In other words, shift in say 15 minutes, or something like that.

DR. BARNES:

Use all of the data available for each Allen variance sample. You can improve the confidence intervals by an unknown amount.

MR. PERCIVAL:

Right.

DR. VESSOT:

I find that the most hair raising part of this is the possibility of getting an imaginary value of sigma, which doesn't give you much confidence in statistics.

MR. WALCEK (Hewlett-Packard):

It seemed to me that you said that 431 was a standard 5061 with a retrofitted high performance tube?

MR. PERCIVAL:

Yes.

DR. WINKLER:

That cesium 431, to my knowledge, was a standard cesium with standard electronics. However, it was outfitted from the beginning with a high performance beam tube, one of the first beam tubes which were produced in the spring of 1971.

MR. WALCEK:

Well, I think it will turn out that that tube was an early version of the higher performance tube.

DR. WINKLER:

I think that is correct.

MR. WALCEK:

It probably is not representative of the so-called standard tube.

DR. WINKLER:

I don't think Mr. Percival has claimed that. In fact, he has pointed out that it was an early bird. We have moved it around from one site to the other, initially when we got it, and we have noticed a considerable temperature sensitivity.

The first environment, into which it was put, was not a temperature controlled room, it was in fact subject to considerable fluctuations, I would say, five degrees centigrade typically, and the cesium behaved very poorly. In fact, you could see on the phase plot, 100 nanosecond full scale phase plot, you could see the instant of a temperature change.

And then it was moved into one of our best environments, and I think almost all of the data referred to these environments after that moment.

MR. PERCIVAL:

Yes, right.

DR. VESSOT:

Are there any other questions?

MR. LIEBERMAN (NAVELEX):

On the 783, which you said was inverted 180 degrees, do you think that was due to the tube, or the crystal? Do you find the same thing on the standard tube?

MR. PERCIVAL:

Well, I am sorry, because I don't think I can answer your question. I don't know enough about the electronics involved to answer it competently.

We haven't really performed these types of tests on any of our other standards. We were asked to do this for Professor Alley at the University of Maryland in order to give him an idea of what this thing would do in outer space, and so we just kind of did it as a side experiment, and we have never tried this as an exact experiment with a conventional 5061.

I think it would be worthwhile to try, but the trouble is that we try to maintain all of our standards at the observatory in good environments so we can use them for our time scale. That is our business. And we really aren't in the business of testing the durability of standards under strange conditions. And to make, of course, a thorough analysis, you would want to shake the unit and vibrate it and twist it.

QUESTION:

Oh, we can do that.

DR. VESSOT:

I would like to ask a question.

Was this tube realigned magnetically after being inverted?

MR. PERCIVAL:

No.

DR. VESSOT:

In that case, it is possible there was some change in the east-west axis, and you rotated it that way.

DR. WINKLER:

No, no. The beam tube was not readjusted according to procedure, and it is my belief that what we see is an affect of mechanical stress in the cavity. If you turn the beam tube upside down, the mechanical situation will be different. From some of the data that I have seen, the frequency shift was quite repeatable.

Remember, on one side we had a frequency shift of two parts in 10 to the 14th different from the reference standard, and the other side there was something like between 8 and 10 parts in 10 to the 14th.

So, the very fact that it produced a rather repeatable frequency variation, a little less than about 10 to the 13th, makes me believe that what we see is an effect of the mechanical change, not of a magnetic change, which would be very difficult to explain (in view of the observed remanences and hysteresis) why it comes back to the same frequency within parts in 10 to the 14th.

DR. VESSOT:

These are reproducible affects.

DR. WINKLER:

Well, I don't doubt that the magnetic field isn't a major influence in all atomic frequency standards. No question about that. But in that particular instance of turning a standard upside down regularly I believe it is, foremost, a mechanical problem.

DR. VESSOT:

The earth magnetic field alone is more like a half a Gauss in this region.

But if you were to invert the field, I would think you might see something from magnetic reasons alone. However, this is moot, a moot point.

MR. ACRIVOS:

By the way, NAVSAT did produce a report on this test. It was done in a magnetic environment test several years ago, and there were two atomic types of cesiums tested, one was an H.P. and the other was an Atomichron. It was done for a magnetic test. It was inverted, and it did show differences, and these were recorded in the report.

I believe it was Navy Facilities at Patuxent that did the test.

DR. REDER:

One question on the same point. I have a question to somebody who knows something about crystals.

Isn't it so that when you turn a crystal oscillator upside down that you get a rather large change? The answer possibly is that if the crystal wasn't exactly adjusted, the servo gain wasn't enough to bring it back.

VOICE:

That was my question, that if you do get enough change in the crystal --

DR. VESSOT:

I think the point is that it is remarkable that it stayed as stable as it did after being changed as much as it did.

Another question.

QUESTION:

I would like to pursue the question that the gentleman raised a while ago.

Have you ever applied barometric test data in your analysis to question any dependency on this parameter?

MR. PERCIVAL:

Maybe I should talk to you afterwards to get a better idea of what exactly you mean.

DR. VESSOT:

I think the question raised was that is it possible that barometric pressure fluctuations might affect the rate of the cesium clocks differently, and thus show this seemingly very large excursion.

I can tell you that we have seen such affects with hydrogen masers, and learned how to fix them. However, I can't visualize a mechanism for the cesium beam tube that would do it, other than some flexure of the cavity.

DR. ALLEY:

I would like to explain just why we have asked for this to be done, to turning the clock upside down.

The point is, it is exceedingly difficult to simulate the conditions of free fall on the Earth for any length of time, and one way of approximating what might happen to a clock in free fall is to see what happens when you change the acceleration by 2 G, rather than by 1 G. If it is reproducible, one has some confidence that when it goes to free fall, you would know that it would fall in between these two extremes. So, this is the background.

DR. VESSOT:

Thank you, Dr. Alley.

Mr. Kern.

MR. KERN (Frequency & Time):

During the period of your measurements, were there any automatic degaussing provisions in this equipment?

MR. PERCIVAL:

No. The units were aligned initially and placed in one of our vaults, and just left to run with no further degaussing at all. It was initially degaussed, but not during the test.

DR. BARNES:

One very quick question.

You turned the instrument so it went through a full cycle in two days, is that correct?

MR. PERCIVAL:

Approximately, yes.

DR. BARNES:

Did you have a data point at two days?

On the sigma tau plot, was it 1, 2, 5, 10?

MR. PERCIVAL:

Yes, it was two days, right.

DR. BARNES:

If it were exactly reproducible, and you were modulating at a period of two days, then it would have to have an inordinately low value at two days. The fact that it didn't implies that there is hysteresis.

MR. PERCIVAL:

I am sure it wasn't done exactly every two days, because we didn't have somebody come in on the weekends and do it. We at least had a weekend variation.

DR. VESSOT:

Dr. Rueger.

DR. RUEGER (APL):

We were wondering about the use of inverting like this, too. Rather than being the physical forces, the thermal gradients, we thought, would be upset, and we thought that might be a larger affect than the stress on the mechanical parts.

DR. VESSOT:

I think you may have hit on a nerve.

MR. HYATT:

I think the comment from APL is correct. It is most likely a thermal effect. At least, to our knowledge, that is the largest coefficient we have, and the magnetic orientation for a two gauss change probably could only explain a part in 10 to the 14th. The oscillator, being sensitive to orientation is also in the order of two or three parts in 10 to the 14th.

However, there is a sensitivity of approximately a part in 10 to the 13th per degree C on the overall instrument, and certainly turning it over will make a significant difference in the cooling.

DR. VESSOT:

As I see there are no other questions, we will have our coffee.

N75 11291

FLEXIBLE BULB—LARGE STORAGE BOX HYDROGEN MASER*

V. Reinhardt**
Harvard University

ABSTRACT

The principal limitation on the accuracy of the hydrogen maser as a primary frequency standard has been the irreproducibility of the frequency shift caused by collisions of the radiating atoms with the walls of the vessel containing them. The flexible bulb-large storage box hydrogen maser allows one to correct for this wall shift within a single device, sidestepping the reproducibility problem, and reducing the frequency error from the wall shift to the level imposed by the device's stability. The principles of the device are discussed including the flexible bulb technique and the complications caused by a multiple region storage bulb. The stability of the device is discussed including a comparison with an ordinary hydrogen maser. Data is presented from a working flexible bulb-large storage box hydrogen maser demonstrating the feasibility of the device and showing some of its operating characteristics. The flexibility of the device is demonstrated by showing how the device's added degrees of freedom allow ~~one to measure~~ measurement of parameters unmeasurable in an ordinary hydrogen maser.

INTRODUCTION

The hydrogen maser, a quantum oscillator operating on the hyperfine transitions of atomic hydrogen, has repeatedly demonstrated frequency stabilities of one part in 10^{14} or better,[1] but has been limited in accuracy to no better than 2 parts in 10^{12} by a non-reproducible frequency shift.[2] The flexible bulb-large storage box hydrogen maser is a device which allows one to correct for this shift, greatly improving the accuracy of the hydrogen maser as a primary frequency standard. This paper will deal with the construction and testing of such a maser.

The frequency shift which limits the hydrogen maser's accuracy is the dark side of what gives the maser its great stability. Atomic hydrogen in an upper hyperfine state can bounce more than 10^4 times on a teflon surface before it is relaxed to the ground state.[3] Using this, one can confine excited hydrogen in a teflon coated storage bulb for about one second, allowing one to produce a maser operating at 1.4 GHz whose atomic linewidth is only one Hertz. But atomic collisions with the teflon walls of the storage bulb also produce a frequency shift as well as relaxation, and this wall shift is not reproducible from storage bulb to storage bulb.[4,5] Only after a comparison of many hydrogen masers with each other and

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**Presently at NASA Goddard Space Flight Center

with cesium clocks was a ten percent correction for the wall shift arrived at yielding the present uncertainty of about 2 parts in 10^{12} for the hydrogen hyperfine transition.[2]

To reduce the effects of the wall shift, two approaches were taken. First, it was reasoned that if one reduced the rate of atomic collisions with the walls of the storage bulb by making the storage bulb larger, one would obtain a maser with a reduced wall shift. This was done in the design and construction of the large storage box hydrogen maser.[6,7] The mean free path between wall collisions was a factor of ten bigger, and as predicted, the wall shift was a factor of ten smaller. Second, it was reasoned that, if without changing the surface, one could change the mean free path between wall collisions in a known way, one could calculate, from the observed frequency shift, the wall shift for that particular maser, and hence, the unperturbed hyperfine frequency.[8] This was tried, first, with a teflon squeeze bottle as variable mean free path storage bulb,[9] and second, with a flexible cone which could be flipped inside and out as part of a variable mean free path storage bulb.[10]

As tried the flexible bulb method had several shortcomings. First, the change in mean free path could not be measured as accurately as one would have liked. Second, the flexible bulb, being inside the microwave cavity which was part of the maser, tended to make the cavity frequency more unstable. And third, when the flexible storage bulb was convoluted, maser oscillation was difficult to achieve.

To overcome these problems N. F. Ramsey proposed to combine the flexible cone with the large storage box maser. First, the wall shift in the large storage box maser is a factor of ten smaller, so the mean free path measurements are much less critical. Second, in the large storage box maser, the flexible cone would not be inside the microwave cavity, so maser stability would not be affected. And third, in the large storage box maser, there is no problem getting the maser to oscillate with a flexible cone in either cone position.

THE LARGE STORAGE BOX MASER

A schematic diagram of the flexible bulb-large storage box hydrogen maser is shown in Figure 1. A beam of state selected atomic hydrogen is produced, just as in an ordinary hydrogen maser, by an RF disociator and a state selecting hexapole magnet. The beam then enters a large teflon coated storage box which is outside two microwave cavities, but which is connected through large openings to storage bulbs inside the cavities. During a stimulated transition the atoms wander randomly between the storage box and the two cavity storage bulbs. One large microwave cavity is not used because the atoms average the oscillating magnetic field over the storage bulb, and so to obtain an appreciable average

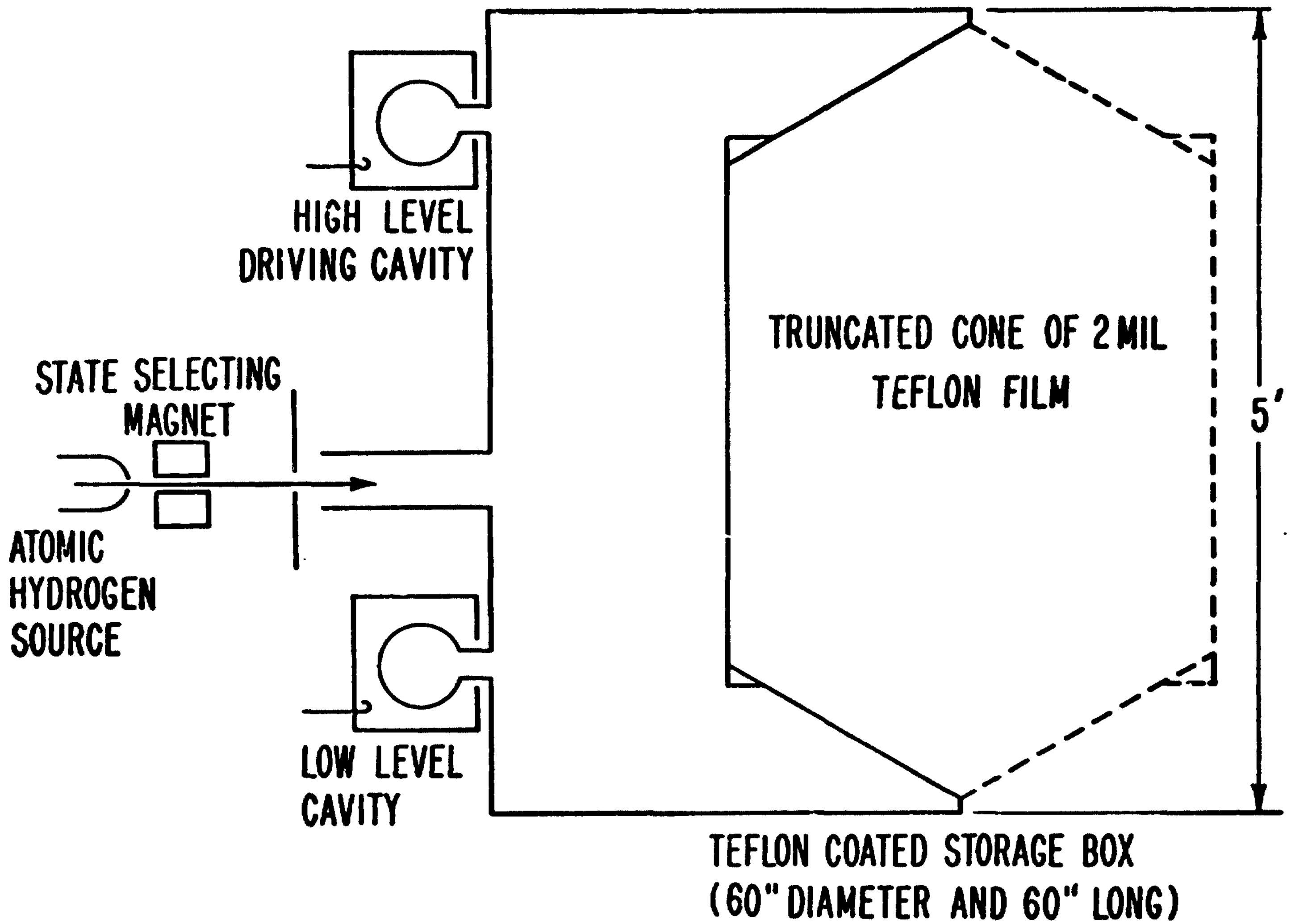

Figure 1. Schematic Diagram of the Large Storage Box Maser with Flexible Box

oscillating field to drive the transition, one must use a cavity whose standing wave in the storage bulb does not have regions of opposing phase. The whole device is placed inside a vacuum can which is inside a triple layer of Molypermalloy shields. As in the ordinary hydrogen maser, a solenoid provides a small static magnetic field parallel to the average oscillating magnetic field. Finally to obtain oscillation, one must connect an 80 db microwave amplifier between the two microwave cavities. A picture of the maser is shown in Figure 2.

The operation[11] of the large box maser is analogous to that of Ramsey coils in a cesium beam. Even though the atoms wander randomly between the cavities, on resonance the atoms' spin precession rate exactly matches the oscillating field frequency, so the precessing spins are always in phase with the oscillating field when the atoms enter the cavities. Thus the atoms effectively see the oscillating field for their whole relaxation time in the storage box, so the maser acts like an ordinary maser with a linewidth governed by the total storage box relaxation time. But again analogously to Ramsey coils, the effective field the atoms see and the effective atomic magnetization the cavities see are reduced from the real quantities by the ratio of the time the atoms spend in the cavities to the total relaxation time. Ordinarily this would reduce the effective coupling between the oscillating field and the atomic magnetization to the point where one couldn't get the maser to oscillate, so to get the maser to oscillate, one must artificially increase the oscillating magnetic field with the 80 db microwave amplifier to the point where the field is strong enough to selfconsistently produce stimulated emission. One cannot get something for nothing though; the low level cavity signal is still very weak compared with an ordinary maser, about 10^{-16} watts as compared with 10^{-12} watts, so thermal noise in the large box maser is much more of a problem. Because of this, in the large box maser, short term frequency stability is much worse than in an ordinary maser; in the large box maser, one trades off short term stability for long term accuracy.[1]

THE FLEXIBLE CONE

On the end of the storage box, in order to change the storage box's mean free path between wall collisions, there is a truncated teflon cone made of 2 mil FEP teflon film. To flip the cone under vacuum, a teflon coated aluminum plate which forms the upper base of the cone is moved in and out by a scissor jack driven through a gear box, chain drive, and rotary motion feedthrough by a motor outside the vacuum system. The jack and drive system are lubricated throughout with dry, high vacuum lubricants to ensure a clean vacuum system. A turns counter is connected to the motor to ensure the reproducibility of the two cone positions. To ensure that the cone is tight yet not stressed in both positions, the upper base plate is attached to the jack through a set of gimbals. For a picture of the cone and drive system, see Figure 3.

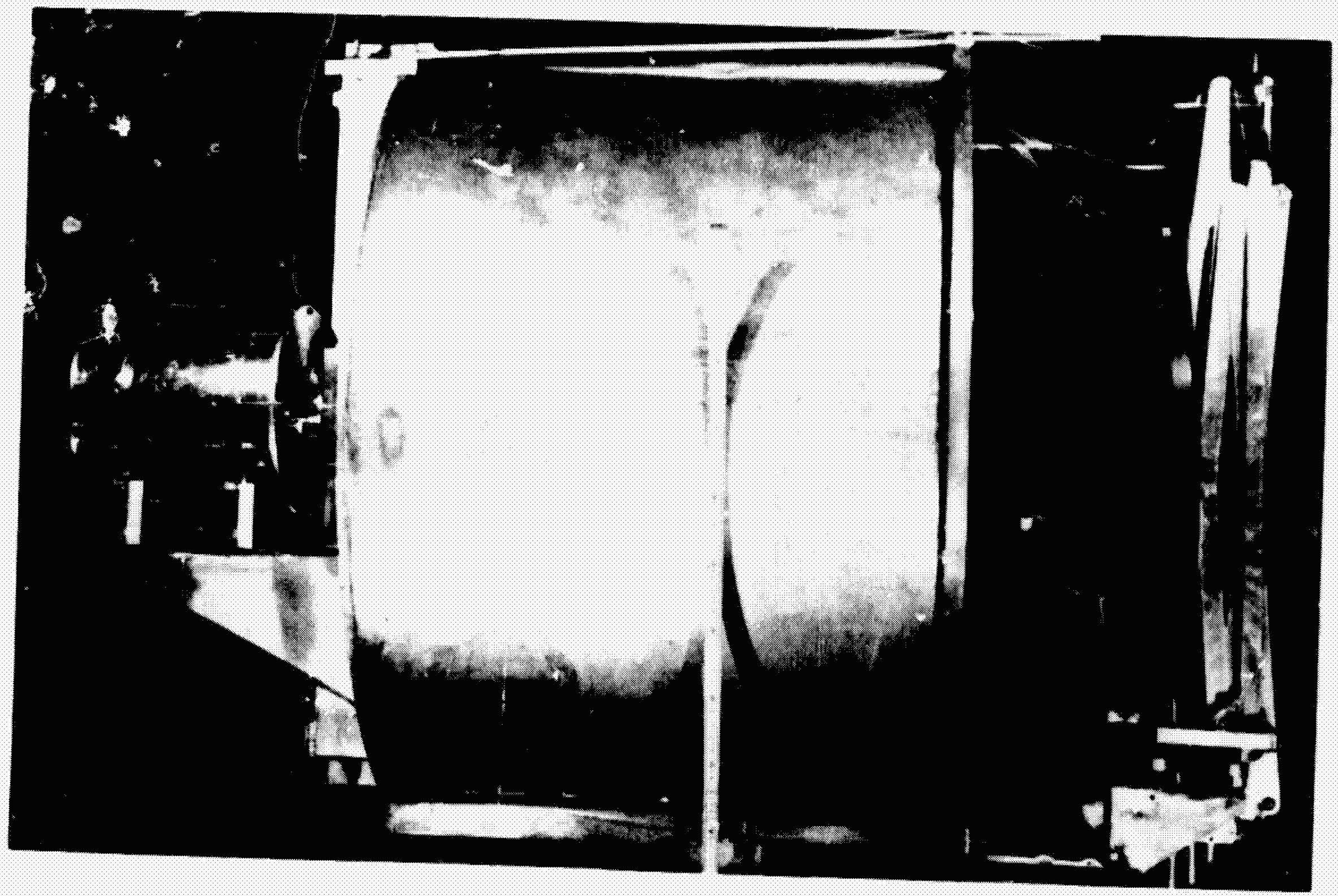

Figure 2. Flexible Cone-Large Storage Box Hydrogen Maser

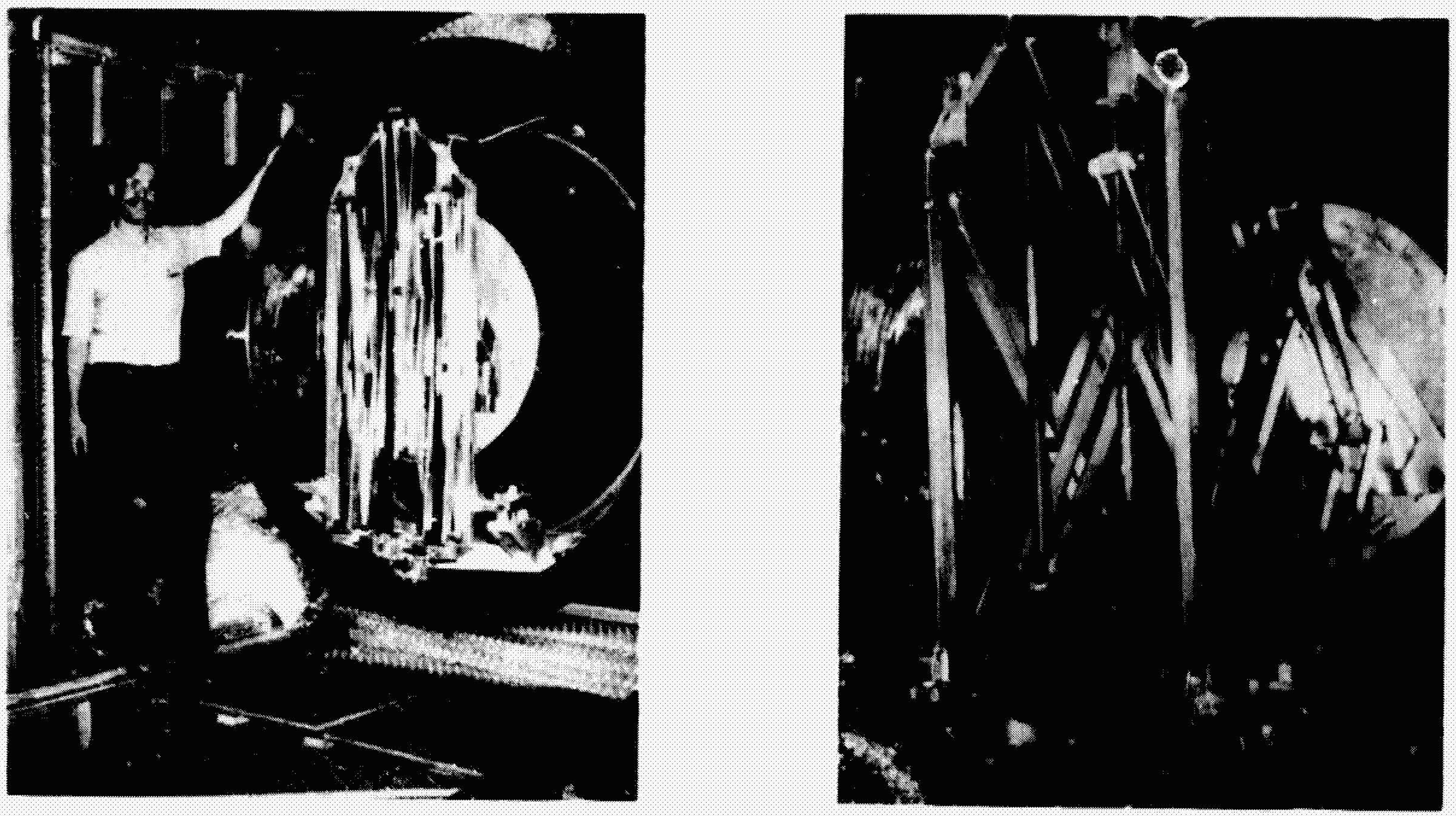

Figure 3. Flexible Cone and Drive

The mean free path between wall collisions of the storage box is given by:[4]

$$d = \frac{4V}{A}$$

where V and A are the storage box volume and area respectively. Thus the wall shift is:[4]

$$\Delta\nu_w = \frac{\varphi}{2\pi}\,\frac{vA}{4V} = \frac{K}{V}$$

where φ is the phase shift per collision and v is the average atomic speed. This means that, in the two cone positions, the maser frequencies will be:

$$\nu_1 = \nu_0 + \frac{K}{V_1}$$

$$\nu_2 = \nu_0 + \frac{K}{V_2}$$

where ν_0 is the maser frequency without the wall shift. ν_0 is then given by:

$$\nu_0 = \nu_1 - \frac{\nu_2 - \nu_1}{\beta - 1}$$

where

$$\beta^{-1} = \frac{V_2}{V_1}$$

Thus to find ν_0, one must know the ratio of the storage box volumes for the two cone positions.

Assuming $\beta = 1.5$ and $\Delta\nu_w = 3$ MHz, to obtain a fractional error of 10^{-14} for the wall shift correction one must know β to 0.1 percent. To do this one uses the ideal gas law. If one seals off the storage box when it is filled with a gas and flips the cone, one can determine β from:

$$\beta^{-1} = \frac{V_2}{V_1} = \frac{P_1}{P_2}$$

where P_1 and P_2 refer to the pressure in the storage box in the two cone positions. To do this without distorting or worse bursting the flimsy teflon cone, one uses the system outlined in Figure 4. This system tracks the pressure in the

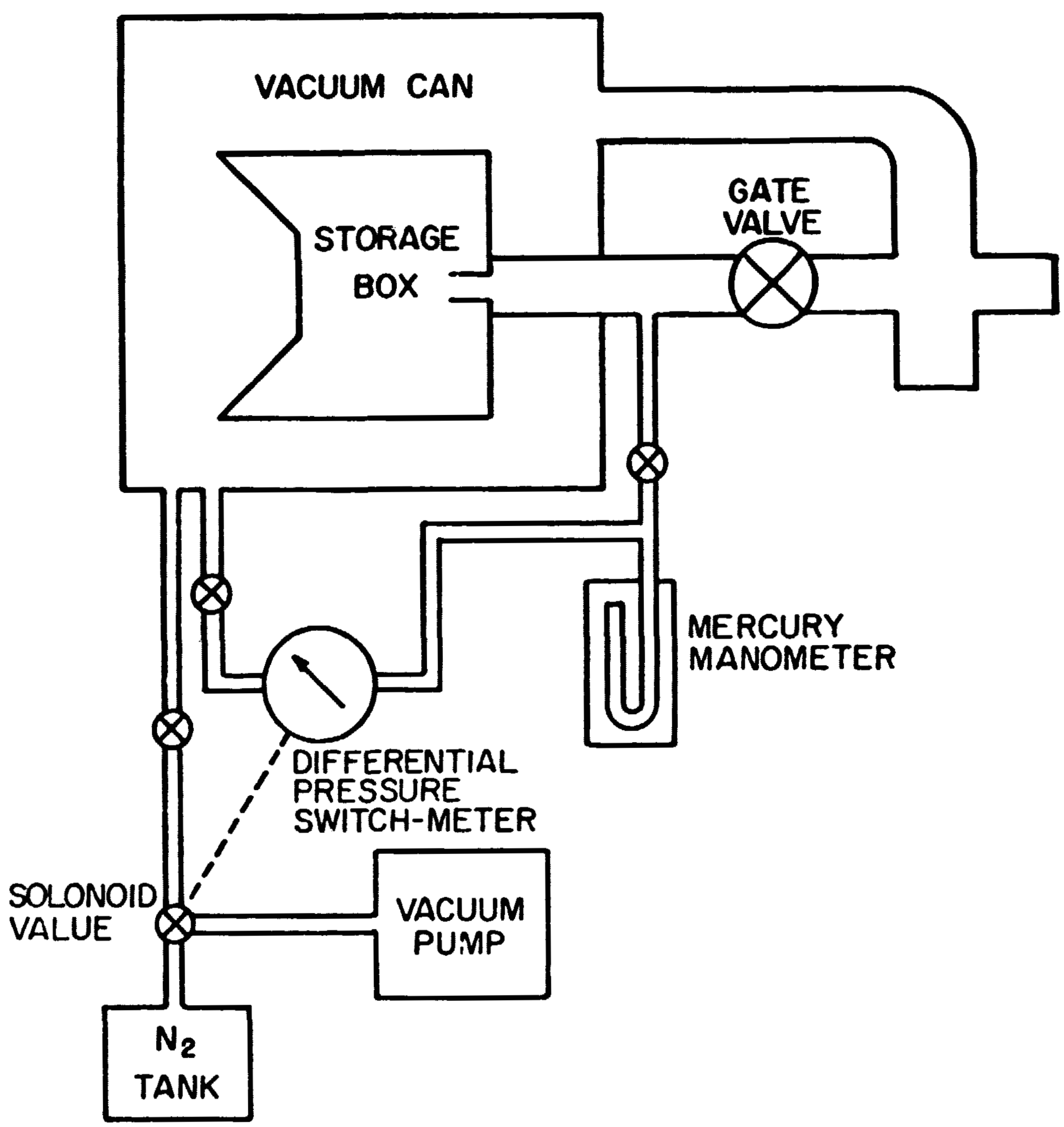

Figure 4. β Measurement System

vacuum can to the storage box pressure while one is flipping the cone. The system is capable of keeping the pressure difference across the cone to within ±0.5 torr, and has the added advantage of allowing one to perform the measurement even though there are leaks between the storage box and the vacuum can.

RESULTS

A plot of the large box maser's frequency fluctuations verses averaging time is shown in Figure 5. The frequency fluctuation measure used is the two sample Allan variance. Notice that, as predicted, the large box maser's short term noise is much greater than that of an ordinary maser. Unfortunately for the long term performance, I was unable to operate the large maser at a low static magnetic field. Because of the extremely narrow linewidth of the large box maser, the static magnetic field's homogeneity requirements for running at low field are much more critical than for an ordinary maser. Also the magnetic shields in the large box maser, being made of overlapping sheets, were not as good as the shields in an ordinary maser. To get a good tuning factor, the lowest field I was able to operate the maser at was about 10 mOe, or at a Zeeman frequency of 10 kHz. The level portion of the σ vs. τ plot can be explained by the observed fluctuations in the static field. To check this, the frequency fluctuations for an averaging time of about one hundred seconds, was measured as a function of Zeeman frequency. A plot of the results is shown in Figure 6. Notice the strong dependence of the frequency fluctuations on Zeeman frequency. Also affecting long term stability, was the fact that I was forced to run the maser with a cracked storage bulb in one of the microwave cavities because of the inability to get a replacement in time. This crack kept us from clamping the bulb sufficiently tightly, and the frequency of the cavity containing the cracked bulb drifted. Another problem was caused by a lack of enough pumping speed in the titanium sublimation pump that pumped on the source. This caused the tuning factor to decay as one ran the maser at high flux.

To compensate for these problems data was taken in the following manner. First the tuning factor of the maser standard the large box maser was being measured against was determined. Then several data runs were taken in which each data run consisted of the following sequence of frequency comparisons:

a. 1BL - 1ML

b. 1BL - 1MH

c. 2BL - 1MH

d. 2BH - 1MH

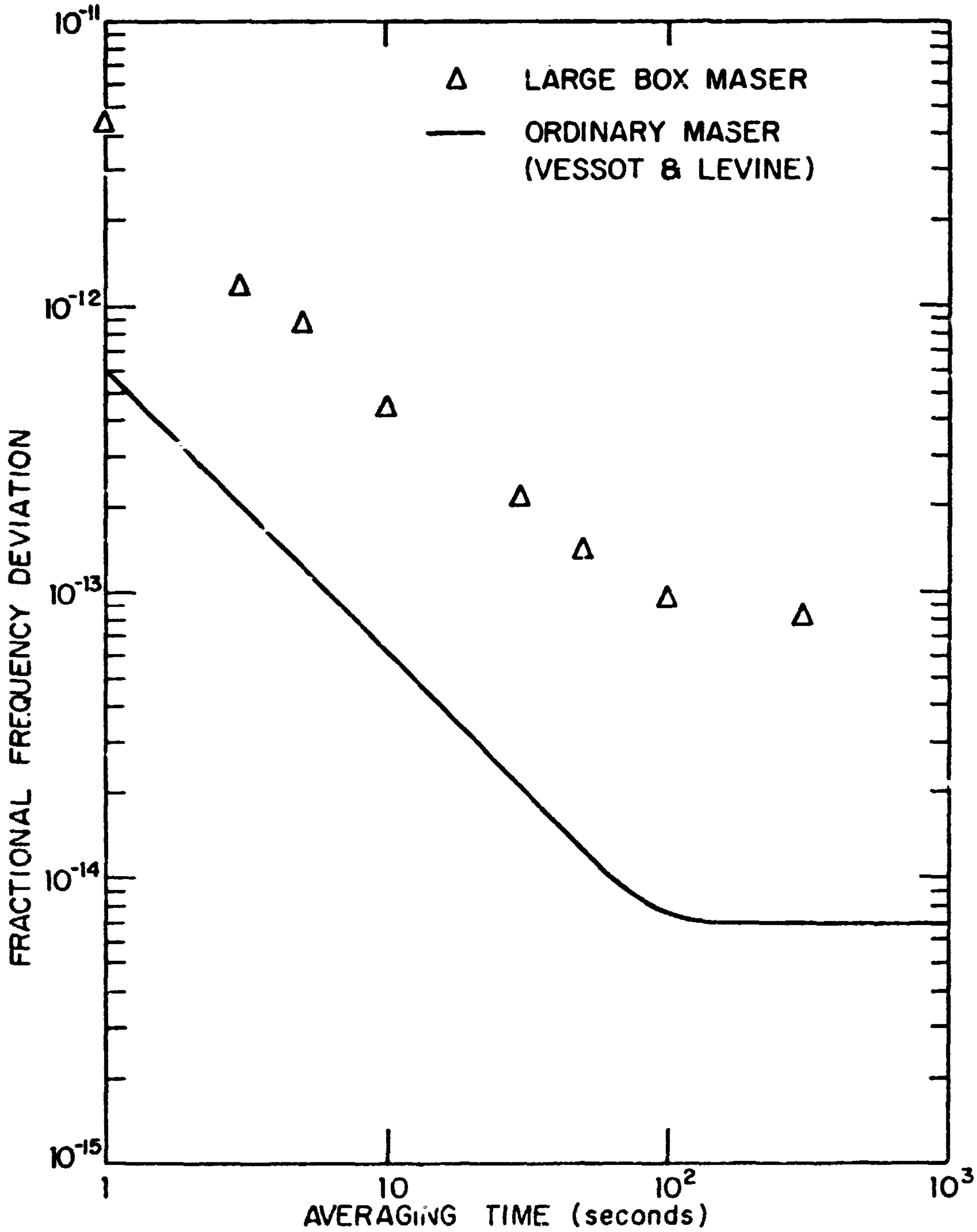

Figure 5. Fractional Frequency Deviations of Large Storage Box Maser (cone out, low flux, ν_z = 15 kHz)

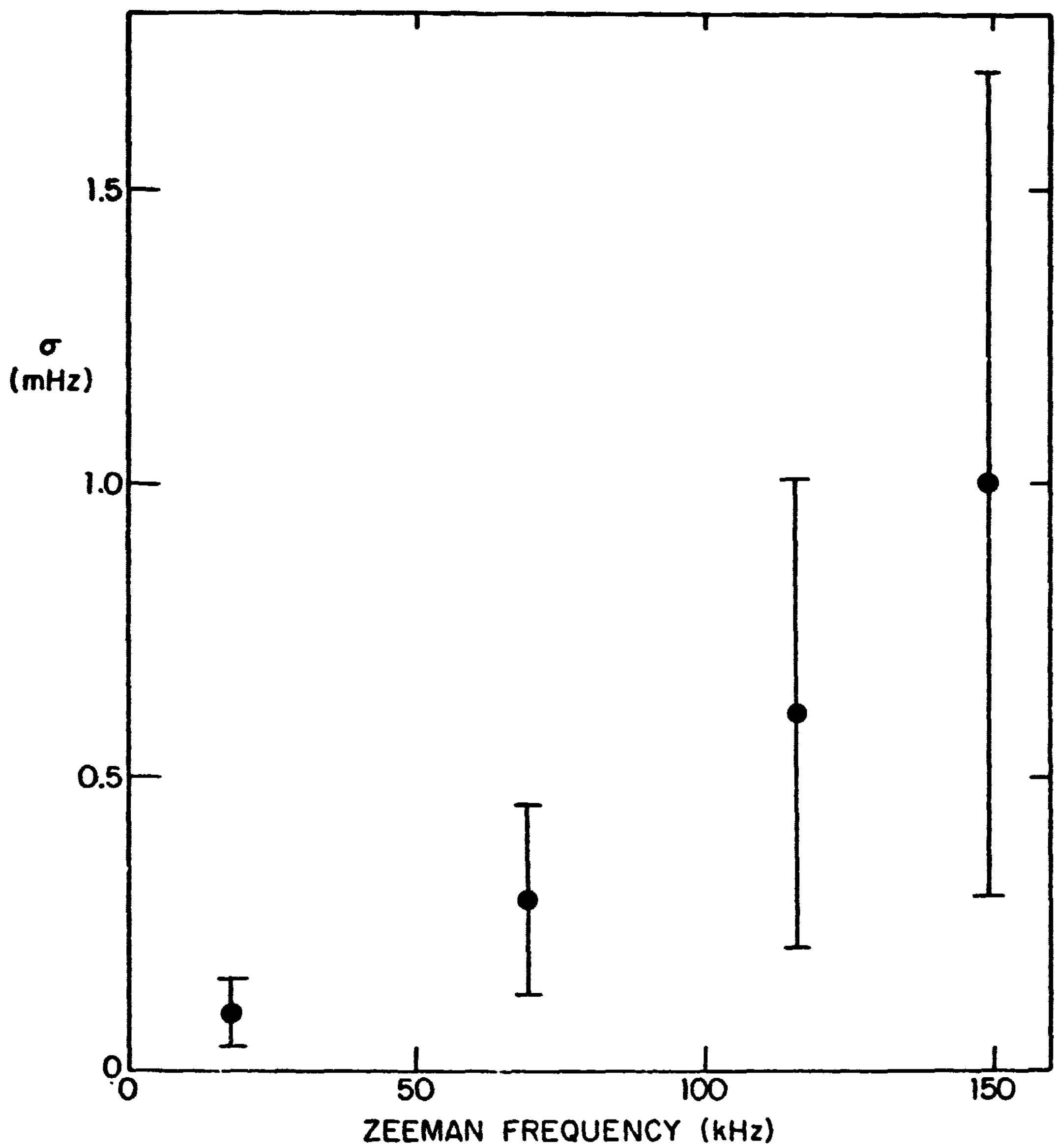

Figure 6. Frequency Fluctuations (~100 sec av) vs. Zeeman Frequency

e. 1BH - 1MH

f. 2BH - 1MH

where 1 stands for a tuned maser, 2 stands for a detuned maser, H stands for high flux, L stands for low flux, B for the large box maser, and M for the standard. Between each run there was a dead time waiting for the source pump to recover. After the runs, the standard's tuning factor was again measured. Also the Zeeman frequency of all the masers was measured before and after the data runs. To analyze the data, the tuning factors of the masers were computed and a series of corrected frequency differences for the two masers were calculated. In order to correct for drifts, for each corrected frequency, the average of the high flux measurements before and after a low flux measurement was used. The mean and variance for the corrected frequencies was then computed. Figure 7 shows a sample data run. FOB - FOM stands for the corrected frequency difference. Notice how the corrected frequencies don't drift even though the individual measurements do. With all the errors folded in, the average error for a six run data set is about 0.5 MHz. This means that for about 30 such sets, or two weeks of data taking, one can correct the maser frequency for the wall shift with an error of about two parts in 10^{13}.

The β measurement system worked as planned. But due to a fairly large leak between the storage box and the vacuum can, probably caused by the cracked bulb, the accuracy of the β measurement was limited to 1.3%. This adds another error of 0.14 MHz to the wall shift correction. The errors in the wall shift measurement, as well as some parameters for the large box maser, are tabulated in Table 1.

CONCLUSION

From Table 1, one can see that the projected error for the wall shift correction is 2.4×10^{-13} of the maser frequency. With the replacement of the cracked storage bulb, the plugging of leaks between the storage box and the vacuum can, and the obtaining of enough pumping speed for the source region, one should be able to reduce the errors even further—easily to less than one part in 10^{13}.

However, Crampton[12] has recently pointed out that two additional shifts can occur in the hydrogen maser, and that these shifts might be as large as one part in 10^{12} of the hyperfine frequency. These shifts are currently being studied.[11,12] Until they are understood well enough to be corrected for, they would limit the accuracy of any absolute measurement of the hyperfine frequency of hydrogen.

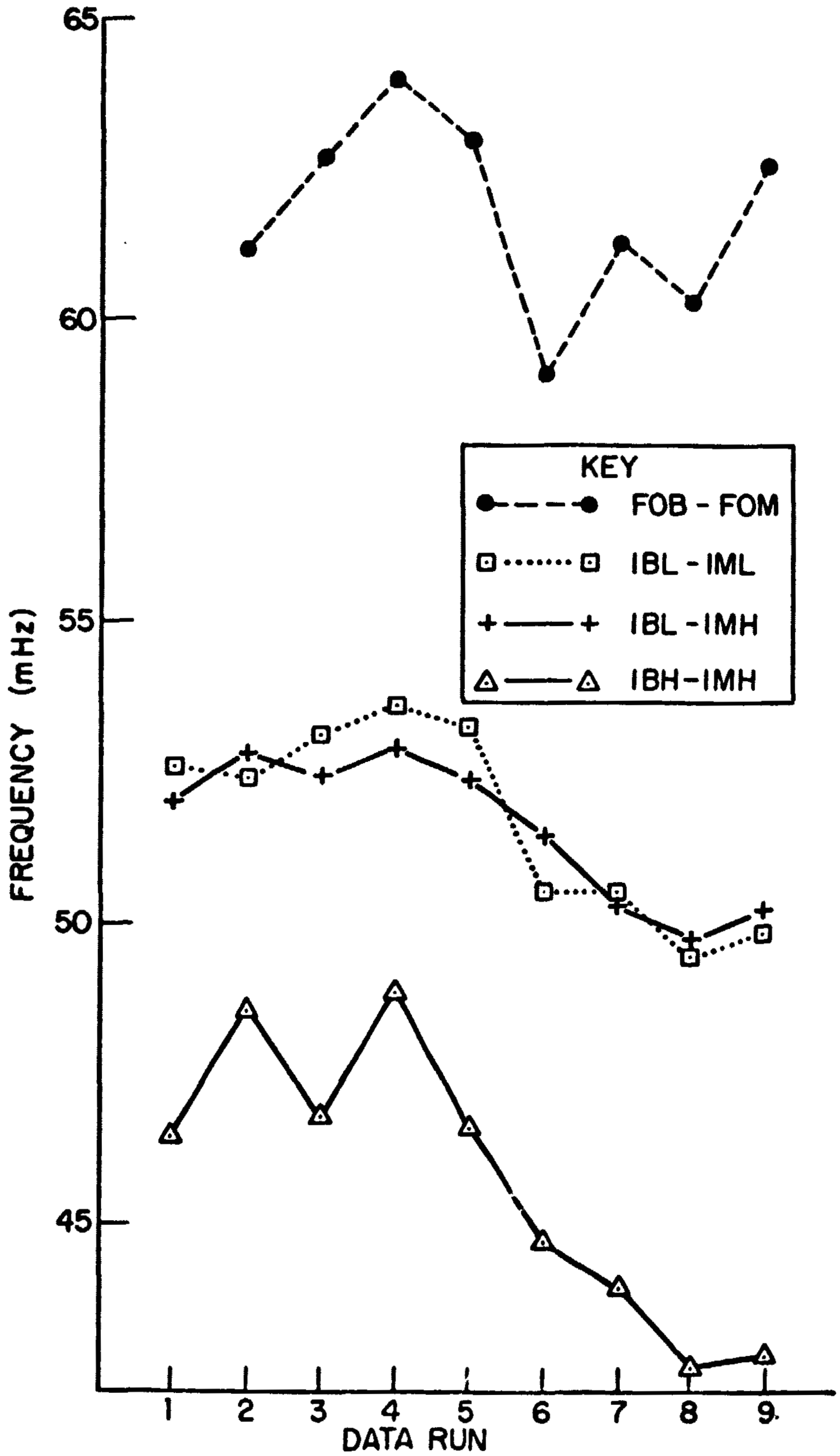

Figure 7. Example of Data

Table 1

Maser Parameters

$\beta = 1.528 \pm 1.3\%$

Power out at low flux $\simeq 5 \times 10^{-17}$ watts

$I_{th} \simeq 1 \times 10^{13}\ sec^{-1}$

	Cone In	Cone Out
T_2	2.4 sec	1.6 sec
Wall shift	-5.3 MHz	-3.5 MHz
Tuning factor	1.33	1.5

Wall Shift Measurement Errors

Source of Error	Error
Statistical Fluctuations*	0.310 MHz
$\langle H_z^2 \rangle - \langle H_z \rangle^2$	0.004 MHz
β measurement	0.143 MHz
Anomalous spin exchange shift	<0.04 MHz
Doppler shift	0.02 MHz
Total error	0.34 MHz
Fractional error	2.4×10^{-13}

*Projected error based on 30 data runs.

ACKNOWLEDGEMENTS

The experiment outlined in this paper is being submitted as a doctoral thesis at Harvard University. I would like to thank Professor Norman Ramsey for both the financial and intellectual support I received as well as for the original idea for the experiment. Thanks are also in order for Ed Uzgiris who built the large storage box maser in its original form. Finally I'd like to thank Robert Vessot and Martin Levine from the Smithsonian Astrophysical Observatory for help in the design of the maser standard used in this experiment.

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13. An experiment to measure one of these shifts is also in progress at Harvard University, being performed by D. Larson.

QUESTION AND ANSWER PERIOD

DR. VESSOT:

I am sure there are questions. Where shall we begin? If not, I have plenty of them.

The first thing is a comment.

There are indeed three ways to get rid of the wall shift. One is to make the bulb infinitely large; the other one is to vary it in a completely known way, as you are trying to do; and the other is to run the maser with the bulk whose wall shift is zero, and you can get this by baking the teflon — putting the teflon at the right temperature.

And, of course, how you know that it is zero means that you have to flex it and vary the collision rates until you seek that temperature at which there is no wall shift.

The thing to be emphasized with this maser is that it has a, something on the order of six times longer storage time than we achieved in, what we would call, the normal masers, which are the ones that are of what I would call passable dimensions about the size of a refrigerator. This is really remarkable. You could live inside it, it is true.

However, there must be some questions of this work. This is quite remarkable in that at last we are getting to the hyperfine separation of hydrogen.

DR. REDER:

Isn't there a fourth way of getting rid of wall shift problems, and that is to buy a cesium standard?

(Laughter.)

DR. VESSOT:

The question is how do you get rid of the wall shift in the hydrogen maser. Of course, your question is correct, you could also buy a Mickey Mouse watch.

The other question, though, is, indeed, there are other ways of doing this, as Mr. Peters no doubt will tell us, and that is to use a beam type approach with hydrogei which he has successfully done.

These are, I think, not techniques that eliminate the wall shift in a maser. However, it is a different approach entirely.

DR. KLEPCZYNSKI:

I did have one question.

Why teflon?

MR. REINHARDT:

Okay. Teflon is not unique, but the best of the materials that have been found. When the hydrogen atom makes a collision with the wall surface, you don't want any free spins around, or any hydrogen around, and the teflon structure has no free spins. It is a carbon spine with tightly bound chlorine on the outside, and you get no spin exchange collision, so there is no great phase shift due to a spin exchange effect.

The effects, the relaxation and frequency shift effects have been pretty much explained in terms of just a slight perturbation of the potential and on spin dependent perturbation, due to the distorting of electron cloud physically; when the atom collides into the wall, there is quite a small effect. If you put in any material that will spin exchange with hydrogen, you just can't get any bounces.

To give you an idea of how small the interaction with the surface is, it takes 10 to the 4th bounces or more with a teflon surface to relax the atom.

If you put in quartz, you have 100 bounces. If you put in a metal, maybe three or four.

DR. HELWIG:

I just have to comment, the wall shift is such that if you look at the hydrogen maser as a clock, the wall shift is not really of primary concern. The wall shift is a concern to the scientist who wants to know the hyperfine separation, and to NBS, and we are concerned about, again, the same question. But if you just look at clocks stable over a very long time period, there are other things to be more concerned about than the wall shift.

MR. REINHARDT:

I think, though, it is a problem because it is not reproducible. If it were reproducible, it would be much less of a problem.

DR. HELWIG:

Again, for a clock which is calibrated or set, it is not the primary problem, because we believe, thanks largely to Harry Peters' work, that over long time periods, there is very little evidence for changes in the wall shift once you have the maser device operating.

DR. VESSOT:

In summary, maybe we could say that it is the difference between accuracy and stability. Accuracy is knowing what you are going to get. Stability is keeping on and continuing to get it. They are both different classes of performance.

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CHARACTERISTICS OF ADVANCED HYDROGEN MASER FREQUENCY STANDARDS

H. E. Peters
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ABSTRACT

In house research and development at Goddard Space Flight Center to provide advanced frequency and time standards for the most demanding applications is concentrated primarily in field operable atomic hydrogen masers. Past work resulted in four prototype maser standards which have been operational since early 1969, and have provided network experimenters with frequency source stability at the highest levels. More recently, research with basic hydrogen maser systems has resulted in further significant improvements and two new experimental hydrogen maser standards have been constructed to operationally test and evaluate the new systems.

Some of the most important goals for the new maser designs have been improved long and short term stability, elimination of the need for auto tuning, increased maser oscillation level, improved hydrogen economy, increased operational life, minimization of operator control or monitoring, improvement in magnetic isolation or sensitivity, and reduction in size and weight.

New design concepts which have been incorporated in these masers to achieve these goals will be described in this paper. The basic maser assemblies and control systems have recently been completed; the masers are oscillating; and operational testing has begun. Data illustrating the improvements in maser performance is now available and will be presented.

INTRODUCTION

Amongst the growing family of frequency standard devices based upon the atomic hydrogen hyperfine transition, the field operational hydrogen maser is the most stable as well as the most fundamental device presently used for time and frequency control for general applications. (Other atomic hydrogen devices: hydrogen beam,[8,12] passive "Big Box" maser,[5] variable volume maser[5,28].) In conjunction with the other laboratory atomic standard devices, the hydrogen maser is also an exceptionally precise and versatile tool for laboratories responsible for maintenance of basic standards or for their utilization.[13,11]

There are seven continuously operating Goddard Space Flight Center (GSFC) hydrogen masers at present, and six of these are being used at GSFC at this time. Four of the seven masers are the NASA prototype masers (NP-1, NP-2, NP-3, NP-4). They were built at Goddard in 1968 and 1969, and have been used extensively since then in a variety of applications.[3,11] NP-3, the only one of these units not at GSFC, is at the Onsala, Sweden, space observatory, where it has been used in various Very Long Baseline Interferometry (VLBI) experiments since March, 1973.[18] Of the other three masers at Goddard, one is an older experimental maser, NX-1, which first oscillated in 1967, and the other two masers are two new experimental units, NX-2 and NX-3. The two new masers have been oscillating for about two months, and while some of the external electronics have yet to be completed, there is presently available operational data which illustrates several significant improvements which have been made in the new design. New measurements have also been in progress for several months with the NP masers, and thus we now have much new experimental data which illustrates some of the remarkable characteristics of both the old and the new hydrogen masers.

However, before discussing data on performance, a brief review of hydrogen maser principles would be appropriate.[19,2] This will provide the basis for a short discussion of the important fundamental perturbations to the maser oscillation frequency, which much of the later data will relate to.

FUNDAMENTAL CORRECTIONS

The atomic hydrogen maser is basically a very simple device. As illustrated in Figure 1, molecular hydrogen enters the source on the left, where it is dissociated into atoms of hydrogen by an RF discharge. Neutral atoms of hydrogen emerge from this source in a beam which then passes through a magnetic state selector. In the state selector, undesired lower energy state atoms are defocussed — they are separated from the beam and pumped away. The higher energy state atoms, still in the beam, pass into a large quartz storage bulb. The bulb is located within a microwave cavity, and due to maser action, the atoms give up energy and produce a coherent output signal at the frequency of 1,420,405,751.77XX Hz.[10] To complete an actual hydrogen maser frequency standard, there are also, of course, a vacuum enclosure, magnetic and thermal shields, magnetic field coils, a thermal control system, amplifiers, synthesizers, and so forth.

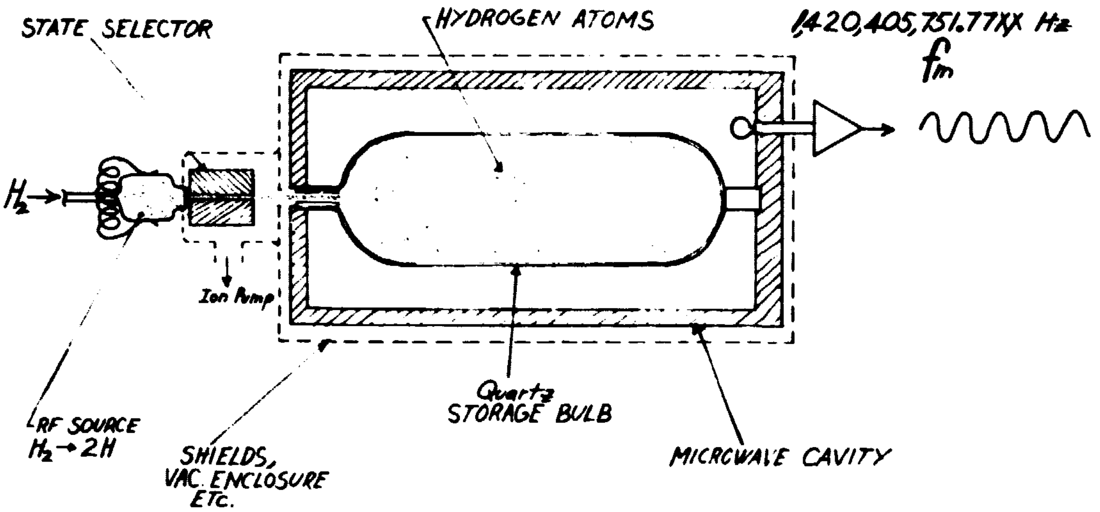


Figure 1. Atomic Hydrogen Maser Schematic

But not to neglect a small, though very important detail, it must also be mentioned that the wall, that is, the inside surface of the quartz storage bulb, is coated with FEP teflon; this teflon is carefully sintered to the inside surface of the bulb at high temperature and under high vacuum. The hydrogen atoms bounce off the teflon wall with very little exchange of energy, and as we shall see later, there is therefore very little change in the output frequency due to the wall.[14,15,16,17,20] Fortunately hydrogen atoms do not attack, or chemically react, with teflon. Teflon is extremely unreactive and non-sticky for most all common chemicals, so that under the high vacuum conditions of operating hydrogen maser frequency standards, the inherent physical properties of the wall surface are preserved rather indefinitely.

As you examine the things that happen to an atom as it passes into the maser storage bulb, and finally, after a second or so re-emerges and is pumped away, a good picture of the fundamental forces that disturb (or perturb, as we say) the oscillation frequency is easily visualized. Figure 2 shows the most significant perturbations.

The atom has a velocity, so there is a Doppler shift. It is, however, only the special relativity time dilation effect. The atomic clock of the traveling hydrogen atom runs slower than such a clock would if stationary in our observers laboratory. There is no first order Doppler shift in hydrogen masers, since the average

$$f_m = f_o + \underline{\Delta f_D} + \underline{\Delta f_{C-SE}} + \underline{\Delta f_H} + \underline{\Delta f_W}$$

$f_m \equiv$ Maser Oscillation Frequency $\quad f_o \equiv$ Unperturbed Transition Frequency

PERTURBATIONS	EQUATION	OPERATING OFFSET	ERROR
Special Relativity Time Dilation	$\underline{\Delta f_D} = -\frac{v^2}{2c^2} f_o$	4.5×10^{-11}	$\epsilon < 10^{-14}$
Cavity & Spin Exchange Pulling	$\underline{\Delta f_{C-SE}} = (K \Delta f_c - \alpha_{SE}) \Delta \nu_\ell$	0	$\epsilon < 10^{-14}$
Magnetic Field	$\underline{\Delta f_H} = K_H H^2$	1×10^{-12}	$\epsilon < 10^{-14}$
Wall Reflection Phase Shift	$\underline{\Delta f_W} = \frac{C_W A}{V}(1 - \alpha_f \Delta T)$	2×10^{-11}	$? < \epsilon < 2 \times 10^{-12}$

Figure 2. Most Significant Correction Factors to the Hydrogen Maser Frequency

velocity of the atom is very effectively zero with respect to any running waves in the maser cavity. The Doppler correction is given by Δf_D (the first equation in Figure 2). This correction is by far the largest correction to the hydrogen maser frequency. It is actually 4.5×10^{-11}. But, it is also the easiest perturbation to correct for, since the velocity depends precisely on the temperature, and a measurement accurate to only .07°C is adequate to bring the Doppler error below one part in 10^{14}. In typical hydrogen masers, we are dealing with temperature stabilities measured in microdegrees per day, so the Doppler effect has no effect on stability, or reproducibility either, and will not be discussed further in this paper.

The second perturbation, Δf_{C-SE}, is the result of both cavity pulling and spin-exchange pulling.[21] Both cavity pulling and spin-exchange are proportional to the atomic line width. This is given by $\Delta \nu_\ell$ in the second equation. The line width can be changed very quickly and easily in hydrogen masers by changing the density of atoms in the storage bulb. Many publications describe automatic (as well as manual) systems for correcting for cavity and spin-exchange pulling.[22,23,24,3] Later, some data will be presented showing the effect of one such "Auto Tuner" on maser stability.

The actual operating offset due to cavity and spin exchange pulling is zero when tuned, and the absolute error is less than one part in 10^{14}. However, in certain operational situations there can be small uncorrected random variations in cavity frequency which effect maser stability, as shall be seen later.

The third perturbing factor shown in Figure 2 is Δf_H — this is the variation of maser frequency with applied internal magnetic field. Δf_H is a quadratic effect, so magnetic instabilities become very small as the field is reduced towards zero. (See Appendix I_g for more details on field inaccuracy effects.) Hydrogen masers operate at extremely small values of magnetic field. The two new experimental masers oscillate well at fields below 10 microgauss, and the older NP units can go lower than 30 microgauss. At typical operating fields of 700 microgauss, the entire magnetic correction is only 1×10^{-12}, and the field can be measured or set with extremely great accuracy by using Zeeman frequency measurements.[2,25] One part in 10^{14} is simple to do. Later, some curves are given which illustrate the precision of the magnetic correction, as well as the stability of the field over long periods of time. One of the most important points for users of hydrogen masers is that these field measurements can be made simply and quickly without disturbing the output phase or frequency significantly.

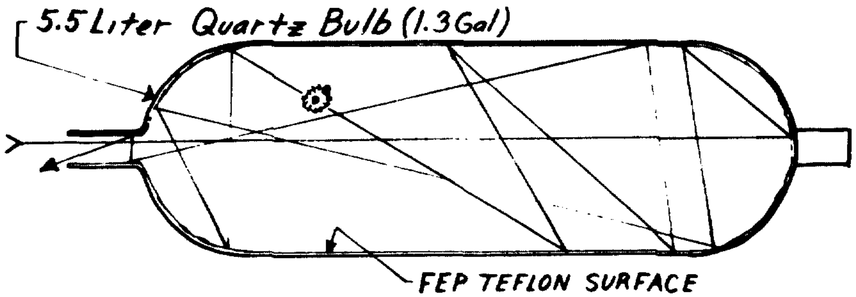
The last factor shown is the wall shift, given by Δf_w. The wall shift varies precisely with the surface to volume ratio (A/V) of the storage bulb (see Appendix I_a). It also varies slightly with temperature — this is given by $\alpha_T \Delta T$; but the temperature factor is less than 1% of the total, and creates no problem, so only the surface to volume factor need be discussed. The total wall shift is typically 2 parts in 10^{11} in oscillating hydrogen masers[10] (NASA NX and NP masers). However, one special design "Big Box" experimental maser device, which was conceived by scientists at Harvard University,[4,5] has a wall shift a factor of 10 smaller, approximately 2 parts in 10^{12}. It is very fortunate that the wall shift is not a large effect, since then it does not really take a very precise experiment to determine the offset accurately. In the past, the main method of determination has been to operate the maser with bulbs of different volumes, and by doing this many research laboratories[13,14,15,16,17,20] have published accuracies of better than 2 parts in 10^{12}.

HOW FREE IS THE HYDROGEN ATOM?

Since the wall shift is so important for metrology, as well as for understanding the methods for making good hydrogen maser time and frequency standards with long term stability and uniformity, it is important to examine in more detail the conditions under which an atom exists within the maser storage bulb. An important question, it is clear, is "how FREE is the atom?" And also, how scientifically understandable are the methods for determining wall shifts? That is the theme of Figure 3. Here we have a 5.5 liter bulb. The atom enters the bulb with a velocity of 2.6 kilometers per second, bounces around approximately 20,000 times, and after a second or so departs. The average distance traveled between wall bounces is 12 cm. The atom also collides about 50 times with hydrogen molecules, which has negligible effect on the frequency,[26] and about 4 times with other hydrogen atoms. The latter results in the spin-exchange correction, with a very small frequency shift effect which is accurately corrected for by auto-tuning, as discussed previously. Only when the atom is within about 1 Å (10^{-8} cm) of the wall is there any appreciable energy exchange or perturbation, so the total disturbed path length is 2 Å per collision. The ratio of perturbed path length to free flight path length is therefore one part in 10^9.

Consider the diagram in the center of Figure 3. The total free path distance, in free fall, within an ultrahigh vacuum environment, is 2 kilometers; that is over one mile, while the total disturbed path distance is 2×10^{-4} cm. So one of the most appropriate visualizations of the hydrogen maser, is that it is equivalent to a free atom beam tube over a mile long between disturbing interactions with the fields at the ends. You can, if you will, compare the end fields (the walls, that is) to the RF fields, the phase shifts, and other mode fields or misalignment problems, etc., encountered in some atomic beam resonance standards, where the disturbed path length is the half wavelength of a 10 GHz transition,[13,6,7] 1.5 cm, compared to 2×10^{-4} cm for hydrogen.

That is really a very good analogy — and this picture also illustrates why the other perturbations, magnetic fields, temperature, etc., are so small with hydrogen masers; this one mile hydrogen beam tube is folded over and entirely contained within the volume of a single mode cavity, so that the magnetic and RF fields are effectively identical over the entire one mile distance. A single magnetic field measurement on a maser establishes the field value over the entire path. People working with cesium beam basic standards, where many Zeeman coils are often placed at several intervals along the beam to measure the field, and the cesium atom only has one shot through the field, so to speak, may particularly appreciate this analogy.



AVERAGE DISTANCE

Between Wall Collisions = 12 cm

Interaction of Atom with Wall = 1Å

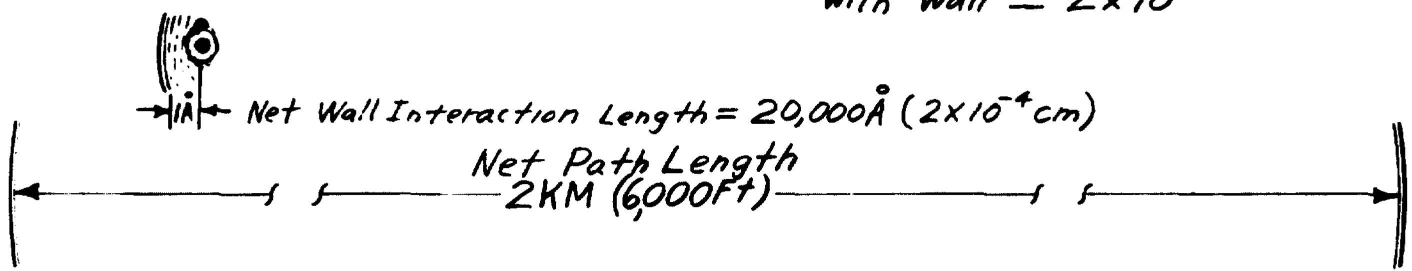
AVERAGE No. OF COLLISIONS

With Background Gas $\ll 1$

With Other Hydrogen Atoms = 4

With Hydrogen Molecules = 50

With Wall $\doteq 2 \times 10^4$



MEAN PHASE SHIFT PER WALL COLLISION $\doteq 10^{-5}$ Radians = 2 Seconds of Arc

NET EFFECT ON MASER FREQUENCY $= 2 \times 10^{-11}$ Offset

NET EFFECT ON MASER STABILITY – Short Term NEGLIGIBLE
– Long Term ~ pp in 10^{13}

FUTURE ACCURACY EFFECT: NO REASON NOT $\leq 10^{-14}$

Figure 3. How FREE Is the Atom in the Maser Storage Bulb?

Note that the phase shift per wall bounce is only 2 seconds of arc! And this is at the frequency of the 21 cm line of hydrogen — 1420 MHz. It takes an atom 46 microseconds on the average, to go the 12 cm from wall to wall, and this corresponds to 65,000 cycles of the oscillation, in unperturbed space, while one cycle is perturbed to the extent of 1.5 seconds of arc (approximately 1.2×10^{-6} cycle). That is what accounts for the 2 parts in 10^{11} offset in maser frequency, due to the wall.

VARIABLE VOLUME MASER

But why can we predict inaccuracy effects no larger than 1×10^{-14} for this tremendous, elongated, beam device? The main reason is that we can change the path length, the effective distance between wall interaction regions, without changing the wall area, or its basic properties. Thus we can change the number of wall bounces per second, without changing the wall. That is the idea of the flexible bulb maser.[4,27]

Figure 4 shows one new and attractive embodiment of the idea. This is a "Variable Volume" maser. The storage bulb is of teflon sheet, which is formed into a convoluted, flexible, bellows. The volume is changed merely by compressing or extending the bellows. The frequency shift is approximately 3 parts in 10^{11} when extended, and twice that amount when compressed to half volume. The curve at the lower right illustrates the ease and accuracy with which one can extrapolate to infinite bulb volume. These flexible bulb masers completely overcome the problem of "understanding" the details of the interaction of the atom with the wall. Just by changing the number of wall encounters per unit path length, the problem is reduced to precise geometry. We do not have to solve the wall interaction, it is circumvented, in a clear cut, scientifically valid manner. Appendix I gives a more detailed discussion of potential error sources with a variable volume hydrogen maser which is presently being developed at GSFC.

MAGNETIC FIELD AND CAVITY TUNING

Leaving the wall shift for the present, some data on the other perturbations will now be presented. Figure 5 shows the variation of the frequency of the NP-1 hydrogen maser as the internal magnetic field was changed. The frequency of NP-1 was measured with respect to NP-3. For the period of the measurements, NP-3 was sufficiently stable to introduce negligible error as a referency standard. (See Section VI on stability.) The magnetic field was measured by making Zeeman frequency measurements. The horizontal axis gives the Zeeman frequency; the fractional change in maser frequency is shown vertically in parts

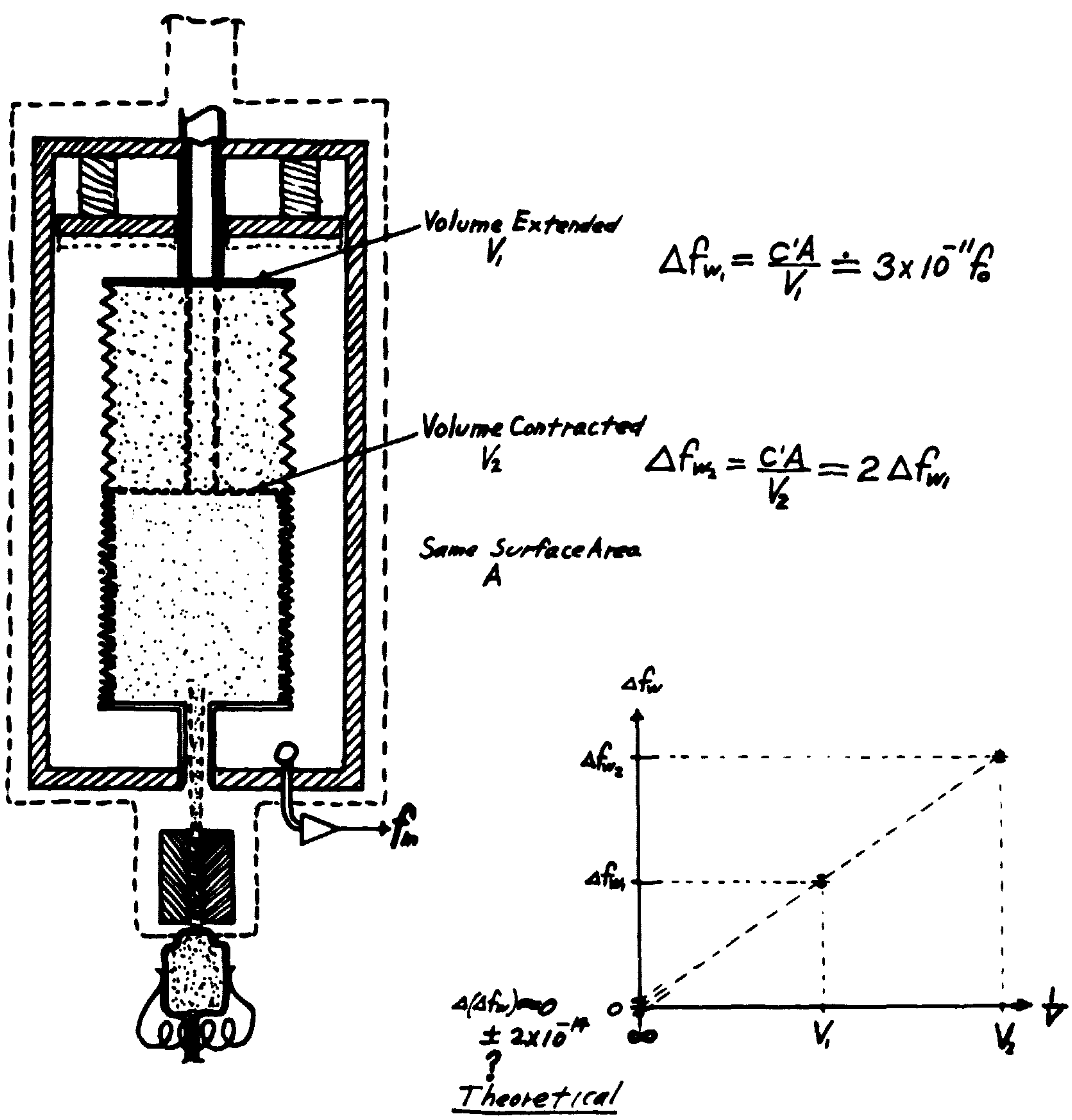


Figure 4. Variable Storage Bulb Volume Hydrogen Maser

in 10^{13}. The solid line in the top figure is the theoretical curve, and the X's are experimental points. Except at fields below 200 or 300 microgauss, there is no significant difference between data and theory. This can be seen better in the bottom curve, which shows the difference between calculated and measured points.

The departure from the calculated curve at very low fields has very significant meaning regarding field inhomogeneities and departures from ideal tuning curves

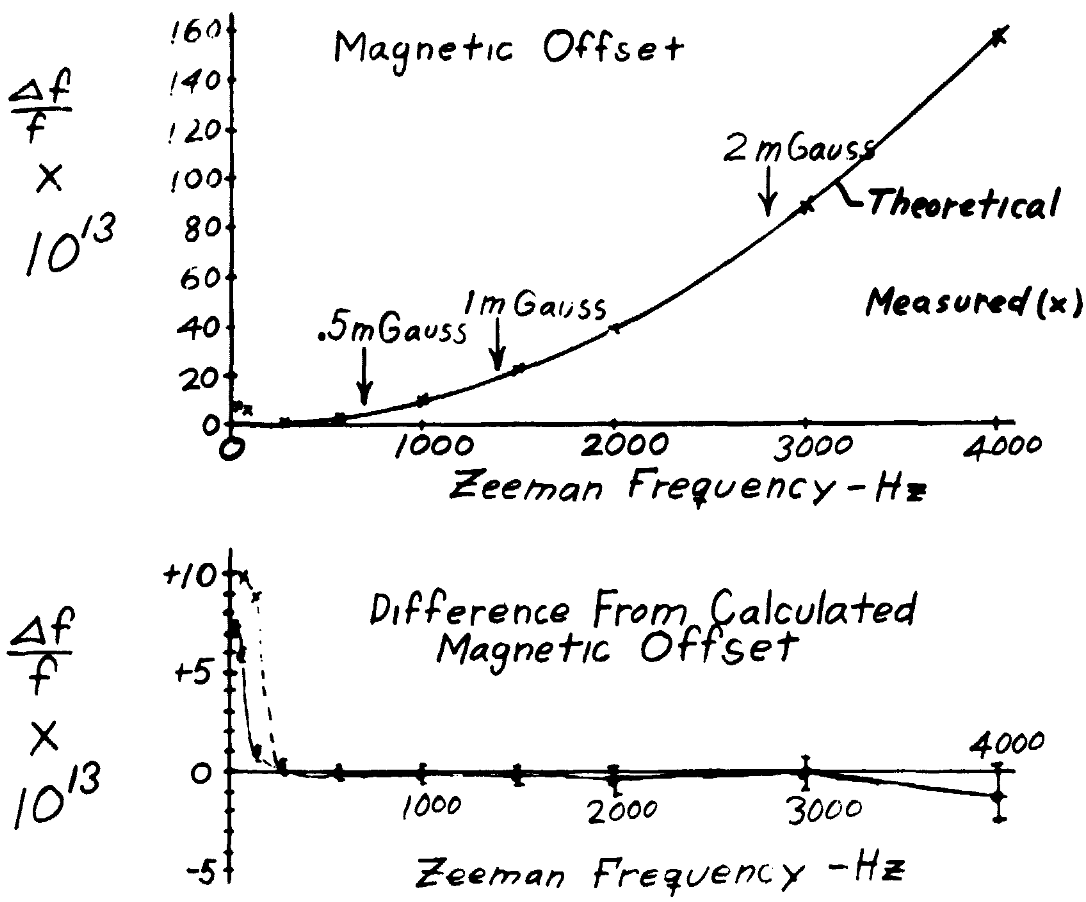


Figure 5. NP-1 Hydrogen Maser Magnetic Correction

which have been published in the literature, as discussed later. Figure 5 also illustrates that in the usual operating range of the NP and NX hydrogen maser frequency standards, between 500 microgauss and several milligauss, the magnetic correction procedure is fully valid.

Another very interesting experiment which was performed in conjunction with the magnetic field experiment just discussed had to do with the accuracy of the cavity tuning correction. Using the NP-1 and NP-3 masers, which have automatic tuning systems[3], the corrected frequencies of the masers, as well as the cavity tuning corrections, were observed while operating at fields from less than 1 milligauss up to fields of 10 milligauss. There was no change in the tuned cavity frequency as the field was changed from one value to another, nor were there any differences in the absolute frequencies when proper correction was made for the field. The precision of this experiment was three parts in 10^{14}.

This, as well as other data, shows there are no significant tuning anomalies with the NP design of maser. Tuning discrepancies have been published for very different designs of laboratory experimental masers when magnetic field inhomogeneities were known to be present,[25,28] so the present experiment was an important one to confirm the NP tuning accuracy (see Appendix I_g for further discussion of this point).

The next question regarding magnetic fields may be, how stable is the field with time? Figure 6 shows the magnetic field corrections which were measured on one of the NP masers (NP-4) for long periods of time. The upper curve shows eight months of operation, using a nominal field setting of 700 microgauss. The field was checked at weekly intervals, and only if the error exceeded 10 microgauss

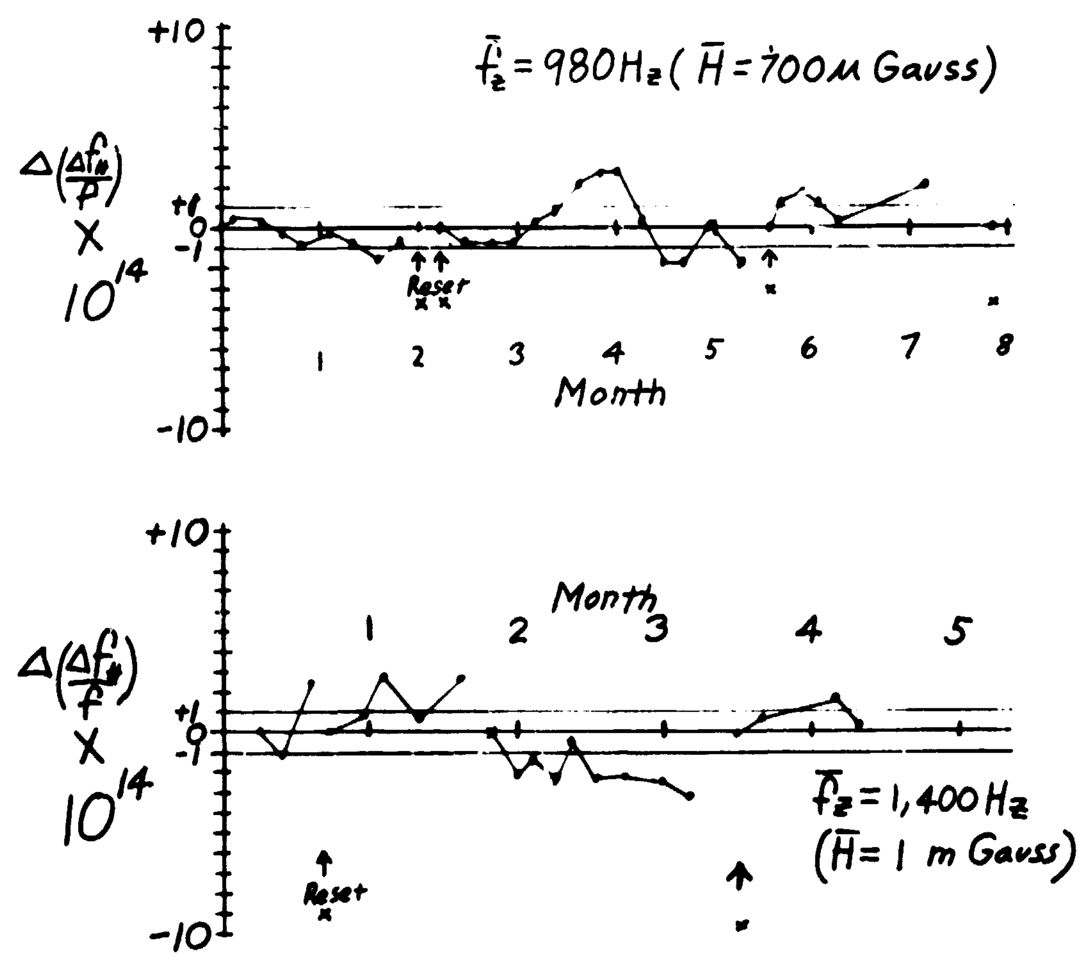


Figure 6. Magnetic Field Correction Variation NP-4 Hydrogen Maser

was it reset. Many of the resettings made were due to known external causes, such as nearby equipment movement, or to experimental work going on nearby. The maser was not in an exceptionally isolated environment for either period shown here.

On the average, the data shows that there will normally be no change in correction over one or two parts in 10^{14} from time to time, and it also shows that the field does not drift badly over extended periods. In the lower curve, the field setting was at 1.4 milligauss, twice that in the upper curve. The field perturbations are expected to increase in proportion to the field value, so the larger deviations shown in the lower curve are exactly what may be expected.

A most important point for keepers of standard frequency and time which is demonstrated by these curves, is that one can measure the magnetic correction in the hydrogen maser precisely and repeatedly without interruption of the maser output signal, with usually negligible effect on the phase, and with no remnant effect on the frequency of the maser.

These curves show only the long term effects — the shorter term variations of field are usually quite small; in a typical laboratory the minute to minute and day to day variations have been observed, and these are usually less than a few microgauss. So magnetic variations typically have small effects on maser stability, although as we are now pushing stabilities into the 10^{-15} or 10^{-16} range, field variations or corrections may become much more important in the future.

STABILITY DATA

Figure 7 gives three frequency comparisons between hydrogen masers under different operating conditions. First consider the bottom plot. This shows the fractional frequency variation between the NP-3 maser and one of the new masers, NX-2. The 1,000 second to 10,000 second stability is between 3 to 5 parts in 10^{15} (Allan variance[29]). There is no significant drift. Note that these masers were not being tuned — it is the free running stability in the lower curve. The average untuned linear drift rate, due to cavity drift, among the NASA prototype (NP) masers is 5×10^{-15} per day. Thus when using these masers in field applications for periods of a few weeks or less, one would not usually want to use auto tuning except, perhaps, in the initial setup.

If you have a second hydrogen maser, and use it for a tuning reference, you can tune to and maintain less than one part in 10^{14} tuning correction on a daily basis. In the center plot in Figure 7, the frequency of NP-3 is compared with NP-1, and both maser cavities are being independently tuned with respect to a third maser

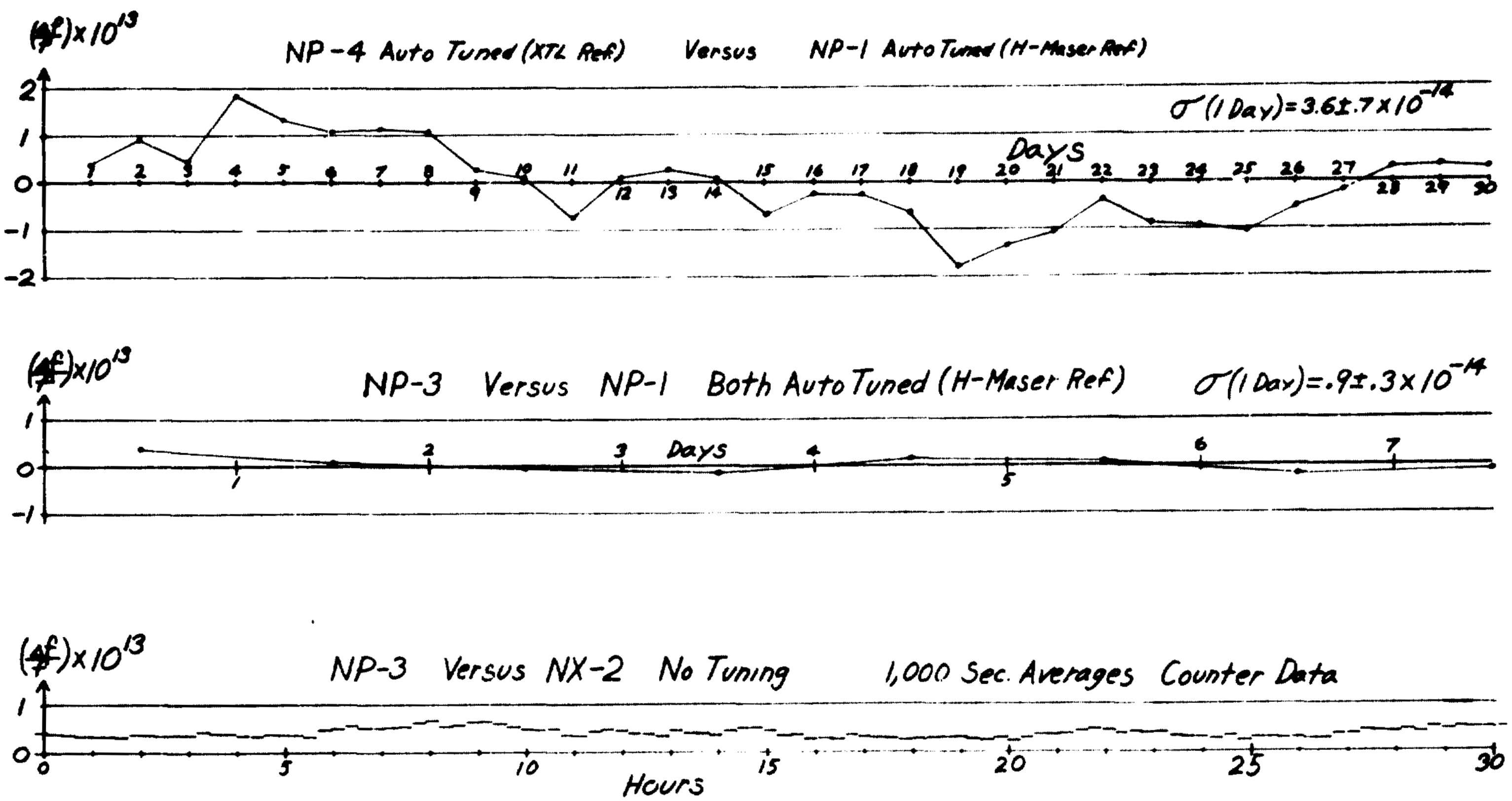


Figure 7. Hydrogen Maser Frequency Comparisons

(NX-2). The fractional frequency deviation (Allan variance) is 9×10^{-15} for a days averaging time in this plot. The absolute tuning correction quickly becomes negligible for longer measuring times when tuning with respect to a second hydrogen maser. But even so, when looking for a few parts in 10^{15} stability for times shorter than a day, auto tuning would not normally be used (or would be discontinued during the period of a particular measurement).

In field operation situations, where one NP type hydrogen maser is available, and an absolute frequency referency is still desired, the maser may use a good crystal oscillator as the tuning reference. However, the day to day frequency variations will then be greater, and this is shown in the top plot in Figure 7. Here the frequency variation between NP-4, with its cavity tuned continuously with respect to a crystal oscillator, was measured with respect to NP-1, which used another hydrogen maser as a tuning reference. Due to the randomness of the crystal tuning data, the stability for a days averaging time is now 3.6×10^{-14}. But the error tends towards zero as the square root of time, so even with a crystal tuning reference very long term (months) inaccuracy due to cavity and spin-exchange pulling should become less than one or two parts in 10^{14}.

The linear cavity drift rate has not yet been resolved accurately on the NX-2 and NX-3 masers. From measurements for periods of a few weeks it appears to be less than two parts in 10^{15} per day. But much more time will be required to measure this effect on the new masers precisely.

In many ways, the most informative and satisfactory description of performance of a frequency standard lies in the real time frequency or phase comparison data under conditions similar to those in which the standard is to be used. For very long baseline interferometry, the usual signal frequencies may run from 10 MHz to 20 GHz or higher, and one limit to the useful integration time is set by the stability of the local frequency standards.[30]

If you are looking at VLBI fringes you are in effect beating the two local oscillators together at some high frequency, like 10 GHz, and do not want the beat frequency or phase rate to change by more than some small amount, typically 1 radian from the average, during the measurement interval. Also, any random noise on the local oscillator directly contributes to the uncorrelated noise flux. — So if the output frequencies of two standards are multiplied to 10 GHz, and the phase and frequency variation observed directly, a vivid picture is obtained of how the standards affect the data. Figure 8 shows beats between two hydrogen masers (NP-3 compared to NX-2) in which the usual 5 MHz output frequencies have been multiplied to X-Band, 9.18 GHz actually, and these X-Band signals are combined in a balanced mixer whence a beat (difference frequency) is obtained. Figure 8 is a photograph of the strip chart data. The same nominal beat frequency occurs

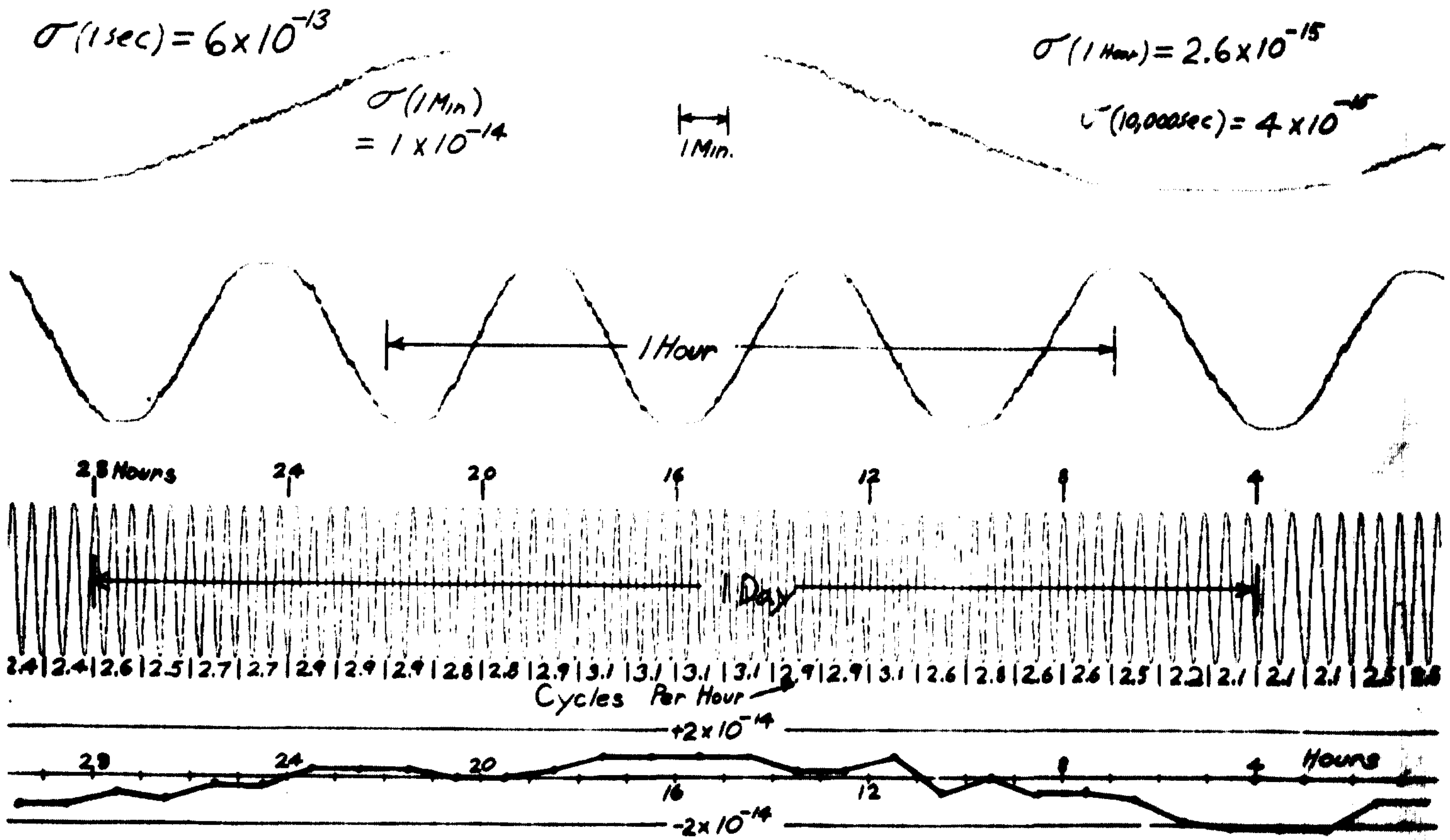


Figure 8. 9.18 GHz Phase Comparison between NP-3 and NX-2 Hydrogen Masers

in all of the three plots, but near the bottom the chart speed is 1 inch per hour, in the center it is 15 inches per hour, and at the top 1 inch per minute.

For those who may be familiar with 1 microsecond phase plots taken between two 1 MHz signals, Figure 8 is similar, except there is 10,000 times greater resolution. One cycle corresponds to 109 picoseconds (1.09×10^{-10} sec) accumulation of time between signals. The average frequency difference is 2.6 cycles per hour, which corresponds to a fixed frequency offset between signals of 8 parts in 10^{14} (8 nanoseconds per day). A change of 1 cycle per hour in beat frequency is equivalent to a change of 3×10^{-14} in signal frequency. As seen from the one day's data at the bottom, where the number of cycles per hour is shown, typical changes are of the order of 0.1 cycle per hour, or 3 parts in 10^{15}. A statistical analysis (Allan variance) gives 2.6×10^{-15} fractional stability for 1 hour measuring intervals, and 4×10^{-15} for 10,000 seconds (which is about 3 hours). At the bottom of Figure 8 the hourly frequency variation is plotted, with a scale of 2×10^{-14}. The peak to peak excursion in this 28 hour period was 3 parts in 10^{14}.

Analysis shows that in a VLBI application, if using these two masers, it would be feasible to integrate for at least 1 hour at X-Band (for 1 radian error) and for over 4 hours at S-Band (2 GHz).

NEW MASER CHARACTERISTICS

Only a brief description of the improved design characteristics of the NX-2 and NX-3 hydrogen masers will be given at this time, since the final receiver and auto tuner systems are just now being completed. The stability data is thus presently limited by the noise level of the breadboard receiver system used. Also, considerable time will be required, of course, to fully evaluate long term performance.

The new masers oscillate with ten times more power than the older NP masers, 5×10^{-12} watts of beam power versus 5×10^{-13} watts. The theoretical stability for one second measuring intervals is 2 parts in 10^{14} with a 10 Hz bandwidth.[31] Present measurements give 2.5×10^{-13} for one second averaging, and 2.5×10^{-15} for 100 seconds averaging. For 1,000 seconds to 10,000 seconds the stability is $3 \pm 2 \times 10^{-15}$. The long term drift of the new masers, without cavity tuning, has not been precisely determined, but preliminary measurements of a few weeks duration indicate it is of the order of 2×10^{-15} per day or less.

The new masers also operate with approximately half the hydrogen flow of the older NP masers. The NP units have pump element life expectancy, as determined experimentally by accelerated life tests, of 10 to 15 years (see Appendix II). They have been operating continuously now for between 4 to 5 years with no replacement required. Thus the new masers should have on the order of 20 years of pump element life expectancy due to hydrogen saturation. However, the new maser pump connections have high vacuum valves which seal off the maser vacuum system from the pumps, so that a pump may be quickly exchanged without breaking maser vacuum. There are two ion pumps on the new system, one of these evacuates the maser storage bulb and focussing magnet region, and pumps essentially only hydrogen; the other pump evacuates the outer vacuum system, and so removes any external gas which diffuses thru the main vacuum seals. This differential two compartment system assures that background gas pressure in the maser bulb, other than hydrogen, is kept extremely low, and that maser frequency will not be perturbed by relatively active molecules, such as oxygen.

The increased efficiency of the state selection and beam optics of the new masers was achieved by using a new, more efficient, design of quadrupole electromagnetically variable state selector which has a much greater acceptance angle from the source exit collimator than the fixed hexapolar magnets used previously.[3] Gaps between poles in the new state selectors provide relatively high pumping speed for unfocussed hydrogen, so that the state selector to storage bulb collimator (entrance) distance could be reduced by a factor of two, to 13 cm vs 26 cm in the NP's. Additionally, the new masers use larger bulb collimator diameters and larger collimator length (1 cm dia. $\times$ 10 cm long vs .6 cm dia. $\times$ 2.5 cm long in the NP masers).

Although the bulb exit relaxation time is decreased in the new masers to .75 seconds, versus 1.3 seconds in the NP units, there is not a corresponding decrease in line Q. This is due to the fact that the line Q of the NP masers was found by experience to be limited by relaxation processes within the bulb, so that the maximum oscillating line Q was 4 to 5×10^9. With the new geometry the line Q is 3.3×10^9, and is much more limited by the bulb exit time constant. Thus the long term stability, which depends predominantly on line Q rather than oscillator power,[31] is not degraded significantly, while short term stability, which varies as the square root of power, is improved by approximately a factor of 3.

The shorter bulb time constant also decreases the susceptibility of the maser oscillation level to disturbances due to magnetic inhomogeneities. In addition, the magnetic conditions have been improved by the placement of an additional magnetic shield over the entire maser and pump assembly. As indicated previously, the new masers oscillate well at fields less than 10 microgauss (by Zeeman frequency measurement), and as an improvement of a factor of 10 or more in incremental shielding factor is expected, magnetic perturbations should be proportionately less significant than the NP results previously described in Section V.

The cavity frequency control system and the temperature controls on the new masers are similar in principle to those on the NP units.[3] The cavity is of aluminum alloy 6061T-6, and the external frequency control is accomplished by varying the balance conditions on the temperature sensor bridge. Improved integrated circuit operational amplifiers were available when the new masers were designed, and additionally, temperature servo time constants, and other details of the system have been improved. The use of aluminum for the cavity, rather than a material with smaller temperature coefficient of expansion such as metallized fused silica, CER-VIT,[32] or ULE[33] titanium silicate, is an outgrowth of early experiments with aluminum cavities at GSFC which were originally intended to establish the realizable limits of temperature control stability[3], as well as to determine the relative predominance of factors other than temperature which affect cavity frequency. At this point it is interesting to note that the present stability of the NX and NP masers of 2.6 parts in 10^{15} for 1,000 seconds measuring times means that the cavity is electrically, mechanically, and thermally stable to 2.6 parts in 10^{10}. (The cavity pulling is proportional to the ratio of the cavity Q to the line Q, which is approximately 10^{-5} in the present designs.) Since the cavity diameter is 25 cm (10 inches), the above stability indicates that the cavity diameter is stable to .6 Å (1 Å = 10^{-8} cm). This is less than one atomic hydrogen diameter! Needless to say, many factors other than temperature enter into stability considerations at the 1 Å level, and such things as high thermal conductivity, thermal isolation, mechanical rigidity, electrical opaqueness, etc., are indeed very important. Since aluminum has an expansion coefficient of approximately 2.6×10^{-5} at operating temperatures of 40°C, the present maser stability indicates the cavities are thermally stable to 10^{-5}°C.

Long term temperature stability data has been accumulating for many years with the NP maser design. The corrections which the auto tuner makes to the maser cavity give a maximum estimate for thermal drift. The average value of 5×10^{-15} per day for the NP masers (NP-1: 1×10^{-14}, NP-2: $\pm 1 \times 10^{-15}$, NP-3: 2×10^{-15}, NP-4: -7×10^{-15}; per day) gives an average thermal drift of 30 microdegrees Celcius per day. Experience with the NP's has shown that this drift is due as much to the instabilities of the "fixed" metal film resistors used in the thermal sensing network as to the instabilities of the selected thermistor beads used. (Veeco TX1821 preconditioned glass thermistor bead-in-glass probe; these are nominally 50 K Ohm probes which are guaranteed stable to .1% per year.) In the new masers, the bridge resistor temperature coefficients were evaluated, and the completed bridges independently tested for temperature coefficient. With the above precautions, the NX-2 and NX-3 temperature servos are essentially the same simple DC bridge and operational amplifier system used on the earlier masers. A significant improvement in thermal control is obtained with the new masers, as indicated by the present stabilities; however, measurement of the true level must wait until the final receiver system is completed.

The new maser standards retain all of the desirable features of the NP masers. They are self contained (on a single chassis), operate for up to 6 hours on stand-by batteries, can be easily moved on their own dollies, and have several well buffered standard frequency output signals. They also contain a very stable crystal oscillator (Oscilloquartz[36] B 5400) as the cavity tuner reference, and they are smaller than the NP units, being only 132 cm (52 inches) high (versus 182 cm for the NP's).

Most of the design effort has been directed towards optimizing performance, since the main goals of the hydrogen maser research program have been to provide the most stable, reproducible, accurate, long lived, and reliable standard for those ground based applications where these factors are most critical. Perhaps the most critical of considerations, considering the long term cost of present time and frequency standard systems, is the fact that the components which are most likely to be unreliable in the hydrogen maser standard are external to the vacuum system, and these factors, such as receivers, synthesizers, power supplies, electronic components, etc., are easily and inexpensively maintained or repaired without changing any basic maser frequency determining elements, or the long term properties of the maser as a standard.

Experience has also shown that there are no large variations in the stability properties of one maser or another of the NP (or NX) type, so that selection of best units for time standard ensemble systems, as presently practiced, would not be nearly so important as is the case with the other standards in use today. With the exception of the very long term instabilities which may be related to changes in the storage bulb surface, all the important fundamental corrections to the maser oscillating frequency may be quickly evaluated on operational hydrogen masers. Thus a most important characteristic which separates operational hydrogen maser standards from other atomic standards, is that each unit is, in itself, a standard which is most closely related to an invariant atomic transition frequency, and so has "intrinsic" accuracy, rather than being necessarily related through calibration procedures with particular instruments which are evaluated for accuracy and maintained by specialists, usually in national standards laboratories.

APPENDIX

WALL SHIFT INACCURACY EFFECTS WITH VARIABLE VOLUME HYDROGEN MASER

The particular design of the variable volume maser illustrated in Figure 4 has several features which minimize potential error sources. A brief outline of these errors and the techniques available for their determination will be given here.[35] A variable volume maser as illustrated is presently being developed at GSFC, and a more comprehensive presentation of this work is anticipated at a later date.

a. Wall Shift Relationship

If ϕ_c is the phase shift per wall collision and ϕ_d is the average phase accumulated in the time T_d spent by the atom at average velocity $\bar{v}$ to go the average distance between wall collisions, λ, then to a very good approximation,

$$\left(\frac{\Delta f}{f}\right)_w = \frac{\phi_c}{\phi_d} = \frac{\phi_c}{2\pi f T_d} = \frac{\phi_c \bar{v}}{2\pi f \lambda}. \tag{A1}$$

We wish now to find λ for a bulb of arbitrary shape having a volume V and surface area A.

From elementary thermodynamics the total collision rate of atoms with the wall is given by

$$N_c = \frac{n \bar{v} A}{4}.$$

Here n is the atom density. If N_T is the total number of atoms in the bulb, then the collision rate per atom (frequency of wall collision for each atom) is given by

$$\frac{N_c}{N_T} = \frac{\bar{v}}{\lambda}.$$

Since $$N_T = n V,$$

it follows that

$$\frac{\bar{v}}{\lambda} = \frac{\bar{v}\,A}{4\,V},$$

therefore

$$\lambda = \frac{4\,V}{A}. \tag{A2}$$

The effect of the bulb collimator may be taken into account by noting that the average pressure in the collimator is 1/2 the bulb pressure, so that the effective bulb volume is

$$V = V_b + \frac{V_c}{2}$$

and the effective bulb area is

$$A = A_b + \frac{A_c}{2}.$$

The above approximation is excellent since typical collimator volumes and areas are less than one part in 10^3 of the bulb values.

Using (A2) in (A1) we obtain

$$\left(\frac{\Delta f}{f}\right)_w = \frac{\phi_c\,\bar{v}\,A}{4\,\omega\,V}.$$

Thus the relationship of wall shift to the ratio of surface area and volume is a very precise and fundamental dependence. The precision depends only on the assumption that hydrogen behaves as an ideal gas, and that pressure and temperature equilibrium occurs; these are valid assumptions to many orders of magnitude in the present case.

The storage bulbs in the NP and NX masers are cylinders with straight section length L $\doteq$ 28 cm and diameters D $\doteq$ 15 cm and with hemispherical ends, also of diameter D. For this case it is found

$$\lambda = \left(\frac{4V}{A}\right) = \frac{2}{3} D \left(\frac{D + \frac{3}{2} L}{D + L}\right). \tag{A3}$$

λ is calculated from the above equation to be approximately 12.1 cm. In the case of a spherical bulb, which is typically used in many other hydrogen masers, it is seen that (A3), with L = 0, reduces to the more familiar equation.

$$\lambda = \frac{2}{3} D.$$

b. Surface to Volume Ratio Determination

Several methods are available for determination of the effective value, or change in value, of surface to volume ratio. First, it may be measured initially by gas volume measurement or similar techniques. It may also be calculated from scaled measurements. If care is taken in making the bellows, so that the diameter remains constant as the bellows is compressed or extended, then the volume change is directly proportional to the change in length, and may be easily determined by counting the turns of the compression screw.

The bulb relaxation time constant is given by $T = V/F$ where F is the collimator pumping speed. Thus measurement of line Q changes, which depend upon T, give the effective volume change. One of the simplest methods to measure line Q is to measure the change in maser frequency as the cavity frequency is changed. If the cavity Q is constant, or if it is measured carefully, the line Q and thus the effective volume change can be measured precisely. Other techniques such as pulsed stimulated emission, decay rates using shuttered beams, and transient response measurements,[2] may also be used. These techniques are well established, precise, and straightforward. It should be noted that basically only the ratio of volumes (or ratio of measures of T_b) are required to make the absolute wall shift determination.

c. Change in Wall Surface Properties Due to Strain

It is estimated that there will be on the order of 1% surface strain as the bulb volume is changed. There is no reason to suppose that the phase shift per collision with the wall is a very strong function of this amount of strain,[35] however the experimental conditions are designed to minimize any associated error. For example, if the change in phase shift is a linear function of the strain, it will cancel in the bellows maser design, since the convex and concave convolutions alternate in compression and extension. That is, as the bulb is compressed, the inside obtuse angle surface will be stressed positively (stretched), while the inside acute angle surface will be stressed negatively.

If, however, the phase shift is a function of the absolute magnitude of the surface strain (a quadratic function for example), then a non-linear curve of frequency versus inverse volume will be obtained, and the error may be determined by making measurements at one or more intermediate volumes. Additionally the strain is maximum only at localized areas of the surface, so that the net wall pulling of that part of the bulb is only a fraction of the total effect. Thus, it does not appear likely that surface strain effects will be a very significant limitation to accuracy.

d. Cavity Instabilities Due to Flexible Bulb

The material of the bulb sides is .5 mm thick teflon. The ends are teflon coated quartz plates. The RF electric field is approximately maximum at the side wall position, so the cavity frequency changes due to dielectric position changes are primarily a function of the teflon wall position (or of the quartz bulb side wall position in fixed bulb masers). The teflon thickness is 3/10 the thickness of typical quartz bulb walls, and the dielectric constant of teflon is approximately 1/2 that of quartz. The frequency effect is proportional to the square root of the dielectric constant, and to the relative thickness, so the teflon bulb cavity pulling effect is approximately 2/10 that of a quartz bulb. In addition, in the expanded position the bulb volume is approximately twice that of an NP maser bulb, so the line Q is increased by a factor of 2, with a corresponding decrease in cavity pulling.

In experience with experimental masers using relatively loosely mounted quartz bulbs, it was found that as long as the maser was not physically shaken or vibrated, no unacceptable instabilities arose in regard to experimental measurements. Since both the mass of the teflon material and its effect on cavity frequency are reduced by as much as a factor of 10, it is not anticipated that instabilities will be a fundamental problem. Additionally, such instabilities as may occur are random, rather than systematic in nature, and long term frequency determinations with regard to stable fixed bulb masers will minimize any instability problem.

e. Filling Factor

To assure oscillation the filling factor of the maser must exceed a certain minimum value. (See Ref. 19 for definition of filling factor and other maser oscillation conditions.) For a centrally located cylindrical bulb 15 cm in diameter and 40 cm long, within a cavity 25 cm diameter by 50 cm long, the filling factor is calculated to be .48. At a contracted volume of 50%, the filling factor is .24. With the favorable oscillation thresholds of a maser using the NASA elongated cavity design, these factors allow a relatively wide range of beam intensity variation while oscillating. Thus tuning corrections can be accurately made, and experimental determinations of wall shift may be made at several significantly different flux levels so as to evaluate second order inaccuracy effects.

f. Errors Due to Density Variations

First, it should be noted that the position of the bulb bottom end, as well as the size and shape of the bulb collimator illustrated in Figure 4, are to remain fixed as the volume is changed. The collimator is also designed so that the bulb time constant is much less than other relaxation times at low oscillation levels. Since the exit pumping speed of the collimator does not change, the pressure in the bulb, which is the product of the collimator speed and the throughput, may be kept constant, or be changed controllably, independently of the bulb volume. Thus wall surface properties which are solely a function of the density of atoms (or molecules, hydrogen or otherwise) will not change as the volume is changed. Therefore the maser may be tuned for removal of cavity and spin-exchange pulling while maintaining identical density conditions for both the expanded or contracted volume, at either high or low beam flux.

As a precaution against background gas pressure being significantly high, or to minimize pressure changes due to manipulation of the bulb, the bulb is evacuated by a separate system as in the new NX masers. Ultra high vacuum conditions are maintained by using only ion pumps, and bellows type rotary feed throughs are used for manipulation. Thus accuracy evaluations may be done repeatedly over long time spans without contamination of the system.

g. Cavity and Spin-Exchange Tuning Errors Due to Magnetic Field Inhomogenieties

It has been shown by Crampton[28] that certain types of magnetic field inhomogeneities can cause an error in the cavity and spin-exchange correction procedure. However, the field inhomogeneities required to create significant error are very much greater than those present in the GSFC hydrogen maser designs. The primary source of the most critical type of inhomogeneity, namely radial DC field gradients, are the center entrance hole in the magnetic shield cap and the associated correcting coils which are used reduce the resulting effect. The correcting coils are not required or used in the GSFC masers since the shield apertures are relatively very small. (2.5 cm diameter versus 10 cm to 16 cm typically used in other masers.) Radial gradients due to either external fields or to fields applied with the internal field coils are thus very much less. This, as well as other favorable parameters, such as very large line Q due to use of large volume bulbs and certain favorable geometrical factors associated with use of very elongated cavities, accounts for the experimentally verified lack of "Inhomogeneity tuning errors" in the Goddard masers. It is also to be noted that such errors are removable for accuracy purposes, if they were present, by operating at sufficiently high field.[2,25]

VACUUM PUMP ELEMENT LIFETIME

Experiments were performed prior to selecting vacuum pumps for the NP masers to determine the useful life expectancy of pump elements of different types. Some prior data was already available with 75 and 240 liter per second pumps used on early Varian Associates hydrogen masers.[19,34] Two other manufacturers pumps which were also possible candidates for use in the NP masers were tested at GSFC in 1966 and 1967. These were the Ultec Corp. 150 liter per second diode type pump, and the General Electric Co. 100 liter per second triode type pump. Both these units pumped approximately 3 moles of H_2 gas in a period of 6 months. Due to the relatively small stray magnetic field of the Ultec pump, it was chosen for the NP masers. However, it was clear that the triode pump had excellent starting characteristics, as well as better capability for pumping inert gasses.

For the NX-2 and NX-3 masers, a new triode configuration pump was selected (Varian Associates 60 liter per second Noble VacIon pump). These pumps had been tested in operation with other experiments,[8] and had the expected starting and gas pumping features desired, as well as relatively small stray magnetic field.

By observing the drop in pressure in the one liter hydrogen storage vessel of the NP masers over the years, the total H flow rate has been found to be between .10 and .16 moles per year. The rate for the new NX masers is .05 to .08 moles per year. Thus the NP pump element life expectancy, ideally, is between 20 and 30 years. However, with a factor of 2 safety factor, 10 to 15 years may be realistically expected. However, the pump which pumps most of the hydrogen in the NX masers is separated from other background gas by partitioning, so it is simulating quite well the ideal conditions which occur in pumping experiments (where gasses other than hydrogen are essentially excluded). Thus 15 years of continuous pump operation should be conservatively expected, and 20 to 30 years life may actually be experienced before replacement is required.

It should be mentioned in fairness to all manufacturers of vacuum pumps, that it appears that most Penning discharge type pumps (ion pumps) with cathode area comparable to the pumps mentioned, would likely work very well at the low hydrogen flux of masers similar to the NP and NX designs. The magnetic field conditions, size, shape and cost, may be the most significant differences to consider.

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32. CER-VIT^R is produced by Owens-Illinois, 1020 N. Westwood Ave., Toledo, Ohio, 43607.

33. ULE (Ultra Low Expansion) titanium silicate is produced by Corning Glass Works, Corning, N.Y. 14830.

34. Varian Associates 75 liter per second VacIon pumps have been tested and have pumped up to 1.5 moles of H_2. Other Varian pumps (240 liter per second) were used on Varian H-10 masers. The useful element life in masers using these pumps was between 6 months and 1.5 years. However the hydrogen flow rates in early hydrogen masers were between 10 and 50 times higher than in the present NASA designs. (Private communication, Varian Associates.)

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QUESTION AND ANSWER PERIOD

DR. VESSOT:

Are there any questions?

MR. REINHARDT:

Not really a question. I just wanted to point out something about the shift that Stuart Crampton measured in relation to what Harry Peters just said.

The shifts he has been seeing have been proportional to the magnetic inhomogeneities that he sees in the maser, and he has been using old masers with large openings. You should see much worse results. Again, his masers they are not clocks.

Also, they tend to be proportional to the distance between the center of the bulb and the center of the cavity. There seems to be a coupling between the magnetic inhomogeneities and in the asymmetry of the oscillating field.

And so, again, in the carefully designed maser, there should be no problem.

DR. VESSOT:

Thank you. Are there any other questions or comments?

There is one thing that bothers me on the flexible bulb technique, and that is that when one stresses teflon, one is likely to change the surface qualities, and in deforming the bulb from an inverted cone, to — what is the other kind of cone — exverted, or when one changes the cone, or when one flexes an accordion like structure, as Mr. Peters has shown us, it is possible, in my mind, that one could have changes in the surface conditions of teflon that might, in fact, introduce a systematic property to this technique.

Do you have anything on that?

MR. PETERS:

Yes, definitely. This very well could be the case. Although from the interaction of an atom with the teflon, I wouldn't think it would be large.

However, in a case where you can vary the low volume continuously, linearly, and get many points with high accuracy, I think that such a stress factor would show up as non-linearity in the curves which you could calculate out. Also, you could put in artificial stresses at different values, and say — there are experimental ways which, if this does become a factor, we should be able to get a good feeling on what it is, and cetainly find out whether it is a limiting factor.

There are a lot of other details that go into the design of the flexible bulb maser. This particular one you saw had a constant opening for the hydrogen flux into the bulb. It was in a fixed position so that if you change the volume, you didn't really change the density of atoms in the bulb, for one thing. You have a fixed opening, and a fixed flux, so it is designed so you have a rather constant operating condition while you change the volume. And as I say, there are many more ramifications and things to consider, but I truly believe that the accuracy is really going to be in this region, and one of the main reasons is because we can get the accuracy of all the other contributing factors. An accuracy which would be a noise process down so low that you get good short term measurements, and you have good short term stability.

DR. VESSOT:

Other questions or comments?

DR. REDER:

But isn't it possible that if you use the compression sum, that instead of getting a non-linearity that you change the slope, and then it would be improbable, wouldn't it?

MR. PETERS:

We will have to see.

DR. VESSOT:

Harry suggested a good procedure, and that is to stress the teflon without changing the volume of the bulb, and look for an effect there. If this can be shown to be null, then the confidence in the accordion bulb or the bulb flexure technique would be very high.

MR. REINHARDT:

Just another comment in relation to that. The reason we chose the particular flexible cone in my experiment, a very thin cone, two mils, was that you could flip the cone. The stressing would only be on the edges of the cone where the material was actually folded over. With a large cone as in a storage box that contributes a very negligible area, and so, even if you assume 100 percent or 200 percent change in the flexible cone device with the thin cone, that is just a negligible problem.

DR. VESSOT:

Thank you.

I had intended to give a paper at this symposium on the work we are doing at Smithsonian, but there was an obvious conflict of interest, and also we have been on the treadmill for NASA getting the rocket probe going, and so I would like to show a few slides, but in order to avoid the conflict of interest, or the appearance thereof, I would like to appoint Dr. Winkler as chairman pro tem.

There are only three viewgraphs, and it is just a study in contrast, perhaps.

You have seen Victor Reinhardt's large box maser. This here is the size of the probe maser which is now oscillating, and this is sort of what it looked like when it was going together. It weights —we think it is between 75 and 85 pounds, but we haven't weighted every nut and bolt yet, and it also consumes about 25 watts of power. Its size there is pretty well given by the size of the concrete block wall behind it, and as you can see, it is getting onto the opposite extreme of Victor Reinhardt's maser. It is now oscillating. It has been through some shake and vibration and survived.

The pumping is done by the absorption technique, and the non pumpable elements, such as argon and other gases that will not absorb are pumped by a very tiny ion pump.

The other maser is one that we have been making several models of, which is on the next viewgraph, and we have built a number of these for radio astronomy and also one for the Naval Research Lab, and this is a sort of size about this high. We have taken data over the last Memorial Day week-end and I would just like to show you the data. The data has repeated itself enough that I think I can say this is not an accident, but we have measured data down to two parts in 10 to the 15th consistently, and our problem now is to get two of these things going so that we can hang onto it long enough to get data so that 10 to the 5th and 10 to the 6th seconds become statistically significant.

We know why it has rolled over at 2 in 10 to the 15. We found a very embarrassing barometric affect in that the cavity's dimensions were being altered by changes in barometric pressure on the confining canister that we used as a vacuuming envelope which, of course, connects ultimately to the cavity.

Well, we found that through some engineering ineptitude there was a coupling, a mechanical coupling, and that sure enough, the fluctuations of the barometer corresponded on a one to one basis with the fluctuations of the maser, resulting in either the world's most expensive barometer, or well, it may still be among the very good clocks.

However, now that we know what this is, I am tempted to take the data, as I still have it on record, and, since we made this calibration in a hypobaric chamber, recalculate and see where we might have gone if the barometer had not gone pretty badly during Memorial Day in New England. New England you recall is a place where we have frequent and violent storms, especially in the spring and fall.

That is all I have to say, and unless there are other questions or comments, then I think that the session is adjourned.

Thank you.

SESSION V

Chairman: Dr. F. H. Reder
U. S. Army Electronics Command

N75 11293

ALL CHAIN LORAN-C TIME SYNCHRONIZATION

LCDR H. T. Sherman
U.S. Coast Guard

ABSTRACT

A program is in progress to implement coordinated universal time (UTC) synchronization on all Loran-C transmissions. The present capability is limited to five Loran-C chains in which the tolerance is twenty-five microseconds with respect to UTC. Upon completion of the program, the transmissions of all Loran-C chains will be maintained within five microseconds of UTC.

The improvement plan consists of equipping selected Loran-C transmitting stations for greater precision of frequency standard adjustment and improved monitoring capability. External time monitor stations will utilize television time transfer techniques with nearby SATCOM terminals where practicable, thus providing the requisite traceability to the Naval Observatory.

Due to funding limitations, the program is being implemented in phases. The first phase comprises upgrading the East Coast, Central Pacific and Mediterranean Loran-C chains and outfitting the training facility. Subsequent phase(s) will upgrade the Northwest Pacific, North Atlantic and Norwegian Sea chains and implement synchronization in the North Pacific and Southeast Asia chains.

Equipment groups are being assembled and tested at the Coast Guard's Washington Radio Station Laboratory. Field installation is scheduled to commence early in 1974.

The paper discusses the time monitor equipment groups and the interrelationships with the ground station equipment. After a brief word on control doctrine, the remainder of the paper addresses forth-coming improvements to transmitting stations and how the time monitor and navigation equipments will complement each other resulting in improved service to all users of the Loran-C system.

INTRODUCTION

A discussion of the Loran-C system as a means for the dissemination of precise time and time interval (PTTI) is contained in the proceedings*, as is Loran-C time and frequency adjustment**.

This paper discusses existing Loran-C ground station equipment and the new time-monitor equipment groups being assembled and tested at the Coast Guard's Washington Radio Station. Current and future improvements in the navigation system will enhance the use of Loran-C for dissemination of PTTI.

Let us first take a look at a typical transmitting station as shown in form of a block diagram in Figure 1. The basic element of the system is the Loran-C timer set. Two timers are installed at each station. The timer performs the following functions.

- Generates Loran repetition rate from frequency standard input.
- Generates transmitter triggers and phase coding.
- Monitors Loran time difference between master-secondary pairs.
- Corrects the transmitted signal for propagation changes at the transmitting site.
- Provides alarms in event of system malfunctions or navigational tolerance errors.
- Provides a means of making phase adjustments to the transmitted signal to correct the navigation grid as directed by the control station.

The Control Indicator Group (CIG) provides operate/standby mode selection and signal routing. The Transmitter Control Group (TCG) generates low level Loran-C pulses from the triggers generated by the operate timer and provides operate/standby transmitter mode selection.

The transmitter then shapes and amplifies the Loran-C pulse to the rated power output. Peak output power is in the range of 160 to 3000kw depending upon the equipment type and transmitting tower at the particular station. All transmitters

*C. E. Potts, "Precise Time and Time Interval (PTTI) Dissemination via Loran-C System", Proc. PTTI Strategic Planning Meeting, December 1970, pp. 32-54.

**C. E. Potts, "Time and Frequency Adjustment on the Loran-C System", Proc. PTTI Strategic Planning Meeting, November 1971, pp. 69-84.

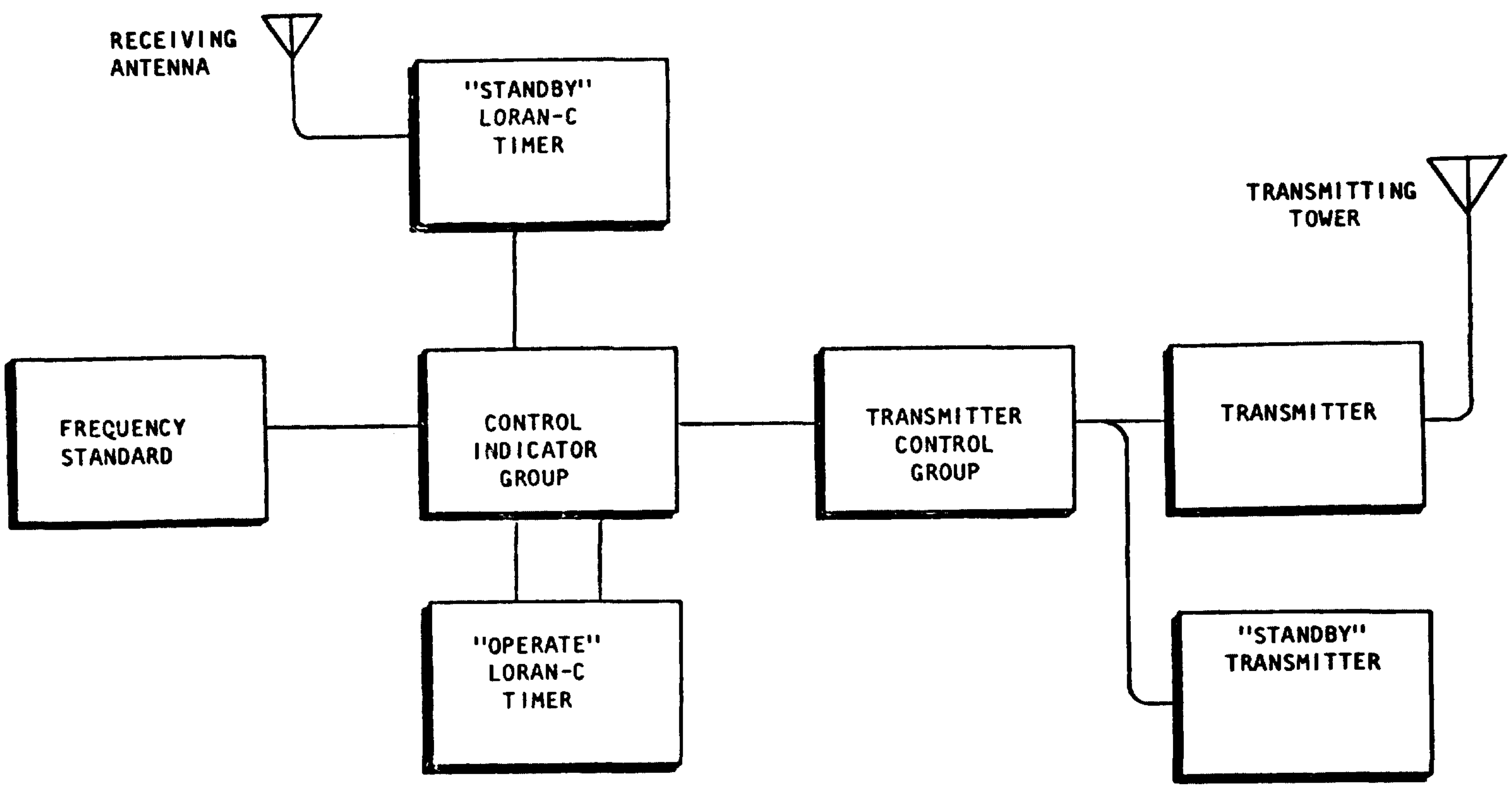

Figure 1. Loran-C Transmitting Station

presently in service are vacuum tube devices. A solid state high power transmitter is being developed under contract and, if successful, should be a substantial improvement in system reliability. The transmitter has traditionally been the weak link in the system.

Until recent years, the master-secondary time difference was controlled by electro-mechanical servo systems in the timers. The servo in the secondary-station timer actively tracked the master signal to maintain the prescribed time difference. This mode of operation, called "synchronized operation", resulted in the servo noise being transmitted on the secondary signal.

With the advent of atomic frequency standards, it was found that the timer servos could be turned off with a substantial improvement in stability of the time difference. This mode is called "free-running operation" and is now employed in all Loran-C chains. All transmitting stations are presently equipped with cesium beam frequency standards.

In the late 1960's, the stability and wide coverage of the Loran-C system were recognized as excellent qualifications for broad-scale dissemination of PTTI. Through cooperation of the U. S. Naval Observatory and the Coast Guard, several Loran-C chain transmissions have been synchronized to UTC (USNO). In order to initially implement the program, additional equipment was developed and installed at the master stations for the East Coast, Norwegian Sea, Central Pacific and Northwest Pacific Loran-C Chains.

The equipment added was a unit called a UT Synchronizer which interfaces with the station equipment and provides a local time reference. The UT Synchronizer utilizes the station frequency standard and performs the following functions.

- Generates and displays time of day.
- Generates and displays time of coincidence of UTC with the first master radiated pulse.
- Provides alarms in event of timing error.
- Provides Loran-C timer reset capability.
- Generates a 1-PPS transmitter trigger (Discontinued in 1972).

Figure 2 is a block diagram of the UT Synchronizer. The frequency standard input to each timer is independently controllable by a phase shifter to permit accurately positioning the transmitter trigger. This enables a fine adjustment

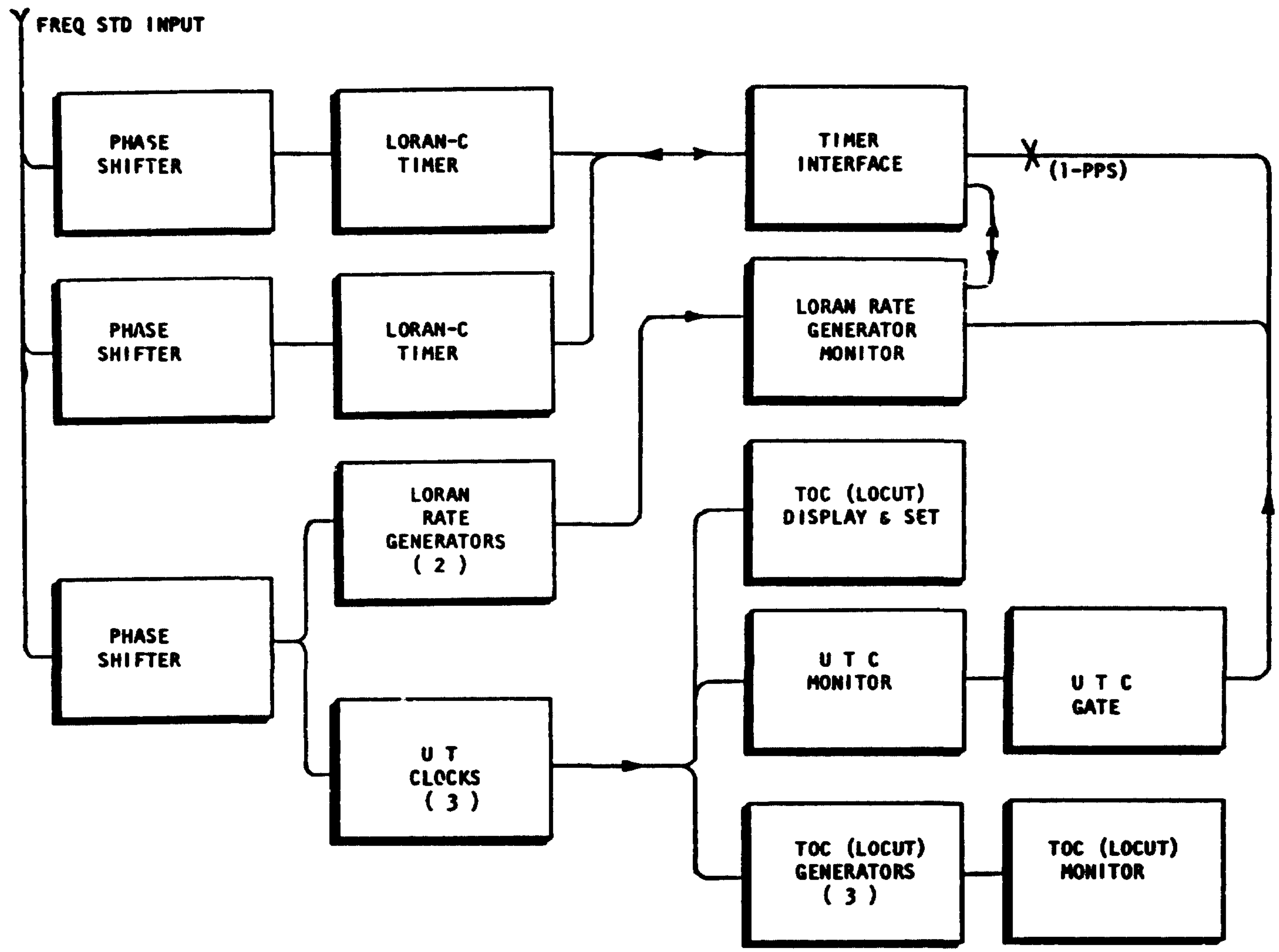

Figure 2. UT Synchronizer

to ensure that the first master pulse occurs at precisely the proper relationship at the time of coincidence (TOC). A third phase shifter controls the phase of the frequency standard input to two Loran rate generators. These independent rate generators are then compared to each other and the timers by the Loran Rate Generator Monitor. This unit also provides the capability of instantaneously resetting the timer to the UT Synchronizer. The remainder of the circuitry still in use comprises TOD clocks and the generation and monitoring of TOC. The UTC Gate was used to initiate a single pulse transmission each second. The 1-PPS transmission was discontinued in 1972, after the conversion of time scale to improved UTC.

The first UT Synchronizer was developed at the Coast Guard Electronics Engineering Center under project W-340 and was installed at Carolina Beach, the East Coast master station. This unit was subsequently installed at the master station in the Central Pacific chain after three improved models were constructed under project W-425. The major disadvantages of these UT Synchronizer equipments are.

- Cost
- Special operator training required
- Complex circuitry with no ability for "hands on" technician training.
- Requires timer modifications, therefore results in non-standard ground station equipment.
- Timer interface unit would require further modification for compatibility with future Loran-C timers.
- No time reference external to station.

Current developments are directed toward replacement of the aging timer equipments. A new generation timer has been developed for use at either Loran-C or Loran-A stations, and is commonly called "COLAC" for COmbined Loran A and C. The Loran-C version, the AN/FPN-54 performs all of the basic functions of the older equipments with one exception. The design is based on the free-running mode of operation, hence it does not have a time difference monitoring capability. A computer controlled monitor/control receiver is being developed under contract, and should be avilable in approximately three years.

Figure 3 shows the basic block diagram of the COLAC timer set. Except for operate/standby control and cross-timer comparison, all of the circuitry is

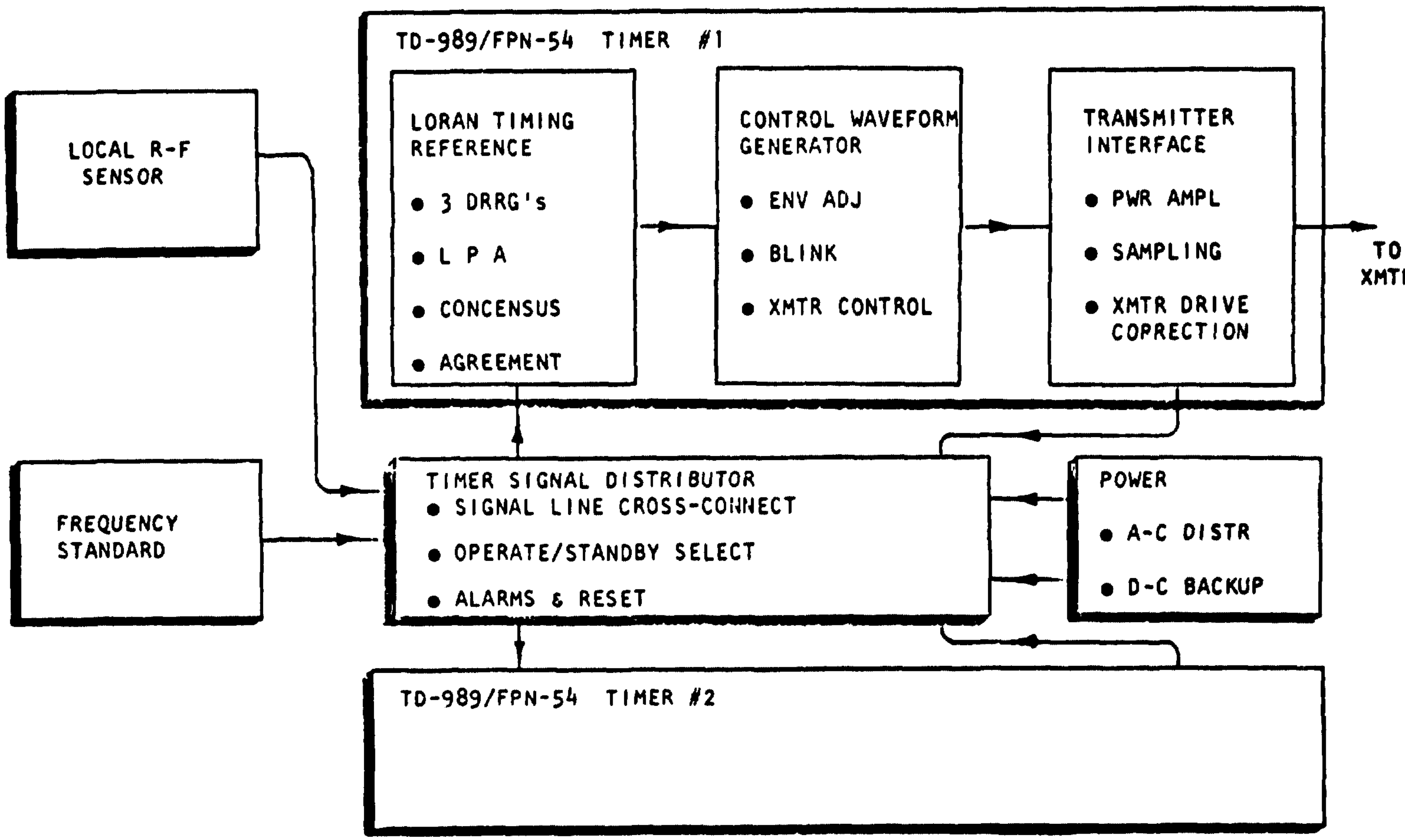

Figure 3. AN/FPN-54 (COLAC) Loran-C Timer Set

contained on fourteen plug-in printed circuit cards. The functions of the two TD-989/FPN-54 timers are:

- Loran Timing Reference
  - Three independent digital rate generators (DRRG)
  - Concensus voting of the DRRG's
  - Timer status indication
  - Cross-timer agreement monitor and reset
  - Programmable phase adjustment (Cycle timing adjustment)
- Control Waveform Generator
  - Transmitter control
  - Envelope adjustment
  - Blink control
- Transmitter Interface
  - Power amplification for transmitter drive
  - Transmitter drive correction
  - Sampling drive signal

The operate-timer contains a digital servo loop to compensate for changes in the local propagation characteristics.

The design of the COLAC timer is geared toward simplicity of operation and maintenance. Provisions have been made for remotely controlling many of the functions via communications link. This will eventually lead to reduced manning levels at the stations.

The initial COLAC installation at Estartit, Spain, has been in operation for over three years and has a remarkable record of only two failures, both in the power supply, during that period. The new-generation timers have been installed for some time at Bo and Jan Mayen in the Norwegian Sea chain, and recently at Carolina Beach, Nantucket, Jupiter and Dana of the East Coast chain. For an aggregate of over seven equipment-years of operation, there has been a total of about thirty minutes bad signal time directly attributable to COLAC. Most remaining stations will be COLAC-equipped within the next two years.

Of particular interest to all users of Loran-C is the development of a new transmitter control unit. This equipment permits individual control of each half-cycle of the transmitter drive signal by literally "building" the Loran pulse. Thus we will have pulse shape control to a precision heretofore unattainable. These new units have just been installed at Dana, Nantucket and Carolina Beach with future installations planned where pulse shape adjustment is particularly difficult due to transmitter type.

The improved stability and reliability of the navigation system suggests a potential for upgrading the PTTI capability as well. DOD has provided the first of two increments of funding to implement improved PTTI on all Loran-C chains. Under the improvement program, all master stations will be equipped for greater precision of adjustment of frequency and a self-monitoring capability. Where required, an additional time monitor will be established at a Loran-C transmitting site to provide the requisite traceability to UTC (USNO).

The following stations are in the program.

- Phase I
  - Carolina Beach — SS7 Master
  - Simeri Crichi, Italy — SL1 Master
  - Targabarun, Turkey — SL1 Time Monitor
  - Johnston Island — S1 Master
  - Upolo Point, Hawaii — S1 Time Monitor
  - Gesashi, Okinawa — SS3 Time Monitor
  - Training Center, New York
- Phase II
  - Cape Race, Newfoundland — SS7/SL7 Cross chain monitor
  - Angissoq, Greenland — SL7 Master

• Ejde, Faeroe Isles	SL3 Master & SL3/SL7 monitor
• St. Paul, Pribilof Is.	SH7 Master
• Attu, Aleutian Is.	SH7 Time monitor
• Iwo Jima	SS3 Master
• Sattahip, Thailand	SH3 Master & Time monitor

Figure 4 depicts the scheme that will be employed in most chains to monitor the timing of the chain. Satellite time transfer will establish the relationship between the SATCOM-terminal clock and UTC (USNO). The secondary transmitting station (Time monitor station) is then updated using passive television time transfer with the SATCOM terminal. The time monitor receives and compares the master transmitted signal to its updated clock.

The master station will also be equipped with timing receivers. One receiver will track the time monitor signal, while the other will track the master's own radiated pulse. Thus, should the master station have a failure of both timers, or some other such catastrophic failure, it will have the capability of reestablishing the relationship to UTC without external assistance.

The block diagram for the time monitor station is shown in Figure 5, and comprises the following major elements.

- Local signal switched attenuator/blanker. Prevents overdriving timing receivers during local transmitting interval.
- Timing receivers. Provides phase-shifted 1 MHz and 1-PPS which are coherent with the signal being received.
- Multicoupler. Signal conditioning and interference rejection.
- Recorders. Provide permanent record of local frequency standard minus received signal.
- Time interval counter. Provides means of comparing various frequency and signal sources.
- Control unit. Selects source for time interval counter. Provides alarm in event of timing error. Visual display and monitor of TOC.

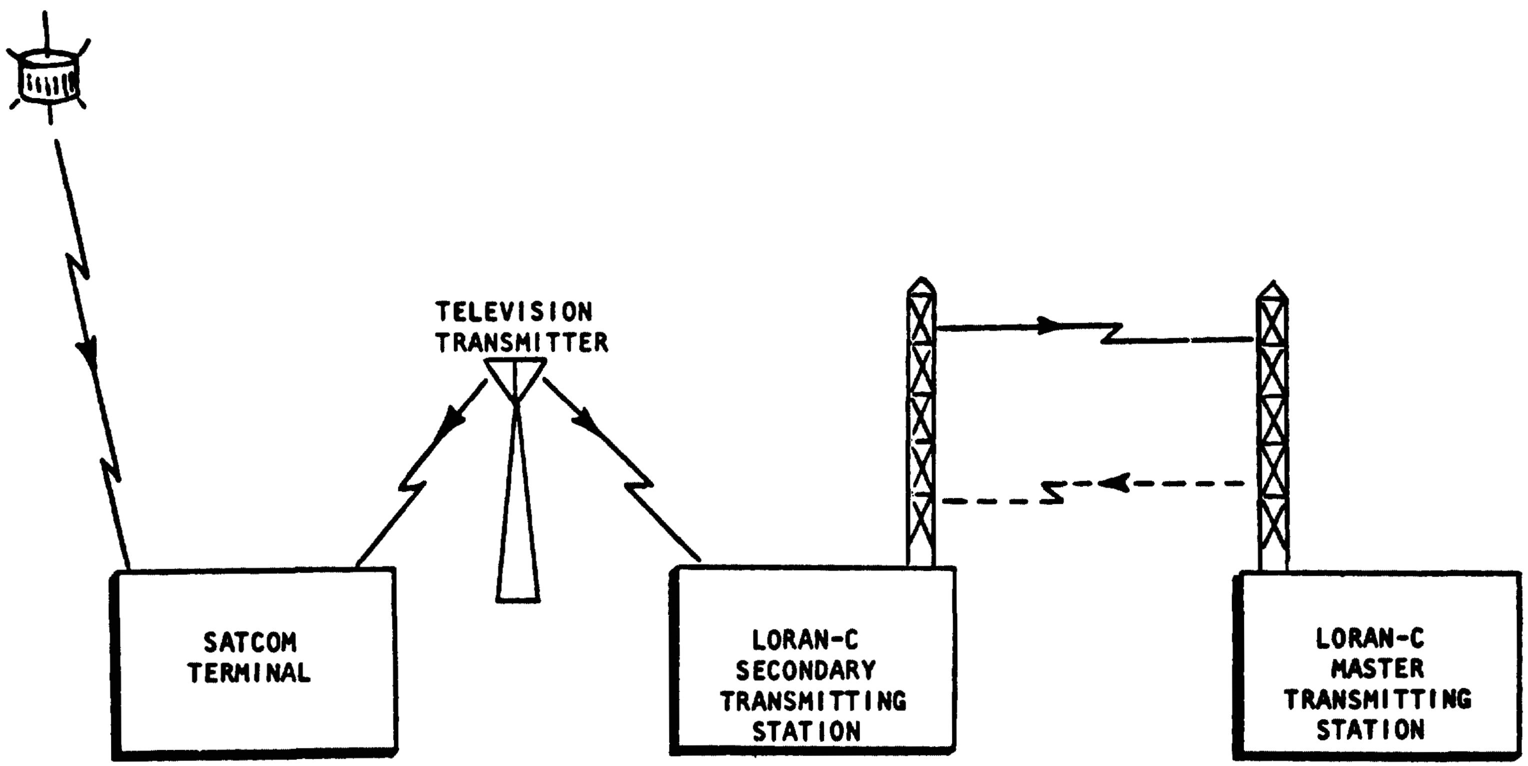

Figure 4. Transfer of UTC (USNO) to Loran-C Chain

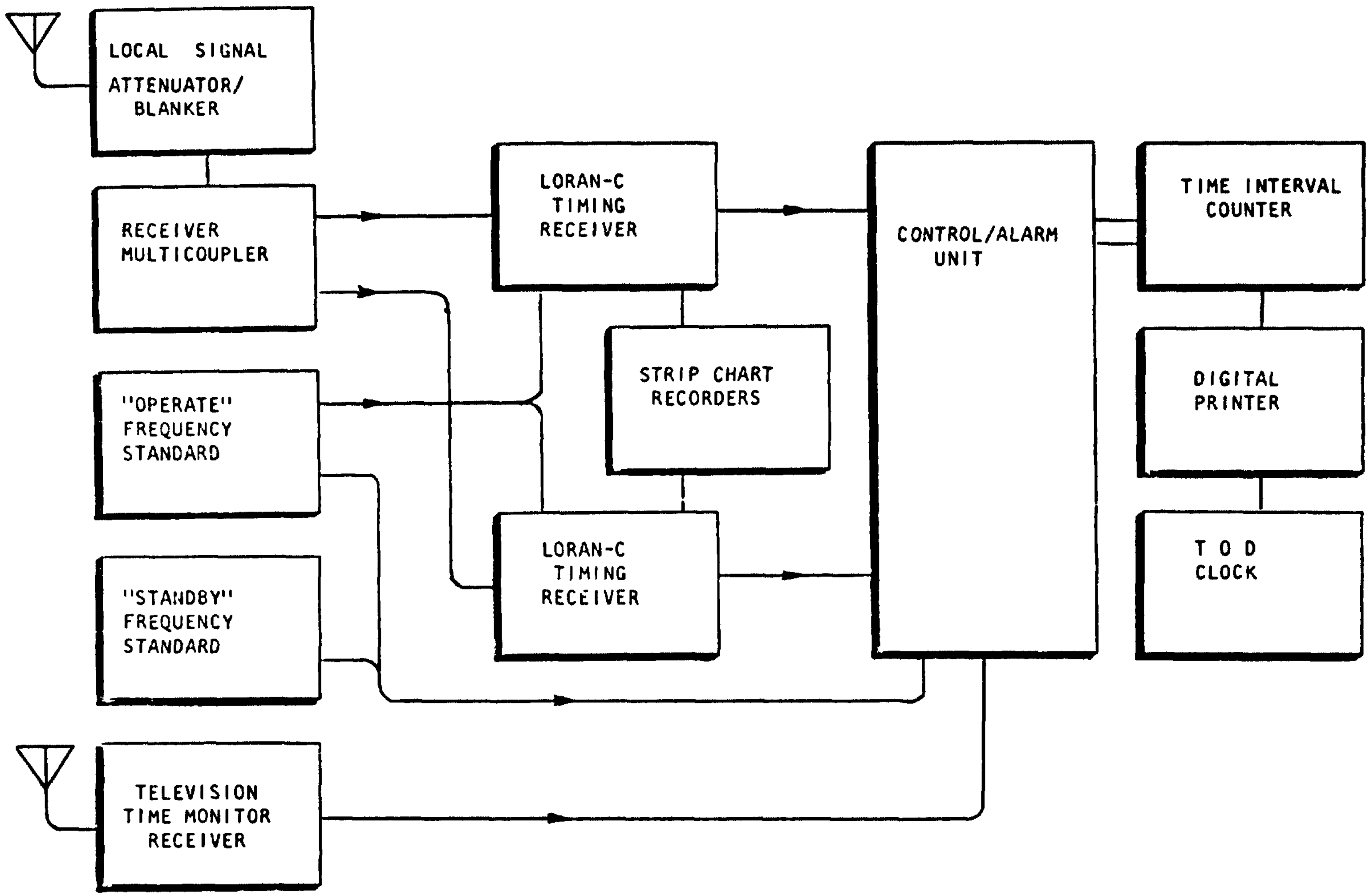

Figure 5. Timing Equipment Cabinet

- Digital printer & TOD clock. Provides permanent record of time interval counter reading and corresponding time of day.

- Television time monitor. Provides an output coincident with a specific TV synchronization pulse for passive TV time transfer with SATCOM terminal.

Experience has shown that the fine frequency control (C-field adjust) of the cesium beam frequency standard is rather coarse when attempting to maintain tight control of the frequency offset of Loran with respect to UTC (USNO). To obtain an improved means of adjusting frequency offset, each master station will be furnished with two phase microsteppers*. These units enable adjusting the frequency offset in increments of one part in 10^{14}.

The high resolution available with the phase microstepper has given rise to a technique which will be evaluated in the near future. The COLAC timer contains circuitry which monitors cross-timer agreement and alarms if the difference between timers exceeds twenty nanoseconds. The scheme which will be studied is shown in Figure 6, and may be the configuration in the future. The primary-frequency-standard/phase-microstepper combination is used as the input to the "operate" TD-989/FPN-54. The standby timer, however, uses the backup frequency standard-microstepper. This configuration would provide continual comparison of the two frequency sources within the twenty nanosecond window. Should the on-line equipment fail, the station would simply change timers (a single pushbutton operation) and resume transmitting without loss of time.

Let us now take a look at the control problem. Stations which are presently contributing to the Loran timing control function are listed below.

- SS7 directly observed by Naval Observatory

- SS7-SL7 measurement made at Cape Race. Reported by daily message.

- SL3-SL7 measurement made at Ejde. Reported by daily message.

- SL1-SL3 measurement made at BIH and H/P in Geneva. Periodic summary provided by message.

*Precise Frequency Offset Generator, model 2055 mfd. by Austron, Inc.

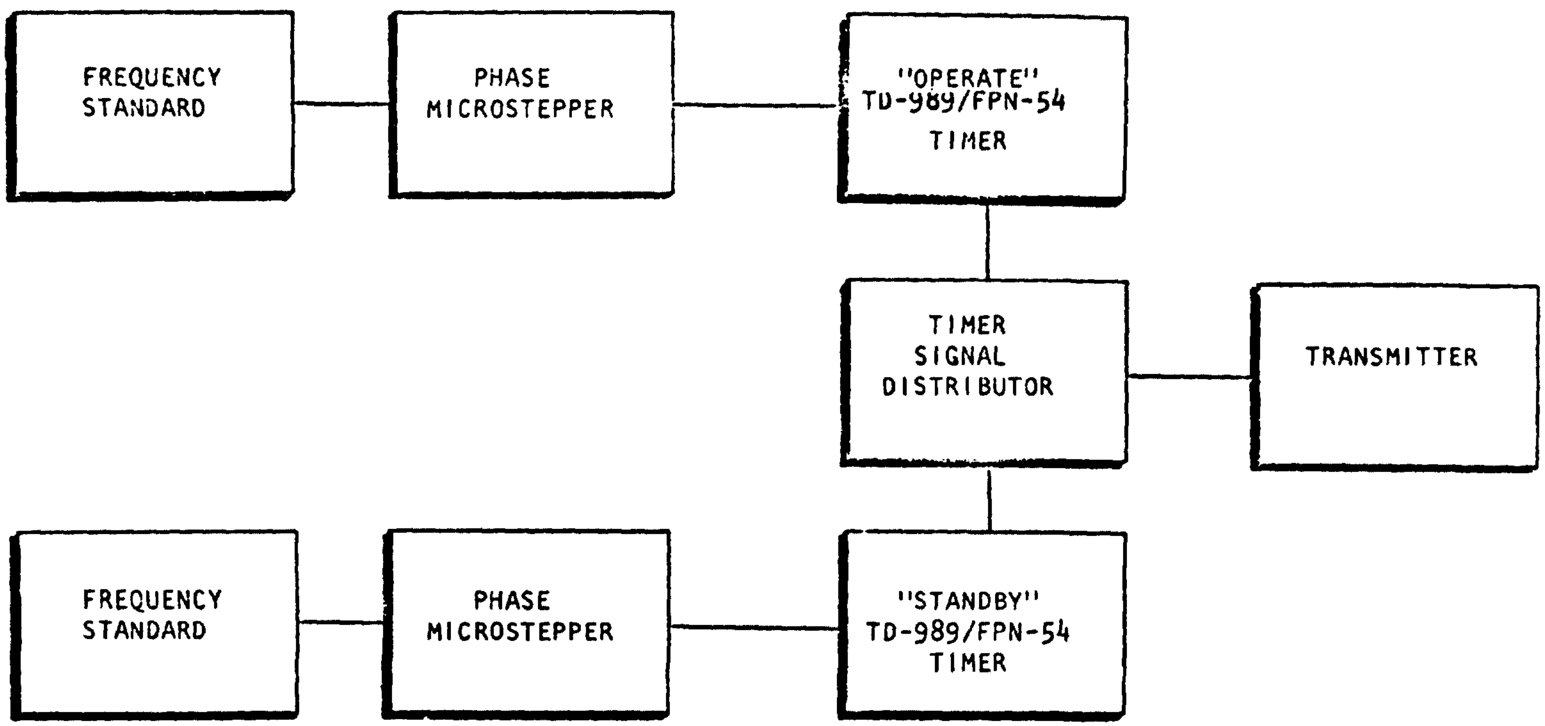

Figure 6. Loran-C Transmitting Station, Proposed Configuration

- S1 monitored by US NAVASTROGRU DET "C". Reported by daily message. UTC (USNO) update from SATCOM terminal at Helamano and portable clock.

- SS3 monitored by USCG LORMONSTA Fuchu. Reported by daily message. UTC (USNO) update by portable clock. Monitor data also provided to USNO by SATCOM terminal at Futenma, Guam.

Based upon the data from these various reports, the Observatory computes the daily phase values, which are then published in Time Service Announcements. Adjustments of operate frequency standards at master stations are directed by Coast Guard Headquarters with the concurrence of the Observatory.

With the availability of UTC (USNO) at the SATCOM terminal, hence at the time monitor, this rather lengthy process could be reduced to a local control function. In fact, local control would be required to implement the mini-step adjustment method which has been suggested*. Although requiring some conventional operating technique of the navigation system, the following is considered to be a practicable control doctrine. This could be implemented with minimal additional equipment, namely, phase microsteppers at the time monitor with additional 1-PPS dividers.

- Time monitor uses "new" 1-PPS source for time transfer from SATCOM terminal.

- Time monitor adjusts own microstepper for zero offset.

- Master adjusts microstepper for zero offset with respect to time monitor as directed by the monitor.

- Remainder of secondary stations maintain relationship to master by local phase adjustments.

The time monitor station would then report the change in frequency offset. An alternate, and perhaps more palatable, method would be for the time monitor to recommend the intended change, but not enter it in the system until concurrence was received from higher command.

*Potts (op.cit.)

The All Chain PTTI Improvement Program depends to a large degree upon the traceability of the time monitor station to UTC (USNO). If satellite time is not available at the SATCOM terminal, or cannot be transferred with an acceptable accuracy, then we will have to continue with the burden of the portable clock. In either event, I am sure that we can meet the goal of maintaining all Loran-C chains within 2.5 microseconds of UTC.

QUESTION AND ANSWER PERIOD

LCDR. SHERMAN:

Are there any questions?

QUESTION:

Your slide on the monitor system didn't show anything for the Alaska chain. I was just wondering, how do you currently monitor the SH-7?

LCDR. SHERMAN:

The Alaskan Chain is not presently timed. I believe that there are some — I know that there are several users. The Observatory has been working on the problem. However, the chain itself is not equipped with a UT synchronizer.

DR. REDER:

Yes, Mr. Lavanceau.

MR. LAVANCEAU:

In regard to the Alaskan Loran-C chain, we believe that in about two weeks from now we may be able to put that chain on time. In other words, asking the Coast Guard to make the time adjustment to the chain which would result in a step of about 15 milliseconds. The monitoring will be done by three different organizations, six stations, located all over Alaska.

In regard to monitoring some of the chains as far as the Mediterranean Loran-C chain, your slide shows that the monitoring was done by the Paris Observatory, (BIH) and through the H. P. Lab in Geneva. In addition, we use monitor data from the USNO in order to detect the timing variations of the North Atlantic chain. Also for the Northwest Pacific we use about 6 or 7 different monitoring sites in addition to the Fuchu site.

DR. REDER:

Any more questions?

Mr. Smith.

MR. SMITH:

Thank you, Mr. Chairman.

I do not wish to ask a question, but if I may for a moment speak as the Chairman of the Directing Board of the BIH, may I say how dependent we are upon the Loran-C system in order to form the international scale of atomic time. We do very much greatly appreciate the cooperation of the U. S. Coast Guard organization in trying to meet these very specialized needs of precise timing in order that the independent atomic time scales may each contribute towards the international scale.

Since Admiral Pearson was present at one of the CCDS meetings, there has indeed been a full understanding by the Coast Guard of this additional responsibility, and I would like to place on record our appreciation of all that has been done.

Thank you.

DR. WINKLER:

Dr. Smith's comments prompt me to add some comments to the discussion which we had yesterday and also to this paper here.

Some users have experienced troubles in picking up time absolutely with sufficient accuracy, and I refer back to Dr. Smith's comments yesterday.

Now, one of the problems in many such cases is that the geodetic position is not known accurately enough. If you do not know your geodetic position, or if there is a question about on which datum that position is, you cannot expect, of course, to get absolute time to within one microsecond.

There is one good way to circumvent that. If you have capable operators in the station, what you do is you determine your Loran Hyperbolic position with the same timing equipment which you use to pick up time. You make difference measurements of time of arrivals from every station of the chain that you can get, and you compute (these programs are available) your Loran position.

If you use, then, that position to compute your absolute time delay, you will find a significantly greater agreement with portable clock calibrations than otherwise.

Thank you.

CMDR. SHERMAN:

Just to add a little bit to Dr. Winkler's comment there. We have at headquarters several programs which will give us the all seawater transmission time, or propagation time from the transmitting station to the monitoring point.

If you know your geographic position, I would volunteer my services — let us know where you are, and what station you want to receive, we will not only give you the baseline distance in microseconds, but we will also give you a computer printout which will tell you how to correct for the terrain between you and the transmitting station.

This additional factor is very important. It is called Additional Secondary Phase Correction, and as a matter of fact we have some little slide rules, which, if you don't want the whole big computer printout, we can send you.

DR. REDER:

Any more questions?

May I ask one myself?

You mentioned that reliability of the transmitter towers is occasionally some problem — how serious is that?

CMDR. SHERMAN:

Well, as with any high powered transmitting equipment, you have equipments that you are really pushing to their extreme.

We frequently have trouble at Cape Race because of lightening. Now, there is not a thing we can do about that. We have been fighting it for years, static drain resistors, other types of suppressors.

DR. REDER:

How important is this? Does it appear weekly, daily, monthly?

CMDR. SHERMAN:

Again, it depends upon the conditions, the age of the equipment, the local conditions, the technicians that we have at the station.

Normally, our signal availability time is better than 99 percent of the time.

DR. REDER:

Another question or comment?

(No response.)

N75 11294

STABILITY AND NOISE SPECTRA OF RELATIVE LORAN-C FREQUENCY COMPARISONS

E. Proverbio
V. Quesada
A. Simoncini
International Astronomical Latitude Station, Cagliari, Italy

ABSTRACT

Relative comparisons of Loran-C frequency transmissions between the master station of Catanzaro (Simeri Crichi) and the X, Z slave stations of Estartit (Spain) and Lampedusa (Italy) are carrying out by the GG LORSTA Monitor Station of the Mediterranean Sea Loran-C chain. These comparisons are able to emphasize the relative and, under certain conditions, the absolute rate of the emitting standard frequencies of the slave stations and some relevant statistical properties of the Loran-C Method for frequency transmission and time synchronization. In fact the stability of each Loran-C frequency standard transmission is subject to perturbations, more or less known, due to the propagation medium and other causes. Following the Allan (1966) method for data processing, the performance of the relative rate of frequency of the transmissions of the X, Z slave stations are described calculating the standard deviation σ (N, τ) of a set of N frequency measurements from its mean averaged during sampling times τ. We designate this standard deviation as the measure of the stability of the Loran-C frequency transmission.

Typical performance of Loran-C transmissions has been successively studied by determining the Spectral density of the relative frequency variations between the X, Z slave stations as regards master station.

One of the parameters addressed by this Interoperability Committee was timing and synchronization. The recommendations, and supporting rationale for these recommendations, will be provided.

INTRODUCTION

In order to study the stability of the Loran-C radio-navigation system in the Mediterranean chain and to determine its typical performance, relative comparisons of Loran-C frequency transissions between the master station of Catanzaro (Simeri Crichi) and the X, Z slave stations of Estartit (Spain) and Lampedusa (Italy) are carrying out by the CG LORSTA Monitor Station of the Mediterranean Sea Loran-C chain. All Loran-C station transmit on 100 kHz and are controlled by cesium-beam atomic clocks. The analyzed data are referred to the period January-December 1972 for the Estartit station and to the period September-December 1972 for the Lampedusa station as this last station is entered upon office only from September 1972. The phase differences $\Delta\phi$ (M - X) and $\Delta\phi$(M - Z) between the frequency of the master and slave stations X and Z as received at the Cagliari Monitor Station has been reconstructed taking in account the corrections produced at the emitting station in order to closely synchronize each slave station to a common reference. The Table 1 gives us a statistical distribution of the phase and time steps carried out at the emitting slave stations. These data show that phase variations due to steps in time are generally smaller than 0.1 μsec this means that the virtual or relative synchronism of the Loran-C time scale is maintained to about 0.1 μsec.

Table 1

Statistical Distribution in Percent of Man Made Time Steps Carried Out in the Emitting X and Z Loran-C Stations of the Mediterranean Chain

Range in microsecond	(M - X) %	(M - Z) %
0.00 - 0.03	0.0	0.0
0.03 - 0.06	16.0	15.5
0.06 - 0.09	35.8	31.0
0.09 - 0.12	42.0	45.7
0.12 - 0.15	4.9	3.1
0.15 - 0.18	1.0	0.8
0.18 - 0.21	0.3	3.9

Denoting by $\Delta\phi$ (M - S) = B (M - S) the daily phase difference of the slave stations X and Z with respect to the primary frequency of the master station as received at the Monitor Station and by $d\phi$ (M - S) the phase steps brought into the emission, the daily calculated phase difference between slave and master station will be

$$\Delta\phi\,(M-S)_{cal} = \Delta\phi\,(M-S) + d\phi\,(M-S)$$

The quantities $\Delta\phi$ (M - S)$_{cal}$ = B (M - S)$_{cal}$ correspond to the theoretical relative phase differences between the master station and the X, Z slave station . Figure 1 and Figure 2 are plotted the real (full points) and theoretical (bla. points) integrated time scales defined as Σ B (M - S) and Σ B (M - S)$_{cal}$.

DETERMINISTIC INSTABILITIES

The theoretical time scales Σ B $(M - X)_{cal}$ and Σ B $(M - Z)_{cal}$ represent the relative performance of the master time scale with respect to the X and Z time scales. The instabilities of each time scale are due to deterministic process such as, for instance, frequency drift or systematic changes (real or apparent) in the path and to non deterministic processes (random fluctuations). From the date given in Figure 1 and Figure 2 we can deduce that the relative rate of the Master with respect to X and Z stations was +29.2 nsec/day and +35.6 nsec/day respectively or about $+3.4 \times 10^{-13}$ and 4.1×10^{-13}. These data show the excellent stability of each time scale and of the cesium beam clocks. The progressive phase differences Σ B (M - S) observed at intervals of fifteen minutes was analysed for emphasizes, the performance of this time scale upon periods included in the intervals of 0.5 - 24 hours and 1 - 45 days. The spectral densities of the time scale Σ B (M - Z) plotted in Figure 3 are the trimensual average of the values calculated on periods of thirty days. It is interesting to point out the existence of peaks common to each curve which could be associated to systematic fluctuations in time scale. On the contrary the spectral density plots of time variation referred to the same scale Σ B (M - Z) for period between 1 and 45 days is given in Figure 4.

The theoretical daily rate of time scales Σ B (M - S), represent a significant parameter for the study of frequency drift in cesium standards (Winkler et al., 1970). The values of the relative daily frequency rate B for the frequency comparison (M - X) and (M - Z) are plotted in Figure 5. No noticeable drift appears for the relative rate B (M - X); as regards the rate B (M - X) the available data are too little to be able to draw a conclusion, because these frequency shifts can only be determined reliably over very long periods of time. It is interesting however to point out a certain similarity in the trend and in the peaks of the common part to the curves. The spectral analysis of the quantities B (M - Z) shows the probable existence of periodical irregularities of about 40 and 120 days with amplitudes of $3 - 4 \times 10^{-13}$. If these fluctuations would result real a their cause could be looking for in the cesium beam standards or in the relative path variations.

NON DETERMINISTIC FLUCTUATIONS

Non random phase fluctuations of the cesium beam introduced along a propagation path may be studied by using suitable statistical techniques. A useful measure in time and frequency domain has been shown to be the value of the standard deviation. Following D. Allan (1966) we have described the performance of the relative rate of frequency of the Loran-C transmission for the X and Z slave stations with respect to master station, calculating the standard deviation δ (N, τ) of a set of N frequency measurement from its mean versus sampling time. We designate this standard deviation as the measure of the stability of the Loran-C frequency transmission. The Figure 7 and Figure 8 shows the trend of the standard deviation $\sigma_y(\tau)$ (black points) of the relative frequency fluctuations versus measurement interval τ in the frequency comparisons between the master stations M and the slaves X and Z. The results obtained in both cases are very similar but more interesting are the results obtained from the B (M - Z) data owing to the very long measurement interval available.

We can see (Fig. 8) that for sampling time $\tau < 1$ day and $\tau > 30$ days about the Loran-C comparisons exhibit white phase noise. For these ranges the stability results

about 100 ns for $\tau < 1$ day
about 250 ns for $\tau > 30$ days

On the contrary Loran-C relative comparisons exhibits "perturbing" noise (white FM noise?) for sample time ranging from 1 day to 30 days about, the existence of these noise could be associated to the existence of long-term drift with period of about 5 - 10 and 40 days (see Fig. 6).

CONCLUSION

The phase fluctuations analyzed are composed of the following components:

$$\Delta\phi\,(\text{measured}) = \Delta\phi\,(\text{propagation}) + \Delta\phi\,(\text{cesium}) + \Delta\phi\,(\text{transmitter}) + \Delta\phi\,(\text{receiver}) + \Delta\phi\,(\text{residual})$$

If we assume that the phase noise in the receiver and transmitter is negligible with respect to the cesium and propagation fluctuations (Allan & Barnes, 1967) we can write

$$\sigma_m^2 = \sigma_p^2 + \sigma_c^2 + \sigma_{rs}^2$$

Assuming, following Winkler et al., (1970), for the daily standard deviations of a cesium clock about $1 - 2 \times 10^{-12}$, we can point out from the observed values of σ_m given in Figure 7 and Figure 8 that fluctuations due to the influence of the medium on the propagation delay result of the same order of the random fluctuation of cesium beam, that is about 10^{-12}.

ACKNOWLEDGEMENTS

The authors express their appreciation and thanks to Mr. C. Y. Potts and to Commanding Officer of the USAC Loran-C Station, Sardinia, for their kind cooperation.

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Allan, D. W., 1966, Proc. of the IEEE, Vol. 54, No. 2, 221

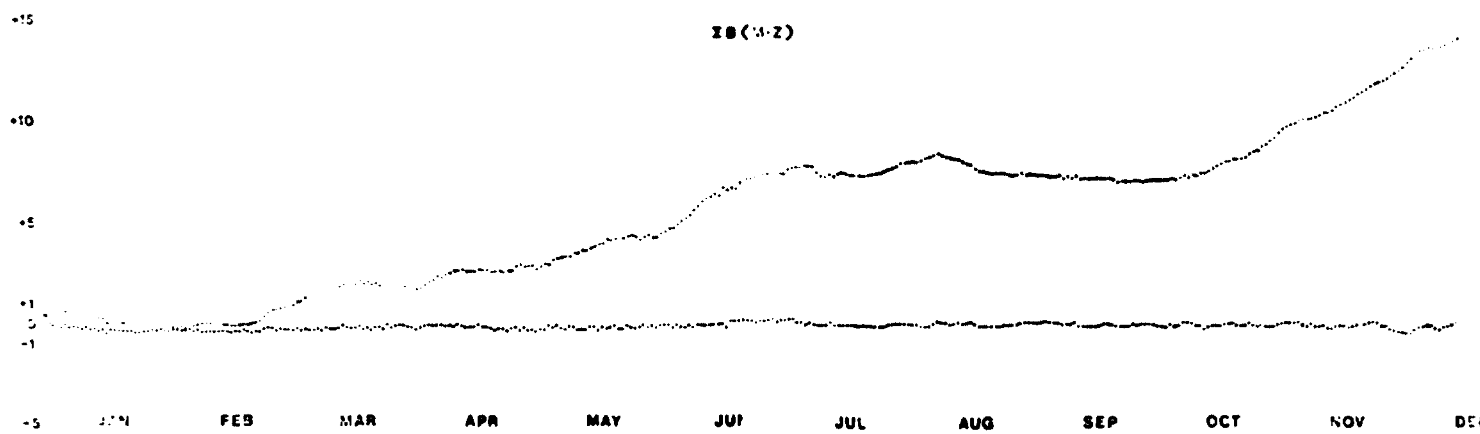

Figure 1. Theoretical relative time scale (blank points) between the Master Station (Simeri Crichi) and Z slave station (Lampedusa) of the Loran-C Mediterranean sea chain during 1972. Blank points represent the real relative time scale after adjustments steps in phase carried out at the emission.

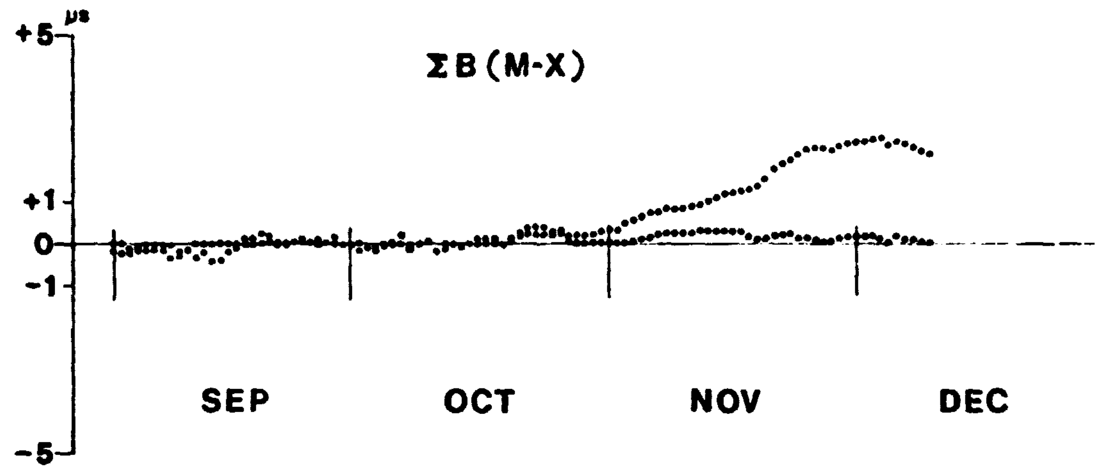

Figure 2. Theoretical and real relative time scales between the Master Station (Simeri Crichi) and X slave station (Lampedusa) as received at the Cagliari Monitor Station.

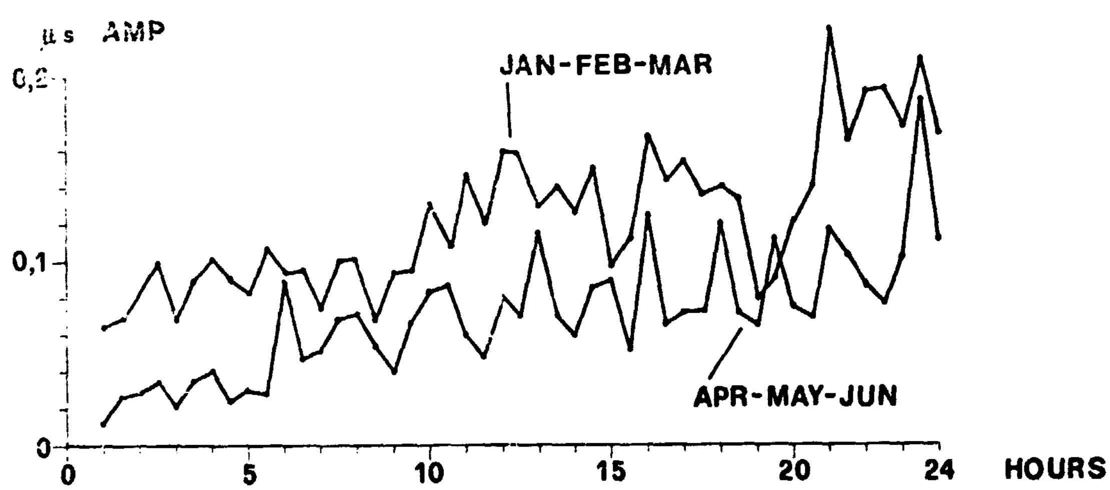

Figure 3. Spectral density plot of relative time scale Σ B (M - Z) determined with a sampling period of 0.25 h.

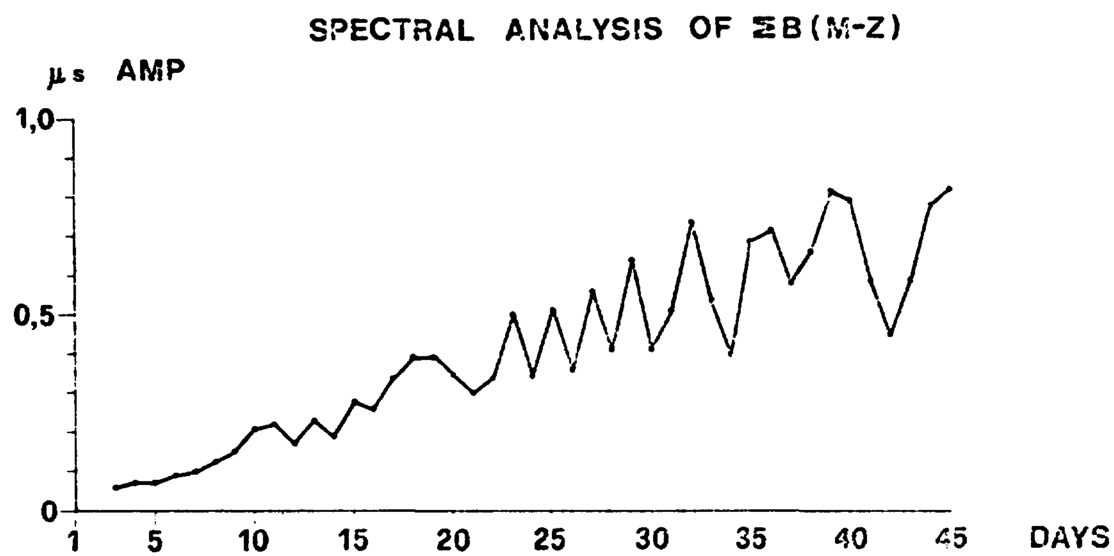

Figure 4. Spectral density plot of relative time scale Σ B (M - Z). Time was determined with a sampling period of 1 day.

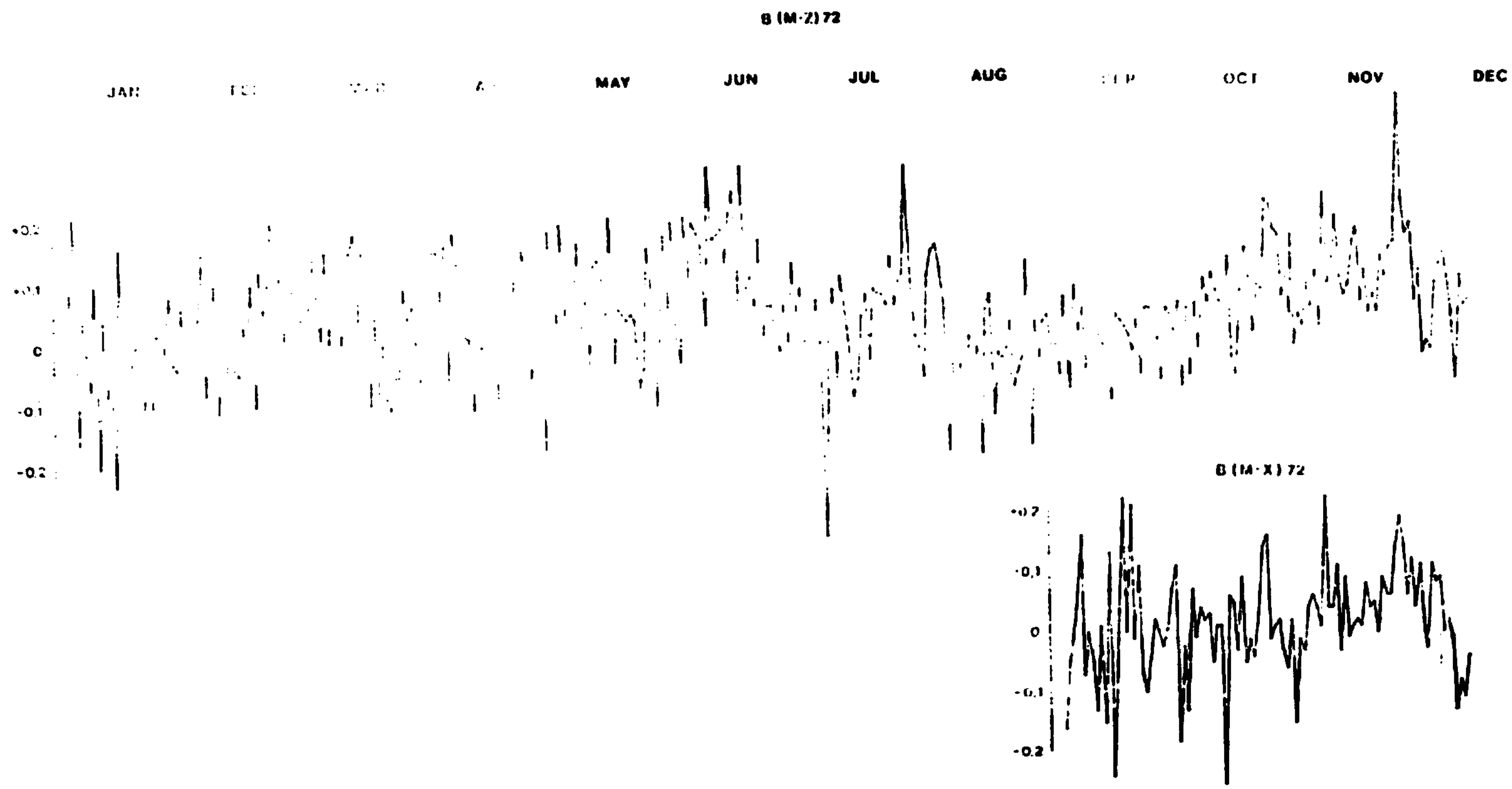

Figure 5. Plot of the daily relative frequency rate of (M - X) and (M - Z) Loran-C stations.

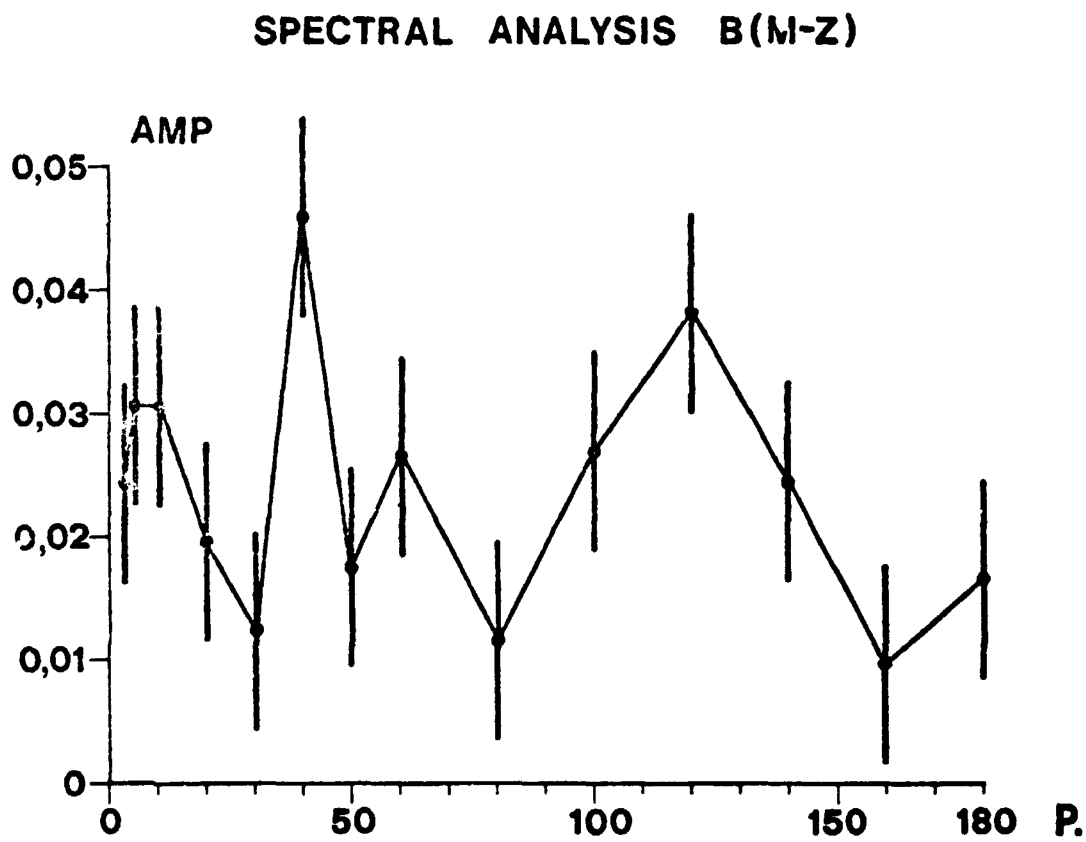

Figure 6. Spectral Analysis of the daily relative frequency rates B (M - Z) versus period in days.

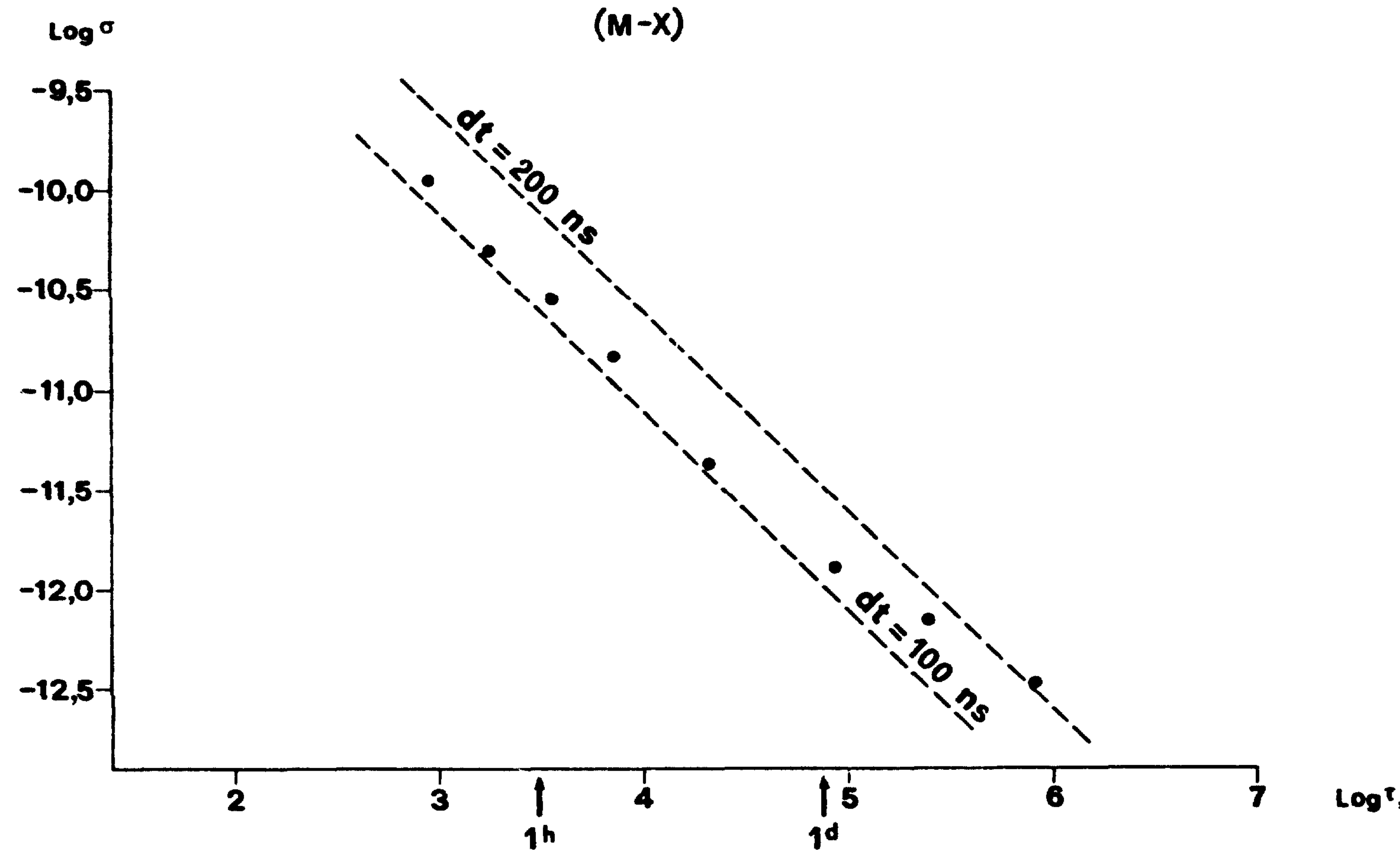

Figure 7. Spectra capabilities of Loran-C relative comparisons between Master Station and X slave station (Lampedusa). Plot of the square root of the variance of $\sigma_y(\tau)$ of the frequency variations. The dashed lines indicate the noise limits for theoretical time stabilities of 100 and 200 nsec based on the assumption of "white phase noise".

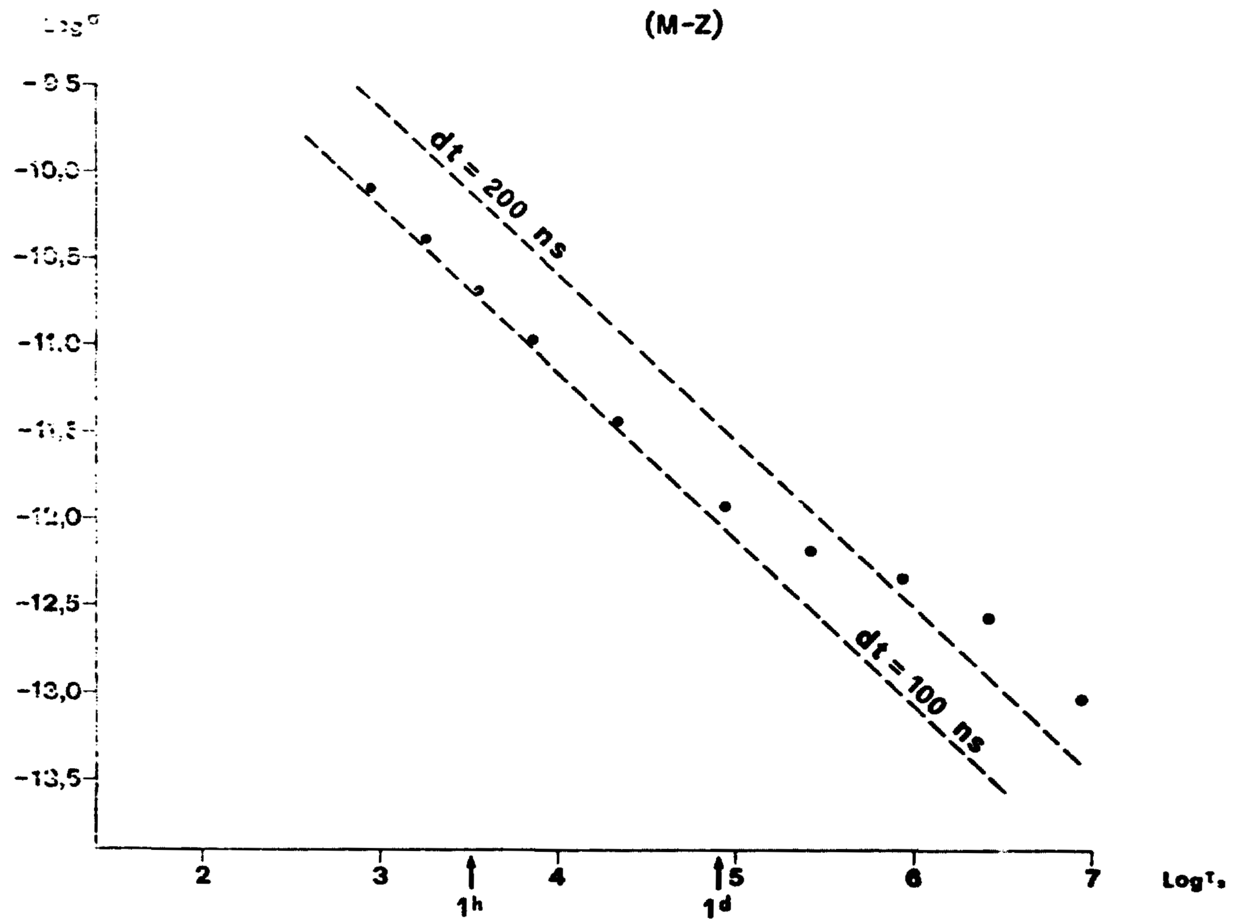

Figure 8. Spectral capabilities of Loran-C relative comparisons between Master Station and Z slave station (Estartit). Plot of the square root of the variance $\sigma_y(\tau)$ of the frequency fluctuations. The dashed lines indicate the noise limits for theoretical time stabilities of 100 and 200 nsec based on the assumption of "white phase noise".

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AN AERONAUTICAL BEACON SYSTEM USING PRECISE TIME

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ABSTRACT

An experimental system using precise time techniques is presently under construction and will be tested in 1974. It will provide accurate surveillance data to the ground based ATC sensors, high capacity data link ground-to-air and air-to-ground, navigation services and air-to-air collision avoidance and proximity warning service. The design takes into account the large disparity in electronic equipment among the various classes of users. The user of the airspace installs only that equipment required for the services he needs.

BACKGROUND

The aircraft using the civil airspace of the United States may be divided roughly into 2600 air-carrier aircraft, 140,000 general aviation aircraft and 20,000 military aircraft. The general aviation aircraft range from very well equipped Gulfstream II and Learjet corporate aircraft down to very small general aviation aircraft with almost no electronic equipment. However, the vast majority of the general aviation fleet is comprised of single engine aircraft of 300 Horsepower or under with an electrical system and a fair market value of perhaps $10,000. The military fleet also ranges from superbly equipped C-5A's and C-141's down to primary and basic trainers which are not really equipped to venture into civil airspace and do not do so.

The problem facing the FAA is that of implementing and operating a system that gives this wide spectrum of users the services they require at a price they are willing and able to pay. An air carrier turbojet costs between $5 million and $25 million to buy and between $500 and $2,000 an hour to operate. A typical general aviation aircraft, as noted above, is worth $10,000 and costs $20 - $30 per hour to operate. Within reason, the cost of avionics is not important to the air carrier so long as it reduces delay and/or increases safety. Delay is not particularly important to the typical general aviation operator but cost, both initial and maintenance, is very important.

The present civil air traffic control system is based on the Air Traffic Control Radar Beacon System (ATCRBS). This system is essentially identical to the military IFR system except that FAA interrogators do not transmit any of the cryptographic messages used by the military. The ATCRBS is based on World War II technology and is beginning to reveal shortcomings as more and more aircraft are equipped with transponders and begin to use the airspace. Many of these difficulties arise from the fact that all aircraft which receive a valid interrogation answer it. This causes interfence or, in FAA jargon "fruit and garble." The interference becomes worst when aircraft are flying close together which, of course, is just when high quality surveillance data are required.

There are other factors which influence the choice of a system. The present air traffic control system is very costly to operate because it is very labor intensive, meaning that there are many controllers watching traffic displays and issuing control instructions and advisories via VHF or UHF voice radio. It would be very desirable to use computers to aid the controllers in their tasks. If the computers are to provide a useful service that increases safety they will have to be able to communicate with the aircraft directly and send short digitally encoded messages. This, of course, implies a data link both ground-to-air and air-to-ground. The air-to-ground link is nessary to verify that the correct message was received in the aircraft as well as for the pilot to send simple messages such as "emergency" and "radio failure."

Navigation in the civil airspace is based upon the Very High-Frequency Omnirange (VOR) and Distance Measuring Equipment (DME). The DME is essentially identical to the military TACAN except that civil DME equipment reads out only range and/or range rate to the selected station instead of the range and bearing read out by a military TACAN set. The FAA installs both VOR and TACAN at most navigational fixes. Such an installation is called a VORTAC and provides service to civil and military users. Carriage of DME equipment is mandatory now for flight above 24,000 feet and this level will probably come down in the near future. Further, a larger percentage of the general aviation pilots are beginning to fly under Instrument Flight Rules (IFR) and find DME a convenience. Much like the ATCRBS, as more and more aircraft are equipped with DME the ground portion of the system begins to saturate. The actual saturation point depends upon the pulse repetition frequency of the airborne equipment but a typical number for today's system is that around 100 aircraft interrogating a given VORTAC begin to degrade its performance. It is reasonably clear that this could become a serious problem in busy airspace such as the Los Angeles Basin or anywhere in the corridor from Washington, D.C., to Boston. Another problem with the DME system is cost. The least expensive airborne DME is $1500. Air carrier sets run well above $10,000.

Yet another facet of the problem facing the FAA is the real possibility that an air-to-air collision avoidance or proximity warning system will be made mandatory by Congress. There are bills in both the Senate and the House directing the FAA to select such systems and require their installation and use in all aircraft; air carrier, military and general aviation. The systems presently being proposed are expensive and complex and would impose yet more maintenance problems on aircraft operators. This rather lengthy statement of the FAA problem of selecting a design can thus be summarized as follows:

a. A new surveillance system is needed which is more accurate and reliable and does not exhibit interference problems as the density of traffic builds up.

b. A reliable, high capacity digital data link is needed which will permit increased use of automation to reduce controller workload and also to increase safety.

c. A non-saturable DME is needed as more operators use this service.

d. An air-derived collision avoidance and/or proximity warning system will probably be made mandatory by Congress.

e. The cost must be kept as low as possible so that general aviation operators can afford to participate in the system.

PROPOSED SOLUTION — GENERAL REMARKS

It should be no surprise that a paper prepared for a Precise Time and Time Interval Planning Conference should propose a solution which is based upon the powerful properties of a system using precise time. As will be seen below, the system is carefully tailored to meet the cost constraint. The precise timekeeping is done by the ground-based system. Thus the basic general aviation transponder is essentially the same as a present ATCRBS transponder and only speaks when spoken to. The more sophisticated users of the airspace would install more complex avionics if they desired the DME and the collision avoidance or proximity warning service. An aircraft with this equipment would receive and process signals with only the basic transponder.

The FAA is already well underway to solving the improved surveillance and data link problems. It appears that most of the difficulties with the present ATCRBS system can be overcome by a discretely addressed beacon system wherein each ircraft responds only when interrogated with its unique digital identity. This technique would reduce the number of interrogations per aircraft by a factor of at least 10, would eliminate synchronous garble, and would also permit the transmission of shourt digital messages to each aircraft. These messages would be encoded as part of the discretely addressed interrogation and only the addressed aircraft would decode the message and display its contents to the pilot. A discrete-address beacon system (DABS) is presently being developed by the FAA.

Historically, the FAA and the aviation community at large have been slow to implement new ground or airborne systems. It can be anticipated that DABS will be implemented slowly, beginning at a few large airports. Thus it will be difficult to convince the aviation community to purchase and install DABS transponders unless these transponders would also perform the ATCRBS function in outlying areas that were not yet DABS-equipped. The ATCRBS is widely installed in aircraft and protected by treaties; hence, ATCRBS equipped aircraft will have to be serviced for a long period in the future. Thus it appears that any new DABS ground installations must be compatible with ATCRBS transponders, and new DABS transponders must function in the ATCRBS mode when flown in areas not yet converted to DABS. In addition, it is desired to keep the transponder design as simple and inexpensive as possible in order to not impose an unnecessary financial burden on the owners and operators of the 135,000 general aviation aircraft in the present U.S. civil fleet. The dual constraints of compatibility with the ATCRBS system and low cost imply strongly that the DABS system should use the same frequencies as the ATCRBS; viz., 1030 MHz for interrogation and 1090 MHz for aircraft response.

The present ATCRBS interrogation of aircraft is relatively undisciplined. Care is taken to adjust the pulse repetition frequencies (PRF) of neighboring interrogators so that they are different, assuring that the condition known as "synchronous fruit" will be only momentary. Other features such as sidelobe suppression and reply-rate limiting are included in the ATCRBS to reduce interference. Nevertheless, many of the present problems of the ATCRBS are due to the lack of discipline in the ground-based system.

The DABS concept envisions sending digital data from the ground to the aircraft and from the aircraft to the ground. It is clear that the addition of a DABS to the present ATCRBS system without imposing some form of discipline on the interrogation scheduling would have an adverse effect on the ATCRBS system and also provide a low message reliability in DABS unless design techniques employing different modulation and error detecting or error detecting coding were employed. These techniques would add to the cost of the transponder and do little to solve the present ATCRBS problems.

PROPOSED SOLUTION — SPECIFIC CONCEPT

One of the concepts being examined by the FAA has a name derived from synchronized discrete address beacon system, SYNCHRO-DABS. The basic concept is straightforward. The ground-based system adjusts the timing of the transmission of an interrogation such that it reaches the particular aircraft addressed; it is received and decoded; and the aircraft begins its response at selected periodic intervals. The effect is as if the aircraft carried on board a cesium or rebidium clock of great precision. It is thus possible to use some of the powerful techniques associated with common precision timing without requiring complex airborne equipment.

Figure 1 shows one form of the possible overall timing of the system. A precision 400 Hz PRF is chosen. Each 2500 μs pulse repetition period (PRP) may be thought of as beginning with a "time-zero" timing pulse.

Consider each 2500 μs PRP to be divided into four 625 μs segments of time. The segment just before time zero is used to send out discretely-addressed ground interrogations; the segment after time zero is used to receive the response elicited from the aircraft, which were discretely addressed. (Rather than impose periodicity on the ground transmissions of the interrogations, the system imposes periodicity when an aircraft received the interrogations.) The remaining two segments are used for transmitting ATCRBS interrogations and receiving ATCRBS replies. The time of transmission of the ATCRBS interrogation is shown dotted to indicate that the time of transmission is jittered at each site to preclude neighboring sites from having the same instantaneous PRF and causing the phenomenon known as synchronous fruit. This is necessary because, unlike the present ATCRBS system, all sites have exactly the same average PRF in the SYNCHRO-DABS system.

Figure 2 shows in more detail the activity during the time devoted to the SYNCHRO-DABS function. Assume that four aircraft, whose ranges are precisely known to the ground system, are to be interrogated during the particular PRP shown. Aircraft 1 is the farthest away; aircraft 4 is the nearest. The discrete interrogations are transmitted in the order shown with timing such that they reach the aircraft, are decoded, and each aircraft begins its response at time zero. These responses are received at the ground in the inverse order to that with which they had been transmitted. It is clearly necessary, when deciding which aircraft to interrogate during a single PRP, to choose aircraft whose ranges from the interrogator differ by more that the message length times the velocity of light, in this case approximately 5 nmi. The time separation of the DABS and ATCRBS functions thus eliminates interference between these two modes at least as far as the one ground site is concerned.

Next, assume that all ground sites are similarly synchronized in time and, further, that the airport surveillance radars (ASR) with a nominal rotation period of 4 s are also synchronized in azimuth as indicated in Figure 3. The dotted lines indicate the area over which each site performs its surveillance function. Except when handing off an aircraft from one site to another and when a facility fails and neighboring facilities must pick up the load, each interrogator would only address aircraft within its assigned area. The combined effects of synchronizing both time and azimuth angle will reduce interference between adjacent sites to a minimal level. Any garbled replies that might still occur would be resolved by reinterrogation. The scheduling of interrogations as depicted in Figure 1 will give a non-ambiguous radar range of 104 nmi. The FAA also operates air route surveillance radars (ARSR) that have a requirement for 200 nmi range and typically have a rotation period of 15 s. These facilities would require back-to-back antennas, one doing ATCRBS full time and one doing DABS full time. The timing of the interrogations would be synchronized as in the case of the ASR's and any garbled replies would be resolved by reinterrogation.

The format of the possible DABS interrogation transmission is as shown in Figure 4. Interrogation is conducted at 1030 MHz (as in the present ATCRBS system), is amplitude modulated, and at a nominal 500 W level. The coding is based on 0.25 μs b widths. FR_1 and FR_2 are 3 b pulses that serve the functions of suppressing the ATCRBS transponders receiving the signal and also of providing level setting and bit synchronizing signals to the DABS decoding circuitry. The identity block contains 24 b that permit upwards of 4,000,000 discrete addresses. The next 5 b are "housekeeping bits" and their individual functions will be decribed shortly. The following 5 b are used for messages type and allow for up to 32 different message types. The next 42 b are for message. (The number 42 allows for transmission of seven alphanumeric characters per interrogation using a truncated ASCII code of 6 b/character.) This is followed by a 3 b framing pulse FR_3.

Figure 5 shows the aircraft response to a discrete interrogation. The reply begins 3 μs after the leading edge of FR_3, to be consistent with present ATCRBS practice. The aircraft transmits at 1090 MHz and repeats the interrogation exactly as received and decoded except for the change in carrier frequency from 1030 to 1090 MHz. After repeating the interrogation, the aircraft can add on 7 b of aircraft-generated message, 11 b encoding the aircraft barometric altitude, and a final framing pulse. The error checking thus is done by the ground-based system and if the response does not match exactly the interrogation that was sent, the aircraft is reinterrogated.

A design goal is to make aircraft entry into the system automatic without adding to either the pilot or controller workload. A "general-call" signal format is shown in Figure 6. The 24 identity bits are all set at "1" and the message type indicates that this is a general call. Any aircraft that had not been discretely addressed within the last 20 s would respond to this general call and would insert its own identify in the identity block in place of the 24 ones. It would also add its altitude bits. The interrogator would add this identity and postion into the memory of the ground system and begin to interrogate the aircraft discretely. The aircraft would no longer respond to the general call.

A method of resolving garbles in replies to general calls would also be needed when, for instance, one surveillance site suffered a failure and an adjacent site was instructed to pick up the load. If a site detected a garbled reply to a general call, it would revert to a semidiscrete interrogation mode whereby it would begin setting some of the 24 ones to zero in the identity block. Those aircraft, which had ones in the corresponding position of their own identity, would not answer this general call.

In the system described above, each DABS-transponder-equipped aircraft flying in airspace covered by the ground-based interrogator will periodically transmit, at a precisely defined time, its identity and altitude. Any aircraft operator who desired a collision avoidance system based on air-derived data could install a 1090 MHz receiver in this aircraft. Each aircraft is ground-synchronized whenever it is interrogated, and it is then possible to install a crystal-stabilized oscillator to maintain synchronization and predict the times of occurrence of time zero in the interval between interrogations. An aircraft that listens at 1090 MHz and also has such a crystal-stabilized clock can then compute the range of other aircraft based upon the time of arrival of their signals. Further, the receiving aircraft can compare the present range of another aircraft with its range measured at a prior response and calculate range rate. The altitude of the other aircraft is also known because it is encoded in its transmission. An aircraft receiving these signals thus derives the range, range rate, and altitude of other aircraft around it and makes determinations as to which, if any, of these aircraft constitute a threat.

It is also feasible to install a small direction-finding antenna on the listening aircraft so that the relative bearing of each nearby aircraft can be displayed to the pilot. Figure 7 shows such an antenna, which is now being tested for this purpose at 1090 MHz. Figure 8 shows the antenna on a light aircraft.

The proximity warning or collision avoidance system described in the preceding paragraph has shortcomings in that it fails if the ground-based system fails, and it only functions in that airspace that has radar coverage. Present planning is that an automated ground-based collision-avoidance service using the DABS data link to send ground-calculated collision-avoidance messages will also be available wherever adequate radar coverage exists. The SYNCHRO-DABS concept can eliminate this shortcoming by putting simple "gap-filler" interrogators and data-processing equipment at very high frequency omnirange (VOR) stations of which there are almost 1000 covering the U. S. These interrogators would have fixed antennas with omnidirectional azimuth coverage. The primary function of these stations would be to send out discrete interrogations to keep DABS-equipped aircraft transmitting and properly sychronized. This is possible since azimuth does not enter into the timing adjustment for airborne synchronization. No use would be made of the range data on the ground nor would air traffic control messages be sent on the data-link channel. An aircraft equipped with the 1090 MHz receiver could now get an independent air-derived collision-avoidance separation service from all transponder equipped aircraft as long as it flew in airspace within line of sight of a VOR (which takes in most of the usable airspace).

The interrogations transmitted by these facilities placed at VOR sites and the responses elicited from aircraft would not interfere with the operation of the DABS facility that was performing a surveillance function for ATC purposes. As an example, consider a VOR site located in a valley 50 mi from a DABS site. The VOR site would use only, for instance, every 1/10 or 1/20 PRP of the 400/s available. The DABS site computer would be programmed to not use those PRP's while working the airspace over the valley in which the VOR was located. Neighboring VOR's would be assigned different PRP's to avoid interference. The interrogators at the VOR sites could also provide the synchronizing service in an area served by a DABS site if the DABS site failed and there were either no neighboring DABS sites to pick up the load or the neighboring DABS site also failed.

The requirement for, and use of, the housekeeping bits shown in Figure 4 can now be discussed. It is desired that the DABS sites, i. e., those using the responses for surveillance inputs to the ATC system, should take precedence over the VOR sites. The DABS bit in the discretely addressed interrogation and in the general call interrogation means that these signals are transmitted by a DABS facility rather than a VOR facility. A transponder being interrogated discretely by a VOR facility would still respond to a DABS general call and be acquired automatically by the DABS. After being interrogated discretely by the DABS, it would no longer answer the VOR, and the VOR would drop the track after a few tries. Similarly, an aircraft flying from airspace covered by a DABS into airspace covered only by a VOR would cease to receive the DABS interrogations and would answer the VOR general call automatically and be picked up and tracked in range by the VOR.

The synchronized bit in the interrogation also requires some explanation. The 4 s rotation period of the ASR antenna and the 10 s period of the ARSR indicate that any tracking and prediction system will have at least 4 s between data samples.

This will not allow the prediction of range with an accuracy such that the timing of the aircraft response will be within some nominal error, such as 100 ns. In addition, the azimuthal estimation on the ground is to be done by monopulse techniques. The interrogator antenna beam shape changes with elevation angle so that it appears prudent to get a target response on each side of the monopulse difference null and perform interpolation to estimate the azimuth. The SYNCHRO-DABS will send two interrogations per scan. The first interrogation will not have the synchronized bit set and will be used to obtain true present range to the aircraft. The second interrogation occurs a few PRP's later and on the other side of the antenna null and will be a properly timed interrogation with the synchronized bit set at one. The aircraft that carried clocks would use this interrogation to reset their clocks. Each aircraft retransmits the interrogation as received, including the synchronized bit. Aircraft that were equipped to receive at 1090 MHz would only process those signals from other aircraft which had the synchronized bit set.

OTHER FUNCTIONS

The availability of precise time makes it possible to offer other services to the aircraft operator at a very modest increase in cost and complexity of the airborne equipment. The signal shown in Figure 9 would be broadcast ten times per second at zero time 1030 MHz from the omnidirectional antennas located at the VOR sites. The identity is the identity of that particular navigational fix; the message type indicates it as a VOR navigational signal; the message contains the latitude and longitude of the VOR to a precision of 100 ft; and the altitude is the altitude of the VOR. The identity code of the VOR would be published in the various aeronautical navigation documents and also keyed to the VOR VHF frequency in a manner similar to the present practice with distance-measuring equipment (DME). The pilot of an aircraft that had this feature installed would simply select, with thumb-wheel switches, the identity of the fix of which he wished to know the distance and the transponder would decode that signal and display the range based upon time of arrival of this signal after zero time. The identity could also be selected automatically by simply tuning the VOR receiver, exactly as in present practice.

A more sophisticated aircraft could receive and process signals from several VOR facilities and compute its position by triangulation. The pilot of this more sophisticated aircraft does not have to manually enter the location of the fix because this information is contained in the received signal. The computer in the aircraft would select those three locations that gave the best geometry and compute position and course including altitude correction. Thus a precise area navigation function would be provided wherever reception of signals from two or three VOR facilities was available.

PILOT'S DISPLAY

The information sent from the ground or derived in the transponder from receipt of other signals must be displayed to the pilot in a clear and unambiguous manner such that it does not add to his workload. The displays shown here represent only one possible implementation. Presumably, any other suitable display that a manufacturer offered for sale and an owner wanted to buy would be satisfactory. (The SYNCHRO-DABS transponder would be available in several levels of performance and cost.) Figure 10 shows the proposed display for the minimum-level transponder. This transponder would respond to ATCRBS interrogations if not being discretely addressed and would decode collision-avoidance messages from the ground-based system. The array of lights on the periphery indicates the relative bearing and relative altitude of nearby aircraft as perceived and relayed-up by the ground-based system. There are 12 azimuthal positions corresponding to the presently used "o-clock" system. Each azimuthal position has three relative altitude lights. The middle light indicates traffic within 500 ft. of own altitude, the upper light indicates traffic 500-2000 ft. above, and the lower light indicates traffic 500-2000 ft. below. These lights would be energized when nonthreatening traffic was within, say 1.5 mi of a low-speed aircraft. If the range rate of the traffic was such that it could cause a collision within 30 s, the appropriate light would be flashed. Just as the outer lights indicate the position of traffic, the inner lights indicate recommended action. The pilot can be told to either DO or DON'T DO certain maneuevers. The DON'T DO crosses are in red and the DO arrows are in green. In the general case when a maneuver command is given to a VFR aircraft, two choices will be given whenever possible. This is done so as not to vector the pilot into a cloud in order to avoid a collision. In the example shown, the pilot is told to turn right (standard rate turn) but that a dive maneuver is acceptable if a right turn is not desirable. The command indicator lights will be flashed if the command is from the ground and is mandatory. They will be simply turned on if the command is advisory or an acceptable alternative to a mandatory command. Each maneuver (climb, dive, left, right) can have either a green arrow or a red cross displayed.

Figure 11 shows a display that combines the collision-avoidance messages and ATC vectoring and frequency information on a single 3-1/8-in instrument. Any ATC messages would be displayed by flashing the numerals until the pilot pushed the WILCO button to acknowledge that he had received and would follow the instructions. Other possible displays would include alphanumeric readouts that could also display short clearances. It is expected that the ATC system of the future will be highly automated and that those aircraft with the ATC data link display could file for better routing and get better service. In a few of the major terminals, viz., New York, it will probably be necessary for an aircraft to have such a display for using the major airport facilities.

The aircraft owner who purchases a DABS transponder with a synchronized clock would also be provided with the DME service or, as an alternative, area navigation. The owner who purchased the updated clock and the 1090 MHz receiver plus direction-finding antenna would also have displayed the location of all nearby transponder-equipped traffic and those aircraft that constitute a possible threat. This information would be displayed on the same instrument as the information from the ground-based system. However, the service would be available in airspace not covered by the surveillance system and would also be available if the ground-based collision-avoidance function failed. (There would be a hiatus lasting for a few seconds after the ground-based system failed and while the VOR's pick up the interrogation load.)

MODULATION AND CODING

Amplitude modulation with nonreturn-to-zero format is shown for SYNCHRO-DABS because of the constraints of compatibility with the present ATCRBS system and low cost. It is clear that any of the constant-envelope phase-modulation schemes (PSK, DPSK, FSK, Quadriphase, etc.) would give 6-8 db better performance in the presence of receiver noise or random interfering signals. However, the signal-to-thermal-noise ratio will generally be in excess of 20 db, the discipline of interrogations should reduce the incidence of interfering signals to a minimal level, and the reinterrogation procedure will resolve remaining problems. Further, interference, if it occurs, can be over a 40 db dynamic range with respect to the desired signal so that it is not at all clear that the added cost of the 6-8 db improvement of a constant envelope system would be justified. It can also be shown, with reasonable assumptions, that the signal-to-noise ratio of the signals used for monopulse azimuth estimation would be approximately 20 db higher for a constant envelope system than for an amplitude-modulated system (more energy, coherent detection). However, it appears that the azimuthal estimation errors due to thermal noise in a system using amplitude modulation will be smaller than errors caused by antenna imperfections and possible multipath effects. The same general arguments apply to the decision to not include error-detecting or error-correcting codes. These codes increase cost and reduce capacity. In the case of error detection, the transponder would simply not reply and would be reinterrogated. In the absence of an error-detecting system, the interrogator would receive a reply different from the interrogation that was transmitted and would reinterrogate. The effect is the same in either case. Simply coding on urgent messages, such as collision-avoidance maneuver messages, is being considered. This coding would consist of repeating the message twice during the 42 b message block and designing the transponder logic circuitry so that it required both message segments to match before energizing the display.

PROGRAM STATUS

The FAA is sponsoring the construction of the experimental SYNCHRO-DABS system described above. The Naval Weapons Center, China Lake, California, will provide three sets of airborne equipment and the DOT Transportation Systems Center at Cambridge, Massachusetts, is fabricating an omni-directional interrogator which will also transmit navigational signals as described above. Testing of this system will be conducted at our National Aviation Facility Experimental Center near Atlantic City and will begin in the spring of 1974. The testing will explore the accuracy and convenience of the air-to-air mode and the accuracy of the DME function.

A few points about the evolving design may be of interest. It is desired to keep cost as low as possible. Thus the use of a cesium, rubidium or methane clock in the aircraft is out of the question. The clock will use a quartz crystal controlled oscillator which must be within 10 ppm of the nominal freguency. Such an oscillator does not need to be in an oven and can use a $1.50 crystal. Simple digital counter circuitry then adds or substracts pulses such that the clock error is never more than 50 nano-seconds, assuming that a synchronizing signal is received at least every 15 seconds from the ground-based system. The displays being procured use light emitting diodes for the traffic warning lights and incadescent bulbs for the "DO" and "DON'T" commands and for the digital indicators. These displays are expensive and consume a lot of power. The newly emerging liquid crystal technology appears to offer an attractive, reliable and low-cost alternative for such displays and experimental units are being procured for test.

SUMMARY

The SYNCHRO-DABS provides a method of introducing the DABS function into the ATC system so that it is completely compatible with the ATCRBS. It also provides additional navigation and collision-avoidance services to those operators who desire it. A key point is that the location of all aircraft with the basic minimum DABS transponder can be displayed to the pilot of any aircraft that has the optional air-derived collision-avoidance equipment.

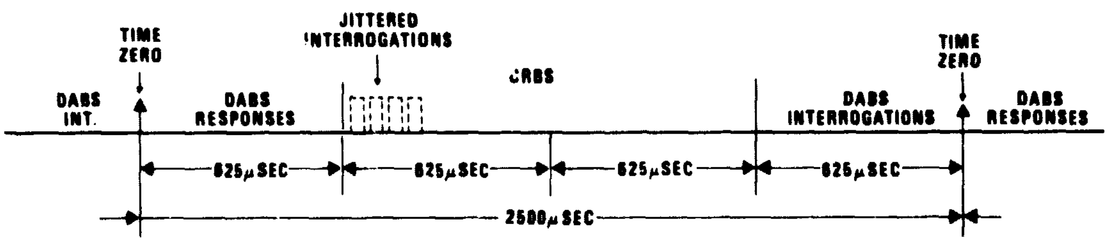


Figure 1. Division of Time Between Functions at Ground Station

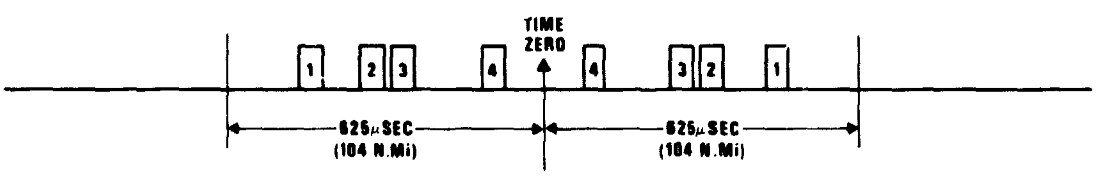


Figure 2. SYNCHRO-DABS Interrogation Timing

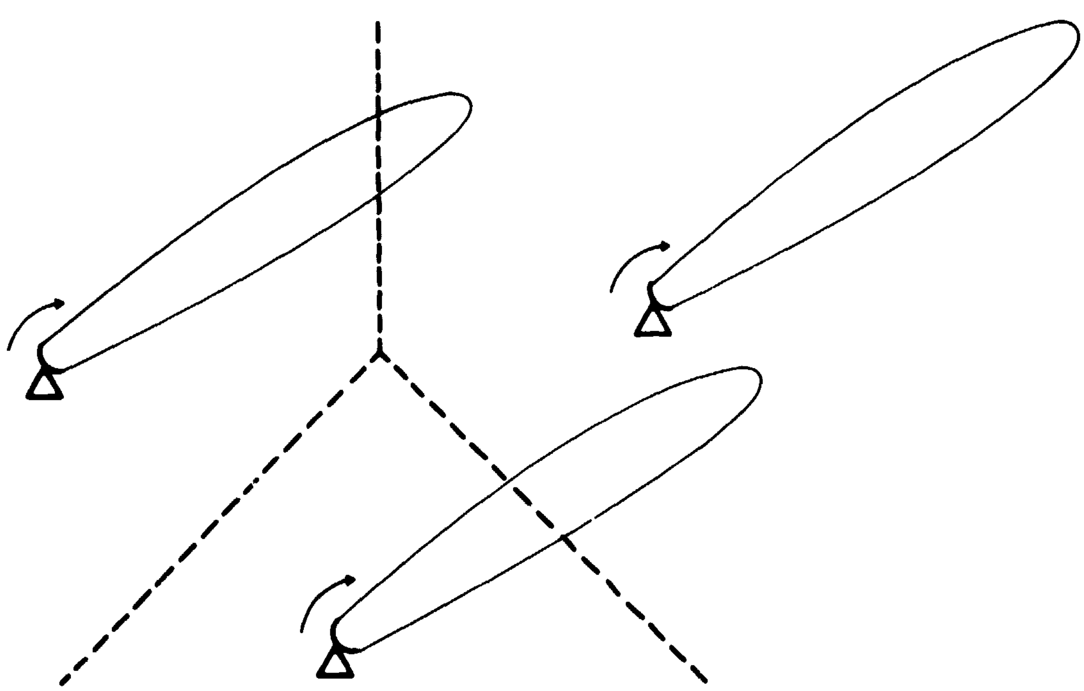


Figure 3. Distribution of DABS Sites

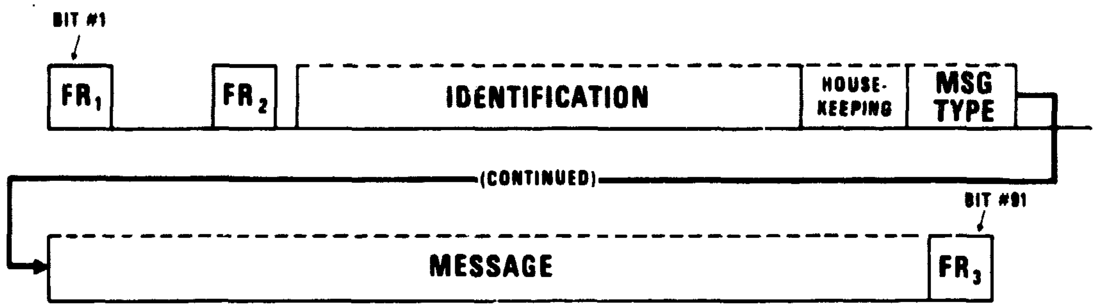


Figure 4. SYNCHRO-DABS Interrogation

Note: 91 Contiguous Bits, Each 0.25 μsec Long (23.75 μsec Total Length), 1030MHz, Non-Return to Zero Amplitude Modulation, Housekeeping Bits Are: (1) Synchronized (2) DABS (3) Lock-In (4) PCA (5) IPC

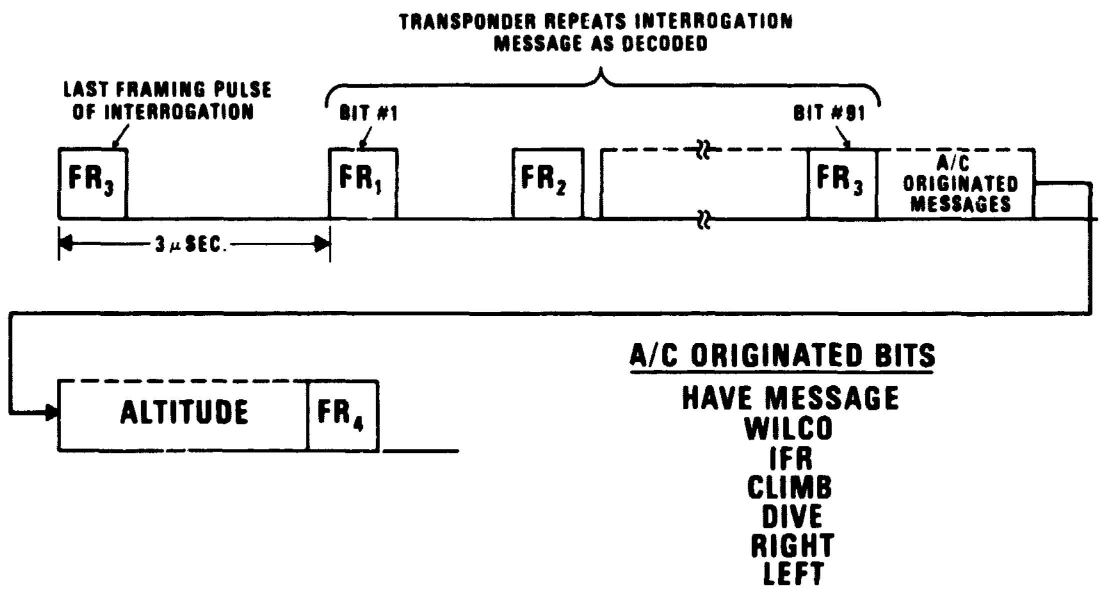


Figure 5. Aircraft Response to DABS Interrogation

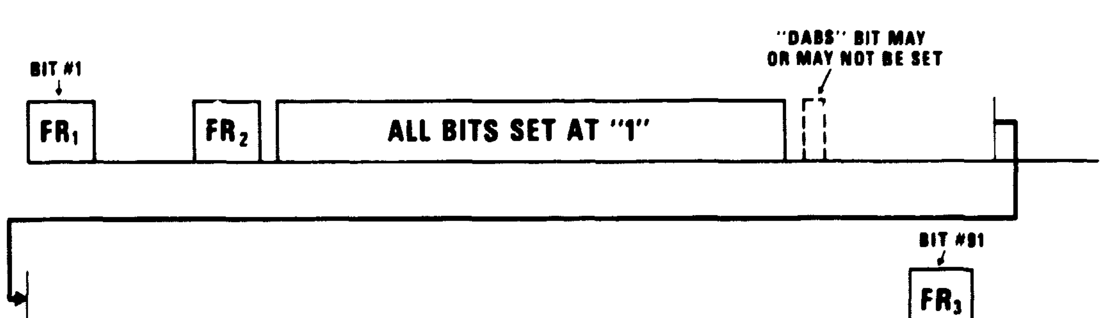


Figure 6. General Call Message Format

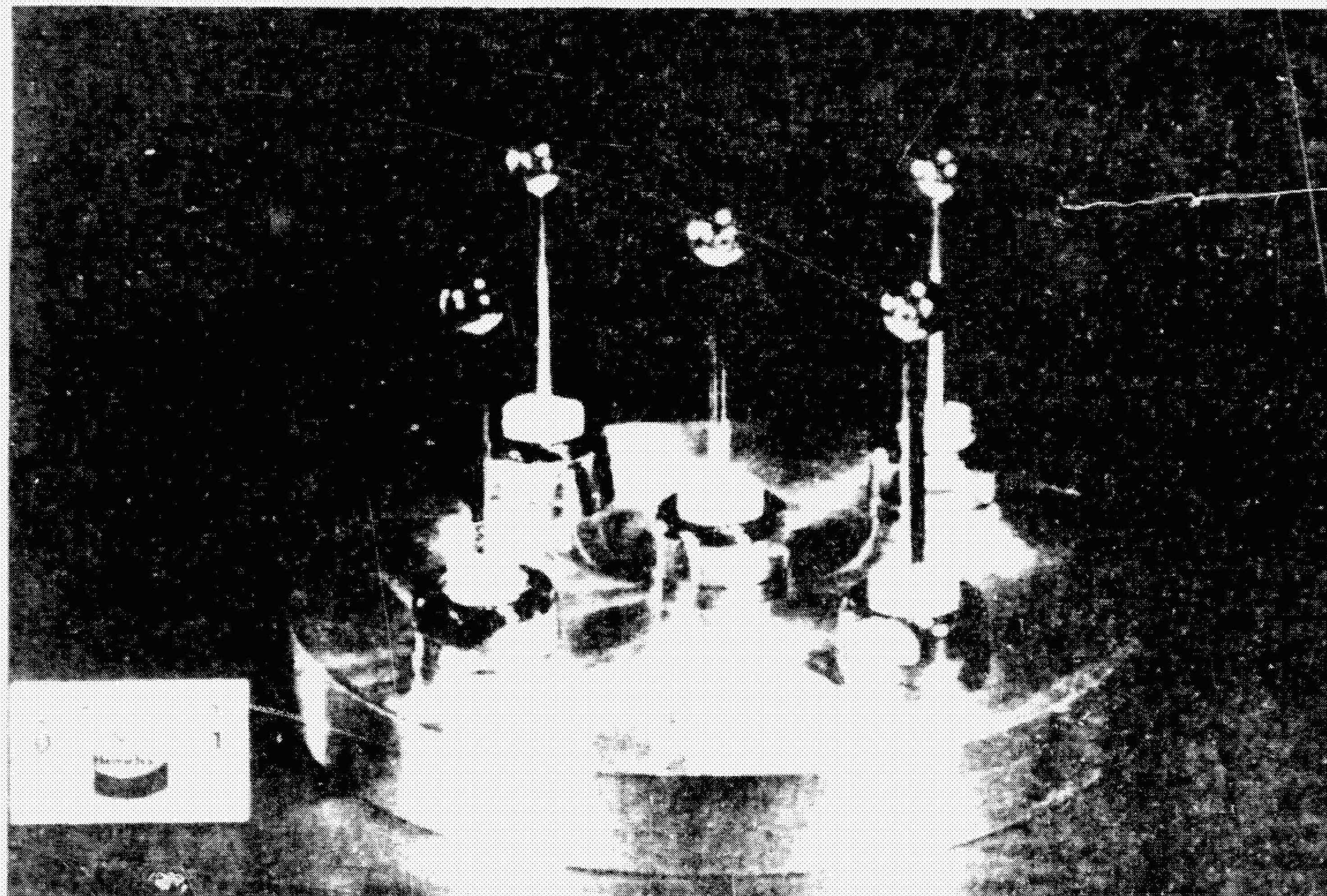


Figure 7. Phase-Sensitive Direction Finding Antenna

Figure 8. Direction-Finding Antenna Mounted on Light Aircraft

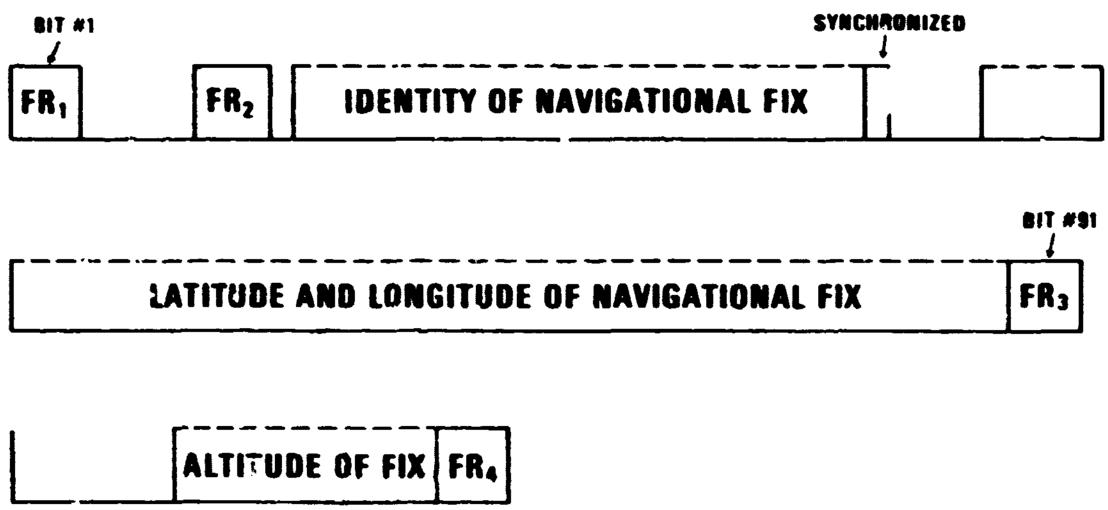


Figure 9. Navigation Signal Broadcast by Ground Stations

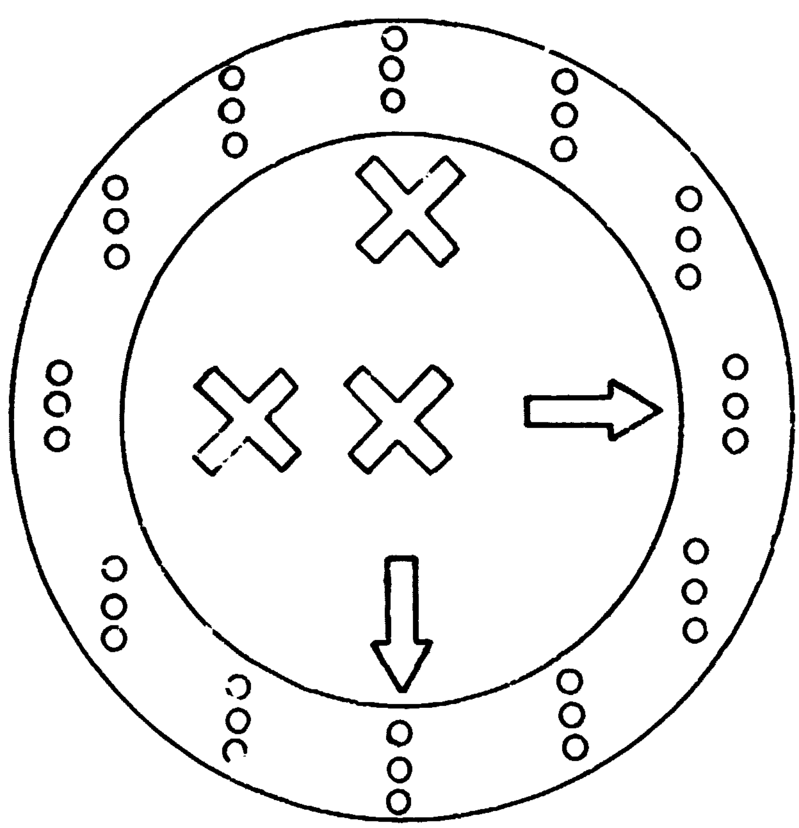


Figure 10. IPC and PWI Indicator

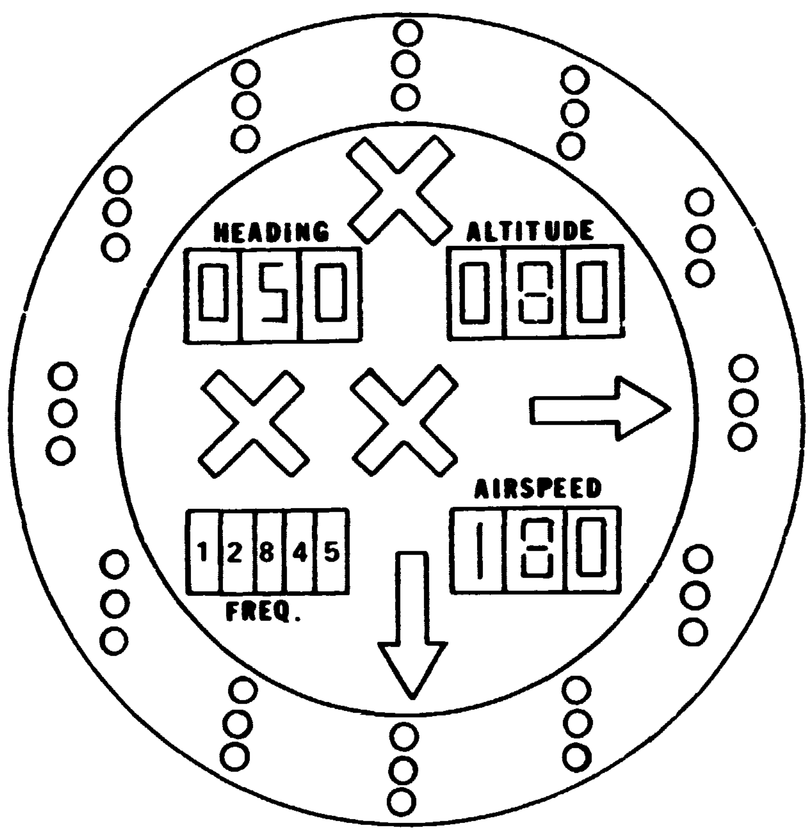


Figure 11. Display of IPC, PWI, and ATC Messages

QUESTION AND ANSWER PERIOD

DR. REDER:

Does anybody have any questions of Mr. Amlie's paper?

MR. MOHR (McDonnell-Douglas):

I didn't really understand how you got the airplane synchronized with the ground station. Maybe you didn't go into it or maybe I missed it.

MR. AMLIE:

The ground station knows the range of the aircraft, and transmits — backs off the time of interrogation so that the interrogation is received at the aircraft at zero time. The ground does the timing.

MR. MOHR:

Thank you.

DR. REDER:

Any other questions? Yes, please, Dr. Henderson.

DR. HENDERSON:

My question is very simple.

Have you any references to present publications which describe your system?

MR. AMLIE:

As a matter of fact, I have a briefcase full of IEEE articles I wrote.

DR. HENDERSON:

I will see you later.

DR. REDER:

Any other questions?

(No response.)

CLOCK SYNCHRONIZATION EXPERIMENTS USING OMEGA TRANSMISSIONS

A. R. Chi
S. C. Wardrip
NASA/Goddard Space Flight Center

ABSTRACT

The OMEGA transmissions from North Dakota on 13.10 and 12.85 kHz were monitored at several sites using a recently developed OMEGA timing receiver specifically designed for this purpose. The experiments were conducted at Goddard Space Flight Center (GSFC), Greenbelt, Maryland; U.S. Naval Observatory (USNO), Washington, D.C.; and at the NASA tracking station, Rosman, North Carolina.

Results show that cycle identification of the two carrier frequencies was made at each test site, thus, coarse time (76 microseconds) from the OMEGA transmitted signals to within the ambiguity period of each OMEGA frequency was extracted. The fine time determination, which was extracted from the phase difference between the received OMEGA signals and locally generated signals, was about ±2 microseconds for daytime reception and about ±5 microseconds for nighttime reception.

INTRODUCTION

Very low frequency (VLF) transmissions, which are phase controlled at the transmitter relative to a time scale such as UTC, have been successfully used for many years with relative ease for frequency control of precision oscillators. This is realized due to the inherent stability characteristics of the D-layer of the ionosphere, for propagating VLF signals. The utilization of VLF signals for synchronization of a clock, however, requires the continual phase count of the received signal relative to an oscillator which drives the clock at the receiver site. This requirement restricts the use of VLF transmissions for precise clock synchronization due to phase discontinuities or phase perturbations such as Sudden Ionospheric Disturbances (SID's). Additionally, the diurnal phase changes, which are on the order of 180°, can also introduce phase discontinuities at sunrise or sunset due to modal interferences on certain propagation paths. All these phase interruptions must be accounted for if VLF transmissions are to be used for clock synchronization.

A technique has been developed which is independent of phase perturbations or SID's. It is by the use of two unique OMEGA signals whose frequencies are closely spaced and whose phase stabilities are rigidly controlled at the transmitter with respect to a master clock. By measuring the relative phase difference of the two received signals, which is a function of the propagation path length, the integer cycle of a carrier signal for a given path length can be determined. The product of the period of the frequency of a carrier signal and the determined carrier cycle by the receiver gives the propagation delay to the nearest period integer. The remaining fraction of a period is obtained by measuring the phase differences or time interval between the coincident positive zero crossings of the received signals and the coincident positive zero crossings of locally generated signals. Thus, the two step approach using the dual frequency technique is independent of perturbations due to SID's and provides an accurate means for clock synchronization with a precision related to the phase stability of the propagated VLF signals.

Description of the Dual VLF Technique

The use of dual VLF signals for clock synchronization is not new; however, the use of OMEGA transmissions for clock synchronization is unique. The emitted VLF signals from OMEGA stations are synchronized to a time scale with reference to UTC of January 1972. Each signal after propagation over a certain path length, experiences a delay of T_p and exhibits a phase change of $n_i \phi_i + \Delta\phi_i$. It is this phase difference between the two transmitted signals that permits the establishment of the time epoch. Ideally, of course, the propagation medium should be homogeneous and isotropic to permit the use of the transmission medium properties. In practice this assumption cannot be made except for closely spaced frequencies. An additional factor for selecting closely spaced frequencies is the fact that the effects due to propagation anomalies are minimized.

OMEGA NAVIGATION SYSTEM

The OMEGA Navigation System is composed of eight VLF transmitting sites strategically located to provide worldwide coverage as shown in Figure 1. Three navigation frequencies (10.2, 13.6 and 11-1/3 kHz) are transmitted by each station in a commutation format as shown in Table 1. Two side frequencies are transmitted in the five remaining segments and may be used for other purposes such as timing. Coordination among various users of OMEGA transmissions resulted in the adoption of the present transmission format. The two frequencies which are separated by 250 Hz are transmitted by each station in duty cycle ratios of 3 and 2 in eight time segments. Thus, the five frequencies make up the total commutation transmission format. The two frequencies can be used for clock synchronization if these signals are phase controlled at the

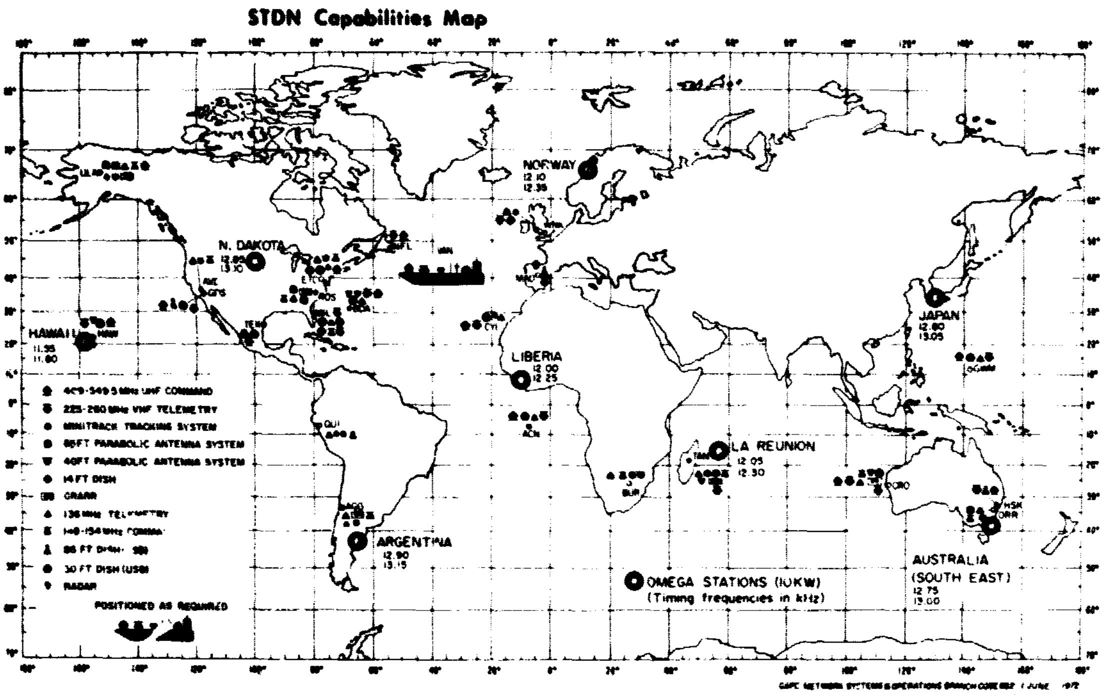
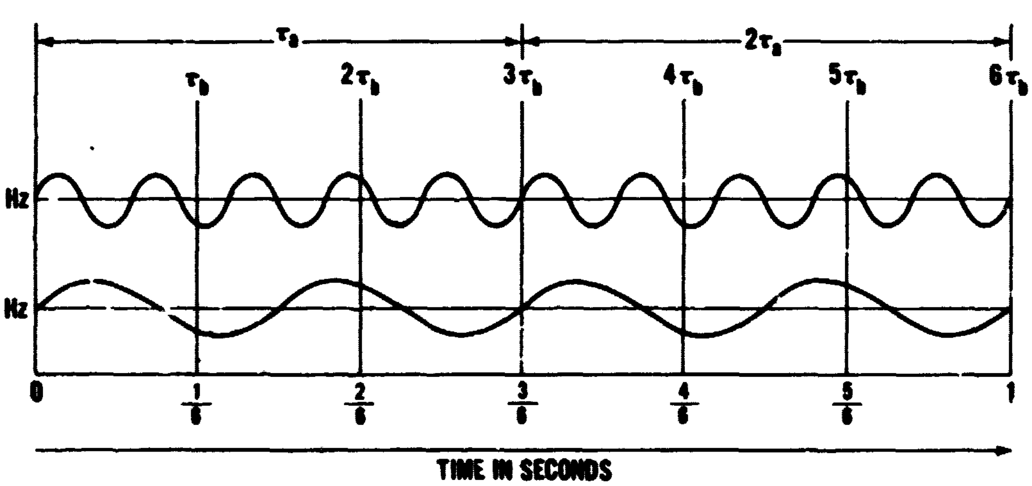


Figure 1.



$F_1 = 10$ Hz

$F_2 = 4$ Hz

$$Q = \frac{F_1}{k_1} = \frac{F_2}{k_2} = 2$$

$$k_1 = \frac{F_1}{Q} = 5$$

$$k_2 = \frac{F_2}{Q} = 2$$

$$k = k_1 - k_2 = 3$$

$$\tau_b = \frac{1}{\Delta F} = \frac{1}{6} \text{ sec}$$

$$\tau_a = k\,\tau_b = \frac{3}{6} \text{ sec}$$

Figure 2.

transmitter relative to a standard clock. They can also be used for aircraft navigation in remote areas by the same scheme as or in combination with other VLF transmissions such as NAA, NBA, NPM, etc.

Presently on the North Dakota OMEGA station transmits the two frequencies, at 13.10 and 12.85 kHz, which are phase controlled at emission coincident to the UTC time scale of January 1, 1972.

Figure 2 gives a pictorial representation of two signals emitted at time t_0 from the transmitting antenna. As the signals are propagated to the right of t_0 the phase difference of the signals increases from 0 to 2π as a function of distance or propagation time delay. One can see that the relative phase becomes zero at integer multiples of the beat frequency periods as shown at 1/6, 2/6, 3/6, 4/6, 5/6 and 6/6 seconds. At 3/6 and 6/6 seconds, the relative phase of the two signals is exactly the same as that at t_0, i.e., both signals are in phase at the positive going zero crossings. The time between coincident positive going zero crossings is called the ambiguity period. To avoid confusion, those beat periods at which the phases of the two propagated signals are the same but not at the positive going zero crossings, are called the pseudo ambiguity periods.

With reference to Figure 3, let t_0 be the time of emitted signals f_1 and f_2 at the transmitter site.

Let t_r be the time of reception relative to a clock at the receiving site. Then the transit time for the signals to reach from the transmitter to the receiver is

$$t_r - t_o = T_p + \Delta t_c \qquad (1)$$

where

T_p = propagation delay = $t_p + \Delta t_p$
t_p = calculated propagation delay and
Δt_p = propagation delay anomaly
Δt_c = clock difference between transmit and receive site.

Rearranging terms

$$t_r - t_o = t_p + \Delta t_p + \Delta t_c$$

let

$$\Delta t = \Delta t_p + \Delta t_c$$

then

$$t_r - t_o = t_p + \Delta t \qquad (2)$$

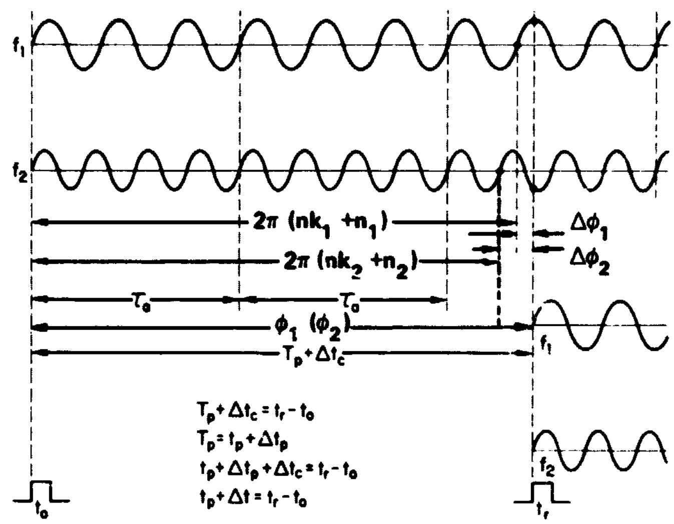


Figure 3.

Table 1

10 Second Time Frame of OMEGA Frequency Commutation Format

STATION \ SEGMENT	A	B	C	D	E	F	G	H
A NORWAY	10.2	13.6	11.33	12.1	12.1/12.35	12.1/12.35	12.1/12.35	12.35
B LIBERIA	12.25	10.2	13.6	11.33	12.0	12.0/12.25	12.0/12.25	12.0/12.25
C HAWAII	11.8/11.55	11.55	10.2	13.6	11.33	11.8	11.8/11.55	11.8/11.55
D N. DAKOTA (La Mour)	13.1/12.85	13.1/12.85	12.85	10.2	13.6	11.33	13.1	13.1/12.85
E LA REUNION	12.3/12.05	12.3/12.05	12.3/12.05	12.05	10.2	13.6	11.33	12.3
F ARGENTINA (Trelew, Chubut Prov.)	12.9	12.9/13.15	12.9/13.15	12.9/13.15	13.15	10.2	13.6	11.33
G AUSTRALIA	11.33	13.0	13.0/12.75	13.0/12.75	13.0/12.75	12.75	10.2	13.6
H JAPAN (Tsushima Is.)	13.6	11.33	12.0	12.8/13.05	12.8/13.05	12.8/13.05	13.05	10.2

|—0.9—| .2 |—1.0—| .2 |—1.1—| .2 |—1.2—| .2 |—1.1—| .2 |—0.9—| .2 |—1.2—| .2 |—1.0—| .2

0.0 1.1 2.3 3.6 5.0 6.3 7.4 8.8 10.0

The transmitted frequencies, f_1 and f_2, are phased at the transmitter such that they both pass through a positive going zero crossing at time t_o which represents the beginning of a second of the standard time scale.

If identical frequencies are generated at the receiver at time t_r (see Fig. 3), and if the respective phase differences $\Delta\phi_1$ and $\Delta\phi_2$ between the generated frequencies at the receiver and the generated frequencies at the transmitter are measured, the time difference in delay $(t_r - t_o)$ can be calculated.

Expressed in terms of phase relationships it can be seen (Fig. 3) that the phase angle ϕ_1, generated by frequency f_1 during time $(t_r - t_o)$ is

$$\phi_1 = 2\pi nk_1 + 2\pi n_1 + \Delta\phi_1 \tag{3}$$

The ϕ's are taken as positive if measured to the right of t_r. Similarly for f_2

$$\phi_2 = 2\pi nk_2 + 2\pi n_2 + \Delta\phi_2 \tag{4}$$

where n_1 (n_2) is an integer and the number of positive going zero crossings of f_1 (f_2) between t_o and t_r within an ambiguity period.

k_1 (k_2) is the number of integer cycles of f_1 (f_2) in τ_a (the ambiguity period). n is an integer, the number of ambiguity period between t_o and t_r.

Let

$$\tau_1 = \frac{1}{f_1}$$

the period of frequency f_1. Also

$$\tau_2 = \frac{1}{f_2}$$

The transit time $(t_r - t_o)$ is equal to the number of cycles of either frequency multiplied by the period of the frequency time length of one cycle, hence

$$t_r - t_o = \frac{\phi_1}{2\pi}\tau_1 = \frac{\phi_2}{2\pi}\tau_2 \tag{5}$$

or

$$t_p + \Delta t = \frac{\phi_1}{2\pi}\tau_1 \tag{6}$$

$$t_p + \Delta t = \frac{\phi_2}{2\pi}\tau_2 \tag{7}$$

Substitute Eq. 3 into Eq. 6:

$$t_p + \Delta t = nk_1\tau_1 + n_1\tau_1 + \frac{\Delta\phi_1}{2\pi}\tau_1$$

or

$$t_p + \Delta t = nk_1\tau_1 + n_1\tau_1 + \Delta n_1\tau_1 \tag{8}$$

also

$$t_p + \Delta t = nk_2\tau_2 + n_2\tau_2 + \Delta n_2\tau_2 \tag{9}$$

where

$$\frac{\Delta\phi_1}{2\pi} = \Delta\eta_1$$

Solving for n_1 and n_2

$$n_1 = \frac{1}{\tau_1}(t_p + \Delta t) - nk_1 - \Delta n_1$$

$$n_2 = \frac{1}{\tau_2}(t_p + \Delta t) - nk_2 - \Delta n_2$$

$$n_1 - n_2 = \left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right)(t_p + \Delta t) - nk_1 + nk_2 - \Delta n_1 + \Delta n_2$$

then

$$n_1 - n_2 = \frac{1}{\tau_b}(t_p + \Delta t) - nk - \Delta n_{12}$$

$$\frac{1}{\tau_b} = \frac{1}{\tau_1} - \frac{1}{\tau_2}$$

and

$$k = k_1 - k_2$$

$$\Delta n_{12} = \Delta n_1 - \Delta n_2$$

By definition k_1 is the integer number of cycles of f_1 in τ_a, k_2 is the integer number of cycles of f_2 in τ_a and k is the integer number of cycles of $(f_1 - f_2)$ in τ_a.

Thus

$$\tau_a = k_1\tau_1 = k_2\tau_2 = k\tau_b$$

Then

$$n_1 - n_2 = \frac{k}{\tau_a}(t_p + \Delta t) - nk - \Delta n_{12}$$

$$n_1 - n_2 = \frac{k}{\tau_a}(t_p + \Delta t - n\tau_a) - \Delta n_{12}$$

Also

$$n_1 = \frac{1}{\tau_1}(t_p + \Delta t) - n\frac{\tau_a}{\tau_1} - \Delta n_1$$

$$n_1 = \frac{1}{\tau_1}(t_p + \Delta t - n\tau_a) - \Delta n_1 \tag{10}$$

also

$$n_2 = \frac{1}{\tau_2}(t_p + \Delta t - n\tau_a) - \Delta n_2 \tag{11}$$

Substituting and rearranging terms in Eqs. 8 and 9 we have

$$t_p + \Delta t = n\tau_a + (n_1 + \Delta n_1)\tau_1 \tag{12}$$

and

$$t_p + \Delta t = n\tau_a + (n_2 + \Delta n_2)\tau_2 \tag{13}$$

<u>Cycle Determination or Identification</u>

Using Equations 10 and 11 the predicted propagation delay, $t_p = 6456\ \mu s$, and

$$\tau_1 = \frac{1}{f_1} = \frac{1}{13100} = 76.336\ \mu s$$

$$\tau_2 = \frac{1}{f_2} = \frac{1}{12850} = 77.821\ \mu s$$

and noting, within the first ambiguity period (τ_a), that n = 0, k = 5, τ_b = 4000 μs and $\tau_a = k\tau_b$ = 20,000 μs we obtain

$$n_1 = 84.574 - \Delta n_1 + \frac{\Delta t}{\tau_1}$$

$$n_2 = 82.960 - \Delta n_2 + \frac{\Delta t}{\tau_2}$$

If t_p cannot be calculated (predicted) it must be measured via a portable clock. Since n is assumed as a priori knowledge of the position of the local clock site (receiving site) relative to the transmitter clock site, n_1 and n_2 can be calculated from Δn_1 and Δn_2 which are measured quantities.

For Δt less than 5 μs, the error contributed to cycle determination for neglecting Δt is only 0.06 cycle. In the sample calculations given in Tables 2 and 3, Δt is neglected. However, Δt can be calculated from $t_p + \Delta t$ using the carrier cycle determined by Equations 8 and 9. If the propagation delay anomaly at 1200 EDT can be considered as negligible then $\Delta t_p = 0$ and $\Delta t = \Delta t_c$. The calculated time difference between the clocks at the transmitter and the receiving site is plotted in Figure 13.

Experimental Results

Using the specially designed OMEGA Timing Receiver and the predicted or measured propagation delays from North Dakota OMEGA station to the four sites where the experiments of clock synchronization had been conducted, we obtained the carrier cycle numbers for f_1 = 13.10 kHz and f_2 = 12.85 kHz given in Table 4. Δn_1 and Δn_2 are the mean of the measured phase differences in units of cycles with Δt = 0. The mean is usually taken from daily measurements at a fixed time for up to seven days except for GSFC. The mean for GSFC is obtained from 25 daily measurements as shown in Table 2.

Diurnal Phase Records

The diurnal phase of the North Dakota transmitted signals, as received at several sites, were recorded. The seasonal variation of the diurnal phase change can be observed from the series of phase records shown on the following pages.

Table 2

Cycle Identification of OMEGA Signals from North Dakota to GSFC, Greenbelt, Maryland at 1200 EDT in June and July 1973

Date	Measured			Cycle Det.			$t_p + \Delta t$ (μs)			Δt (μs)
	Δn_1	Δn_2	Δn_{12}	$n_1 - n_2$	n_1	n_2	$(n_1 + \Delta n_1)\tau_1$	$(n_2 + \Delta n_2)\tau_2$	Mean	
June 22, 1973	0.595	0.968	0.373	1.987	83.979	81.992	6458	6456	6457	1
23	0.594	0.968	0.374	1.988	83.980	81.992	6458	6456	6457	1
24	0.590	0.965	0.375	1.989	83.984	81.995	6458	6456	6457	1
25	0.588	0.960	0.372	1.986	83.986	82.000	6457	6456	6457	1
26	0.586	0.960	0.374	1.988	83.988	82.000	6457	6456	6457	1
27	0.588	0.965	0.377	1.991	83.986	81.995	6457	6456	6457	1
28	0.592	0.966	0.378	1.992	83.982	81.994	6458	6456	6457	1
29	0.587	0.958	0.371	1.985	83.987	82.002	6457	6456	6457	1
30	0.594	0.944	0.350	1.964	83.980	82.016	6458	6455	6457	1
July 1	0.590	0.952	0.372	1.986	83.984	82.008	6458	6455	6457	1
2	0.590	0.954	0.364	1.978	83.984	82.007	6458	6455	6457	1
3	0.586	0.952	0.366	1.980	83.988	82.008	6457	6455	6456	0
4	0.595	0.966	0.371	1.985	83.979	81.994	6457	6456	6457	1
5	0.614	0.932	0.318	1.932	83.960	82.028	6459	6454	6457	1
6	0.595	0.940	0.345	1.955	83.979	82.020	6458	6454	6456	0
7	0.595	0.965	0.370	1.984	83.979	81.995	6458	6456	6457	1
8	0.595	0.950	0.355	1.969	83.979	82.010	6458	6455	6457	1
9	0.586	0.963	0.377	1.991	83.978	81.997	6457	6456	6457	1
10	0.584	0.962	0.378	1.992	83.990	81.998	6457	6456	6457	1
11	0.586	0.963	0.377	1.991	83.988	81.997	6457	6456	6457	1
12	0.586	0.958	0.372	1.986	83.988	82.002	6457	6456	6457	1
13	0.582	0.958	0.376	1.990	83.992	82.002	6457	6456	6457	1
14	0.580	0.956	0.376	1.990	83.994	82.004	6457	6456	6457	1
15	0.575	0.954	0.379	1.993	83.999	82.004	6456	6455	6456	0
16	0.578	0.955	0.377	1.991	83.996	82.004	6457	6456	6457	1
Mean	0.589	0.957	0.368	1.982	83.985	82.003	6457	6456	6457	1
Cycle ID	–	–	–	2	84	82	–	–	–	–

Table 3

Cycle Determination of OMEGA Signals from North Dakota to GSFC Greenbelt, Maryland at 1200 EDT in September and October 1973

Date	Measured			Cycle Det.			$t_p + \Delta t$ (μs)			Δt (μs)
	Δn_1	Δn_2	Δn_{21}	$n_1 - n_2$	n_1	n_2	$(n_1 + \Delta n_1)\tau_1$	$(n_2 + \Delta n_2)\tau_2$	Mean	
Sept. 13, 1973	0.590	0.964	0.374	1.986	83.984	81.996	6457	6456	6457	1
14	0.595	0.972	0.377	1.991	83.979	81.988	6458	6457	6457	1
15	0.600	0.975	0.375	1.987	83.974	81.985	6458	6457	6457	1
16	0.594	0.962	0.362	1.976	83.960	81.998	6458	6457	6457	1
17	0.589	0.972	0.378	1.992	83.985	81.988	6457	6456	6457	1
18	0.590	0.966	0.377	1.991	83.984	81.994	6457	[illegible]	6457	1
19	0.587	0.966	0.376	1.990	83.987	81.994	6457	6455	6457	1
20	0.590	0.965	0.378	1.992	83.984	81.995	6457	[illegible]	6457	1
21	0.586	0.965	0.375	1.987	83.988	81.99[illegible]	6457	6456	6457	1
22	0.590	0.966	0.380	1.994	83.984	81.994	6457	6456	6457	1
23	0.586	0.963	0.378	1.992	83.988	81.997	6457	6456	6457	1
24	0.585	0.970	0.386	2.000	83.989	81.990	6457	6457	6457	1
25	0.584	0.957	0.377	1.991	83.990	82.003	6457	6456	6456	0
26	0.580	0.956	0.376	1.990	83.994	82.004	6456	6456	6456	0
27	0.580	0.941	0.371	1.985	83.994	82.019	6456	6454	6455	-1
28	0.570	0.960	0.375	1.987	84.004	82.000	6456	6456	6456	0
29	0.585	0.957	0.375	1.987	83.989	82.003	6457	6456	6456	0
30	0.582	0.960	0.375	1.987	83.992	82.000	6457	6456	6456	0
Oct. 1, 1973	0.585	0.964	0.377	1.991	83.989	81.996	6457	6456	6456	0
2	0.587	0.955	0.375	1.991	83.987	82.005	6457	6456	6456	0
3	0.580	0.955	0.375	1.991	83.994	82.005	6456	6456	6456	0
4	0.580	0.942	0.374	1.988	83.994	82.018	6456	6455	6455	-1
5	0.568	0.953	0.375	1.991	84.006	82.007	6456	6455	6455	-1
6	0.578	0.955	0.376	1.990	83.996	82.005	6456	[illegible]	6456	-1
7	0.579	0.952	0.376	1.990	83.995	82.008	6456	6455	6455	-1
8	0.576	0.952	0.376	1.990	83.998	82.008	6456	6455	6455	-1
Mean	0.585	0.959	0.374	1.988	83.989	82.001	6457	6456	6456	0
Cycle ID	–	–	–	2	84	82	–	–	–	–

Table 4

Preliminary Results of Propagation Delay Measurement Using OMEGA North Dakota Transmissions and Known Local Clock Time

LOCATION	MEASURED				PREDICTED
	$n_1+\Delta n_1$ (cycles)	$n_2+\Delta n_2$ (cycles)	$(n_1+\Delta n_1)\tau_1$ (μs)	$(n_2+\Delta n_2)\tau_2$ (μs)	t_p (μs)
NELC, SAN DIEGO, CA.	96.795	94.924	7388.9	7387.1	7388
GSFC, GREENBELT, MD.	84.589	82.957	6457.1	6455.8	6456
USNO, WASHINGTON DC	84.100	82.488	6419.8	6419.3	6420
STDN, ROSMAN, N.C.	78.561	77.056	5997.0	5996.6	5995

Figure 4 shows a daytime phase record of 12.85 kHz transmitted from North Dakota to Goddard Space Flight Center (GSFC) during mid June 1973. The diurnal phase change during sunrise goes from 0.33 cycles to 0.05 cycles (26.14 μs to 3.9 μs) and sunset goes from 0.05 cycles (3.9 μs) to 0.33 cycles (26.14 μs), or a total diurnal change of 0.28 cycles (3.4 μs). The daytime phase record has a resolution of ±0.001 cycles (±0.078 μs) and is stable from 1100 to 0100 GMT or for about 14 hours.

Figure 5 shows typical daytime seasonal changes of the diurnal phase records of the VLF signals for the North Dakota to GSFC path for mid-June, July, August, September, October, November through mid-December 1973. The useable daytime phase record decreases from about 14 hours in June to less than seven hours in December.

Figure 6 shows typical nighttime diurnal phase records for the 13.10 and 12.85 kHz signals transmitted from North Dakota to GSFC during mid months of June through December (excluding July and August). The nighttime phase variations are between 0.3 and 0.4 cycles and useable to within ±0.05 cycles (±3.5 μs). The length of the nighttime phase record increases from about 10 hours during the summer months (minimum in June) to 15 hours during the winter months (maximum in December). The nighttime phase variations remain

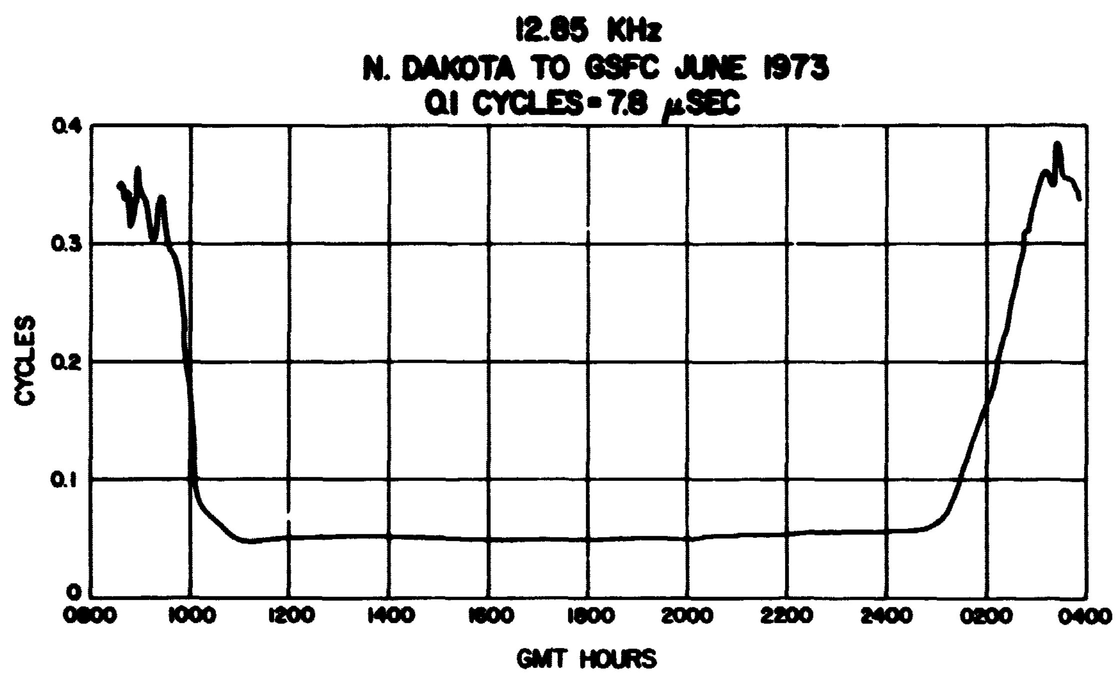


Figure 4.

fairly constant for the six months (between 0.3 and 0.4 cycles). Figure 7 is a typical phase record of the path for the 12.85 kHz signal between N. Dakota and the NASA tracking station at Rosman, N.C. for mid-November 1973. Figures 8 and 9 show the diurnal phase record for the VLF signal from North Dakota to USNO and NELC California, respectively. Typical modal interference effects during sunset for west to east propagation was observed between 2100 and 0100 GMT.

Figure 10 shows simultaneous observations of phase perturbations caused by Sudden Ionospheric Disturbances (SID's) on the 12.85 kHz and 13.1 kHz signals on September 27, 1973. The first SID occurs at about 1615 GMT and decays very slowly lasting for about five hours. The second SID occurs at 2230 and lasts into the evening diurnal. The phase record is readable to within an accuracy of about 0.025 cycles (2 μs) throughout the effects of the first SID.

Figure 11a shows a small SID occurring at 1530 GMT and lasting until 1730 GMT.

Figure 11b shows a large SID occurring at 1400 GMT and lasting beyond 1600 GMT.

Figure 12a shows two SID's occurring within three hours of each other, the first at 1600 GMT and the second at 1900 GMT. The phase record for the day is not useable to better than 0.05 cycles (4 μs).

Figure 12b shows a small SID occurring at 1650 GMT and recovering rather rapidly at 1800 GMT.

CONCLUSIONS

Based on the results obtained at GSFC (Figure 13), Rosman, and USNO, it can be said that the dual frequency time transmission technique has provided a capability of time synchronization of remote laboratory clocks to an accuracy of ±1 microsecond if daytime transmissions are used and less than an order of magnitude of degradation if nighttime transmissions are used. It is not certain if the same results can be realized if longer propagation paths are used. Plans have been made to conduct longer path length experiments at Grand Canary Island and Canberra, Australia during 1974. These results will be given in future reports.

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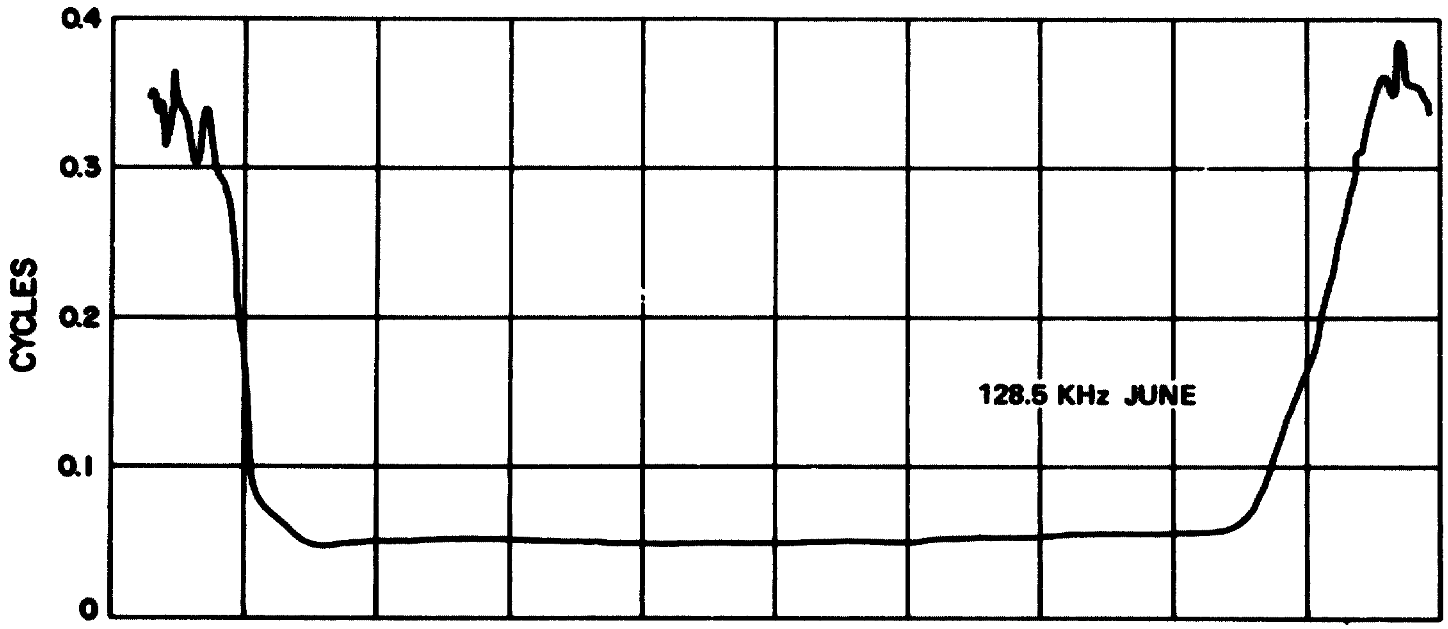

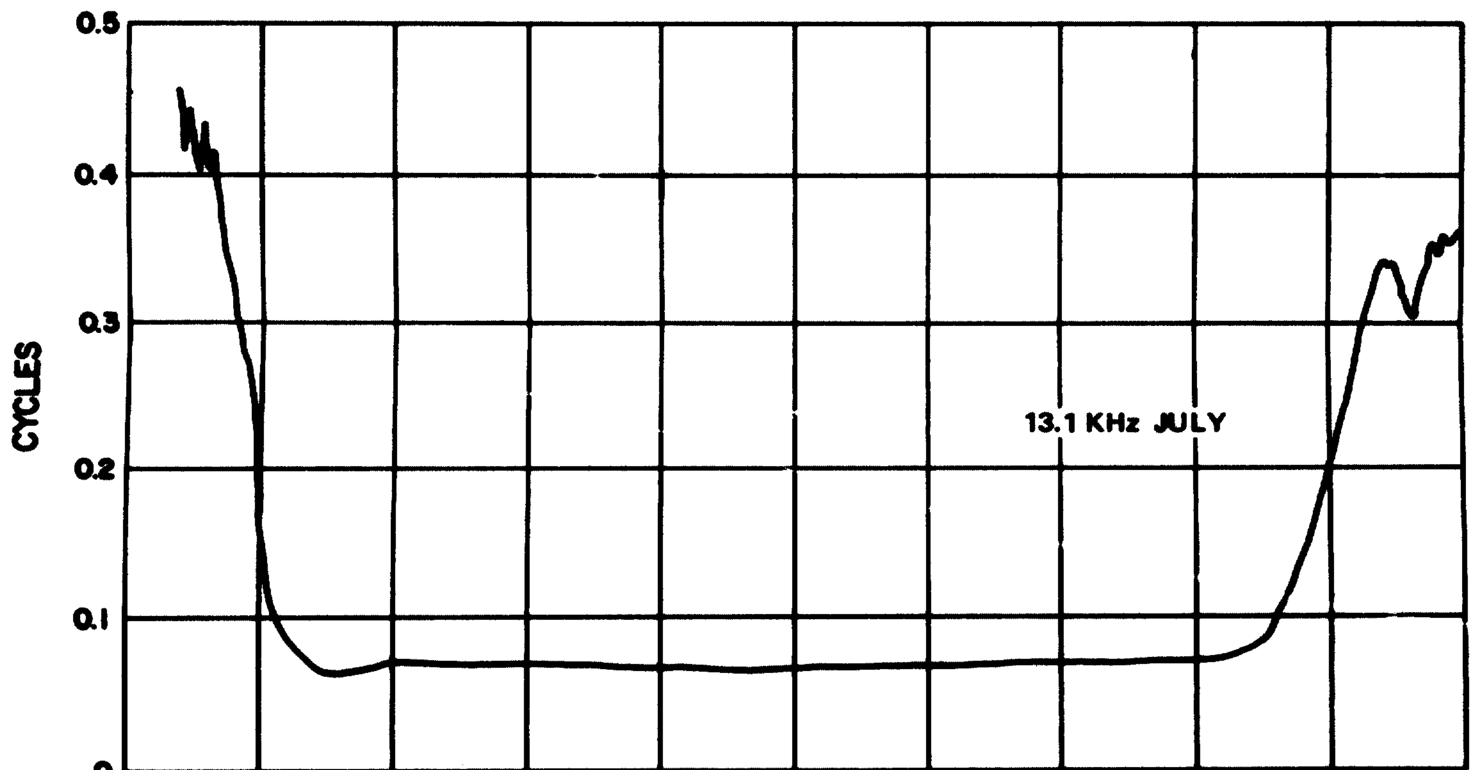

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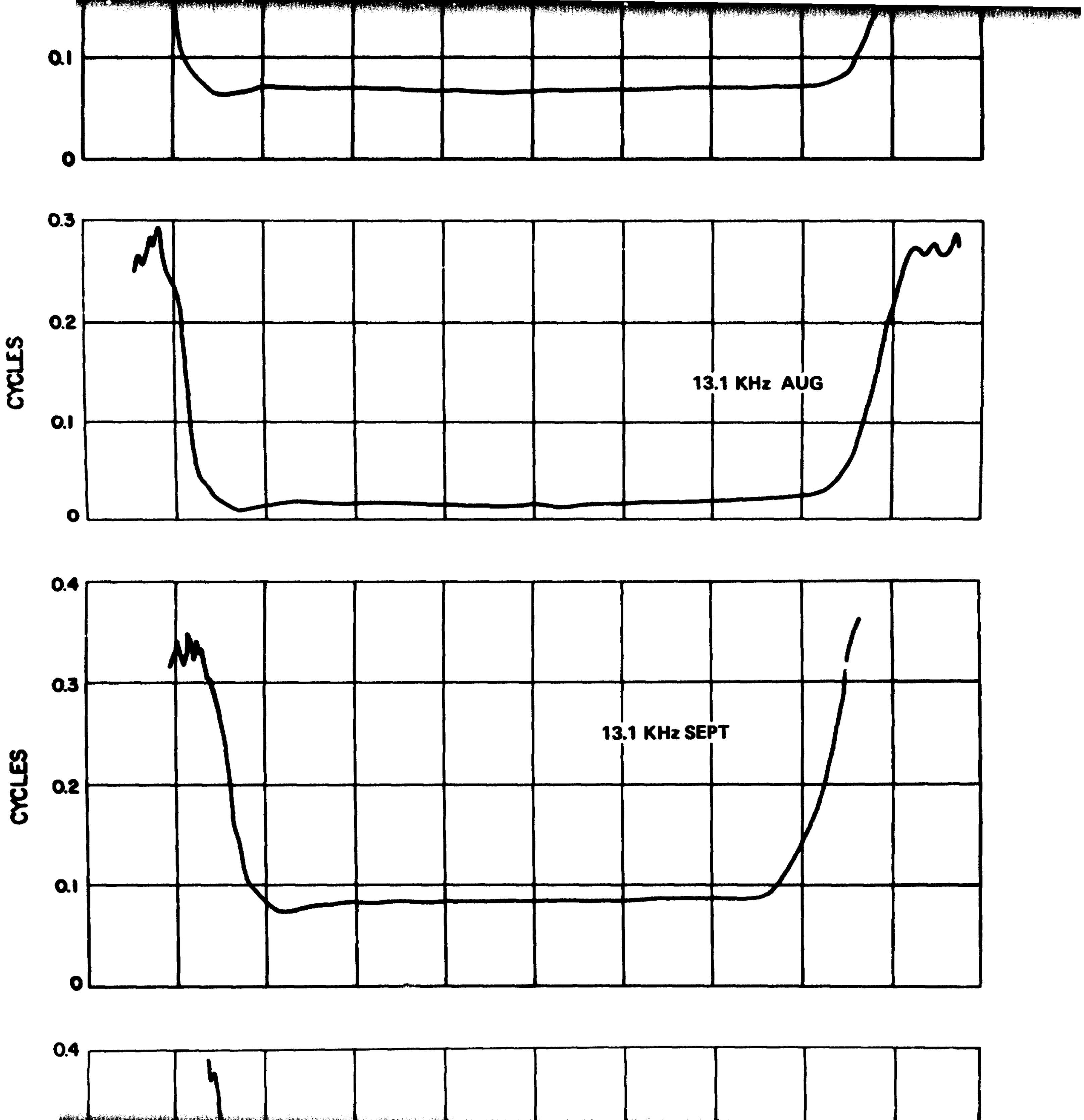

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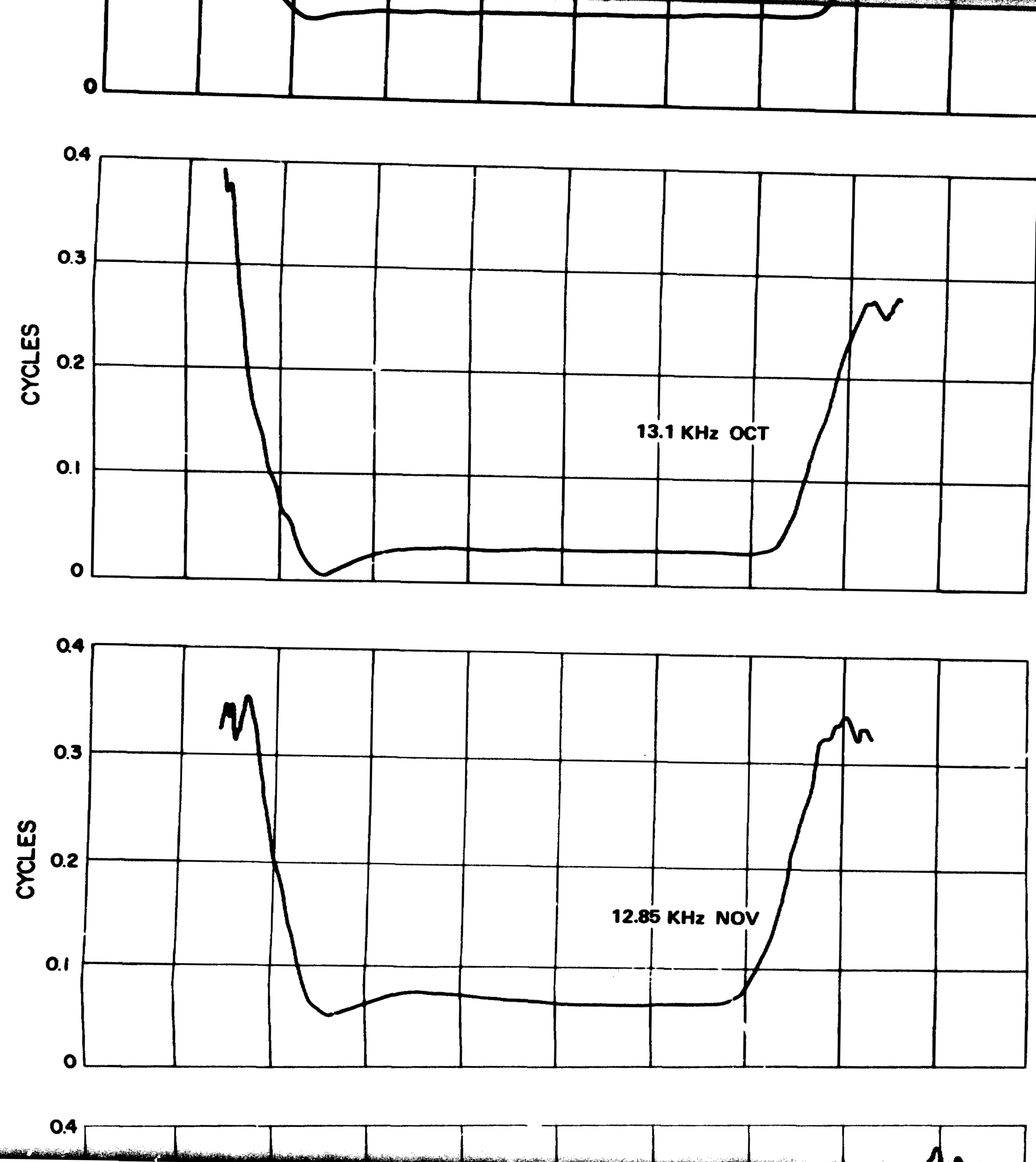

Figure 5. Daytime Se
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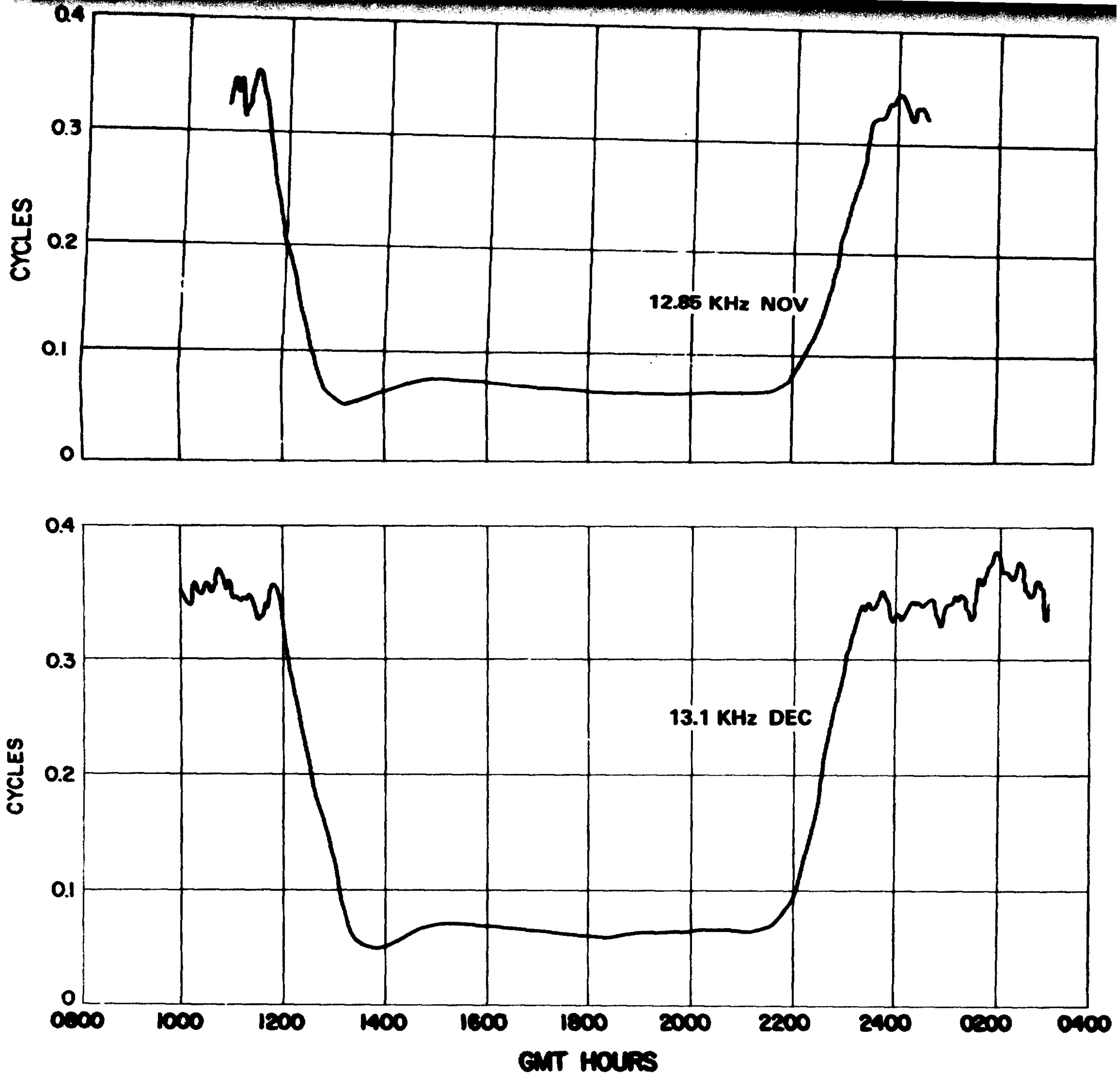

Figure 5. Daytime Seasonal Variations of the Omega Signals from North Dakota to Greenbelt, Maryland (GSFC), June through December 1973

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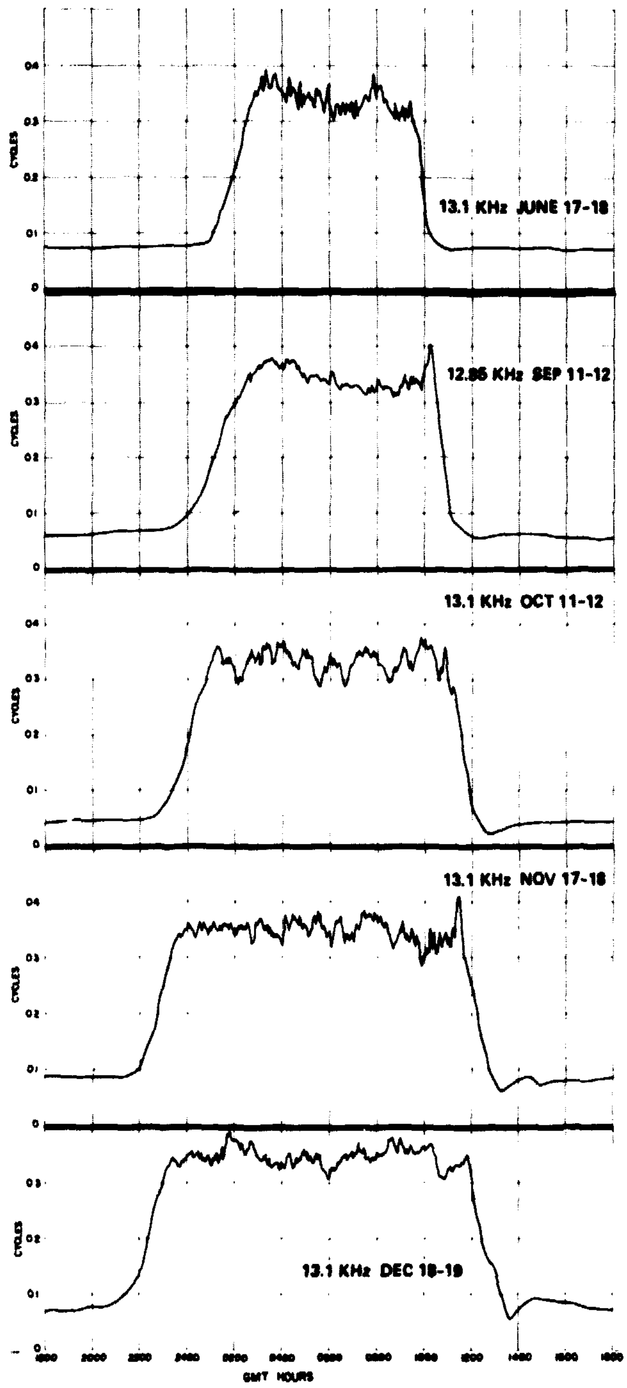

Figure 6. Nighttime Seasonal Variation of the Omega Signals from North Dakota to Greenbelt, Maryland (GSFC), June through December (July and August excluded) 1973

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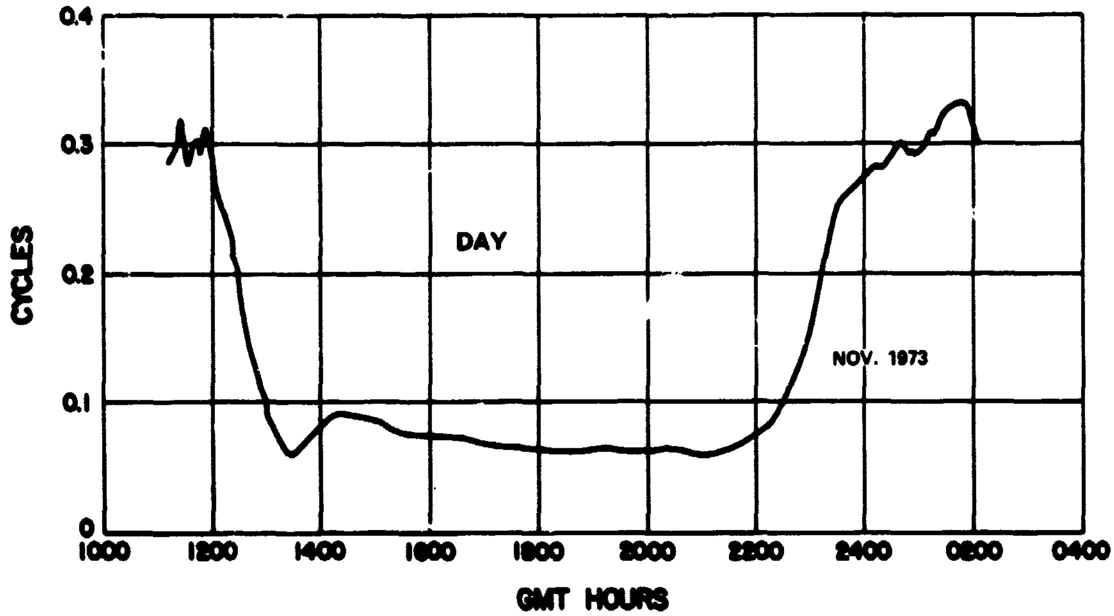


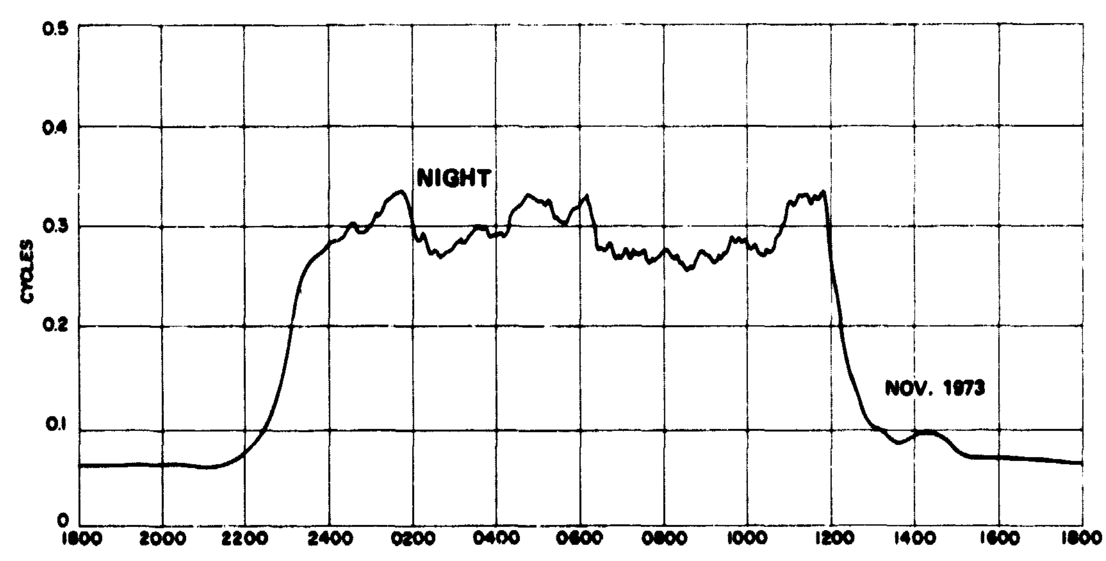
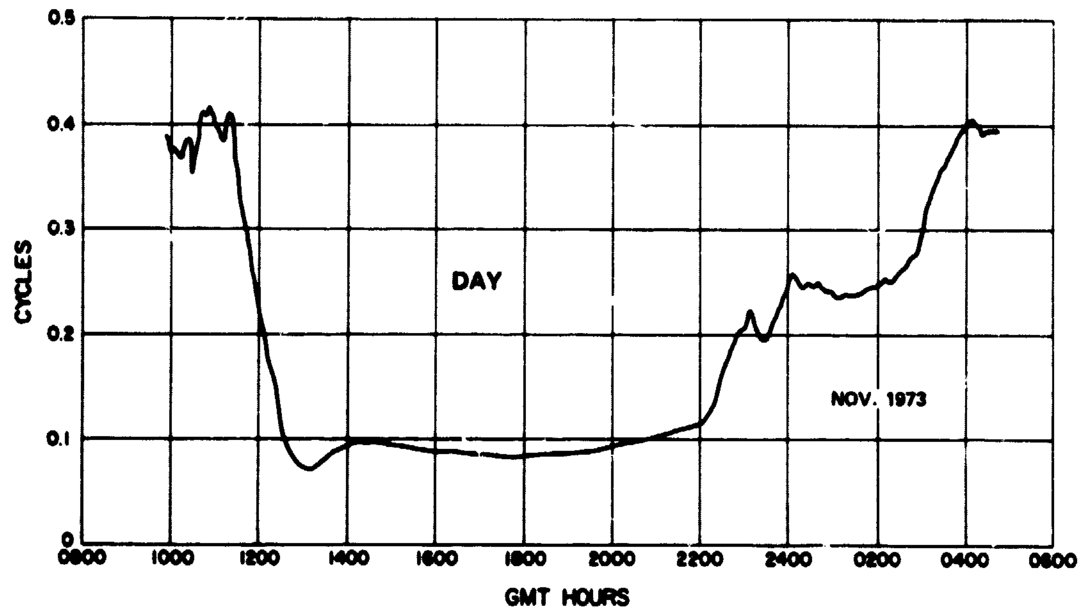


Figure 7. 12.85 KHz Signal from N. Dakota to Rosman, N.C.



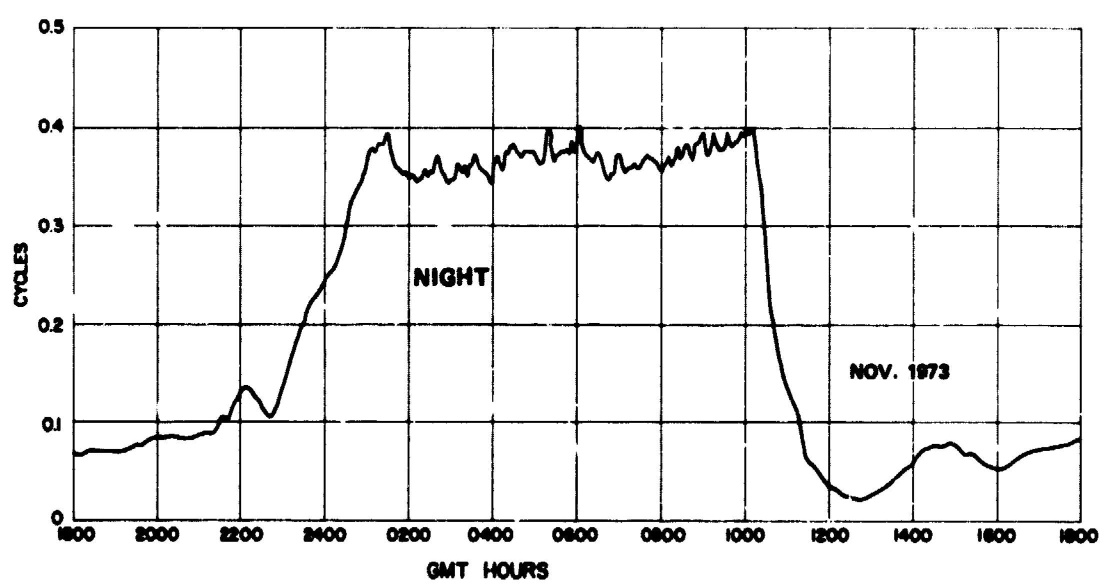


Figure 8. 12.85 KHz Signal from N. Dakota to USNO, Washington, D.C.

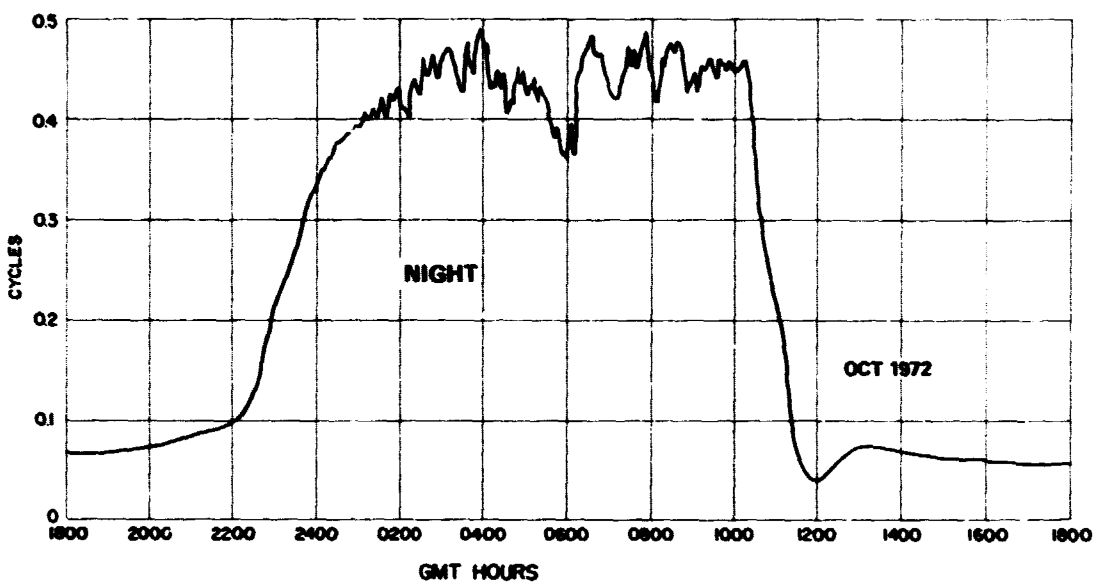


Figure 9. 13.1 KHz Signal from N. Dakota to NELC, San Diego, Ca.

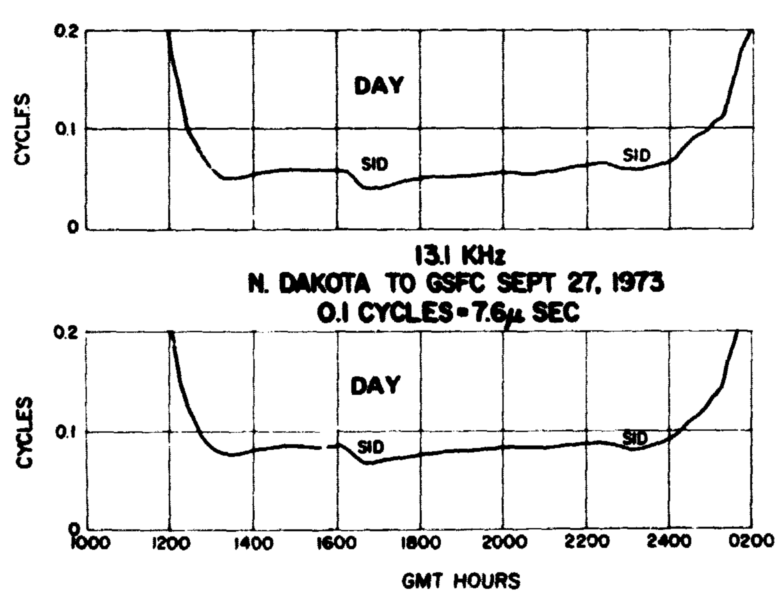


Figure 10. 12.85 KHz Signal from N. Dakota to GSFC, Greenbelt, Maryland

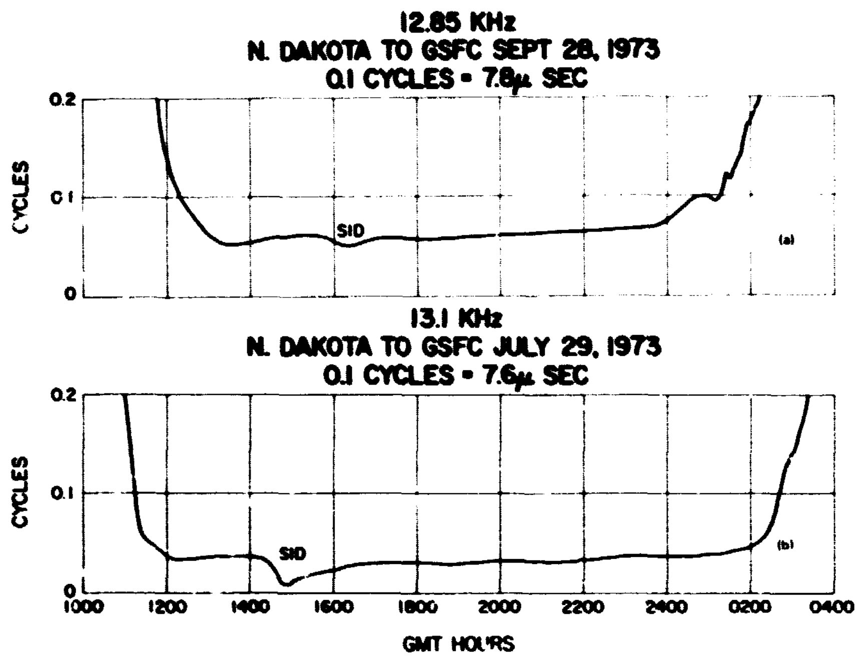


Figure 11.

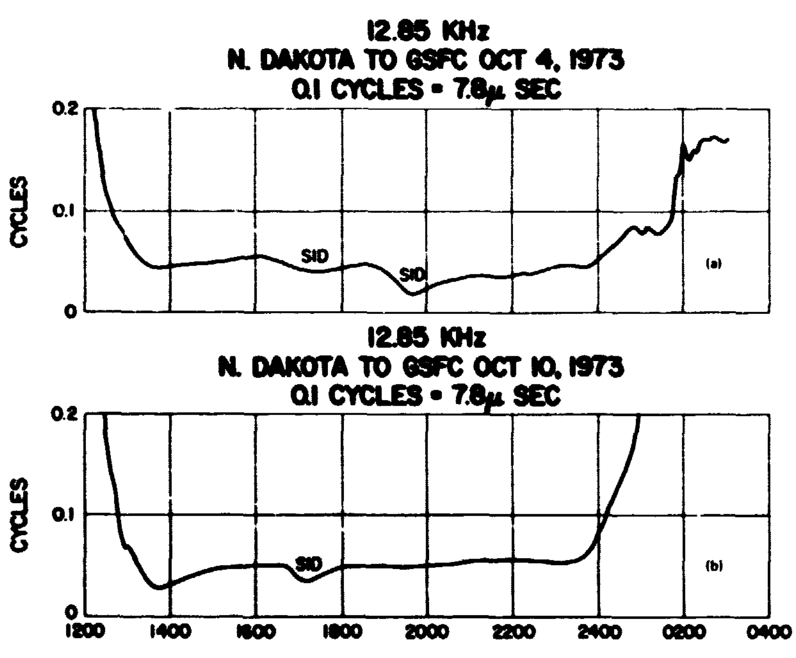


Figure 12.

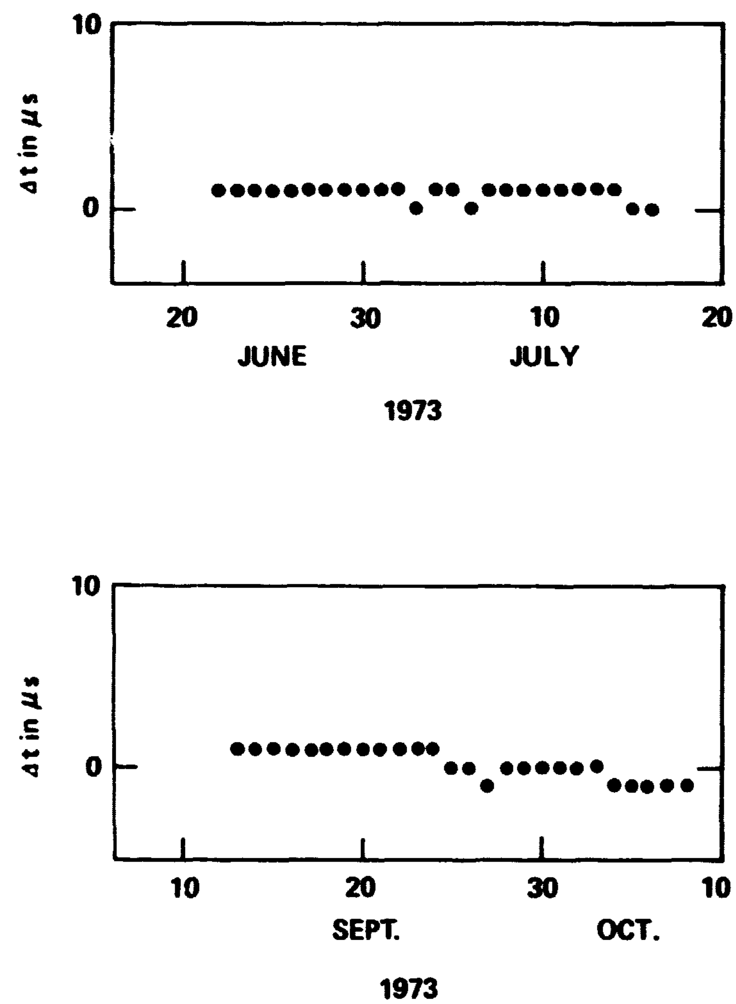


Figure 13. Time Comparison Made at 1200 EDT Between Received Omega North Dakota Time Transmission and GSFC Clock at Greenbelt, Maryland, (t_p = 6456 μs)

QUESTION AND ANSWER PERIOD

DR. REDER:

Any questions, please? Dr. Winkler.

DR. WINKLER:

I wonder about an apparent discrepancy. You first said that we didn't have any propagation delay problem between the Observatory and North Dakota, but I have seen in your last slide a comparison between the predicted delay and measured. Could you elaborate on that?

MR. CHI:

Well, first, in the absence of a known clock difference, there could be a fixed bias. All our clocks are referenced to your clocks.

DR. WINKLER:

Okay. That brings me exactly to the main point that I am going to make.

Yesterday, and this morning, I did not share Dr. Smith's concern about the problems in using the Loran system for absolute measurements, because I feel that one can live with a relative system which is checked every half year, maybe, by portable clock measurement.

Today, however, in the Omega system, the problems are about ten times larger.

What we are concerned with is the difference between relative day to day, or week to week measurements, and the possibility to recover your epoch if you have lost it, with some confidence.

I think for that, the system is probably good enough to one or two microseconds, or maybe three, if you are careful in taking seasonal effects into account.

But when it comes to starting from scratch, and to come to a new location and to use a precomputed propagation delay, I think you will find you will often have discrepancies in the order of 20 and more microseconds, particularly in distances across the Continental United States, where you cannot ignore higher mode propagation and where you really have a very hard time to predict, without prior calibration with portable clock visits, a propagation delay.

At the moment, we do have discrepancy. I have received predictions from NELC, and they do not at all check with our measurements. We will have to send a portable clock to resolve it.

So, again, we have the difference between relative measurements and epoch recovery capability, versus absolute timing.

MR. CHI:

Well, I would like to make a few comments. One is that so far as the relative time, clock time of North Dakota relative to the U.S.N.O., is concerned, we have made the request to send a portable clock to North Dakota. As a matter of fact, my request was to measure that at an interval of six months, so we will know what it is.

The second comment I have is this, the system is not in any way competing with Loran-C, in that this is a system which will be good for microsecond, up to maybe 100 microseconds.

Certainly, it will be better once you determine the cycle. It is much better than one period, which is 77 microseconds.

So, most likely, if you use 24 hour time to determine, to recapture the time difference, you can do it to 10 microseconds. If you do it with care using the daytime phase record, you should be able to achieve or obtain one microsecond.

Now, the advantage of this is the fact that it is a VLF signal — the signal propagates much further than Loran-C, and stability of the phase record is well known that I do not have to impress on you how good it is.

Anyone who has used VLF will know that the distance coverage is much greater than Loran-C. In that respect, you have some gain, perhaps maybe for your coarse time for one microsecond, and use Loran-C to obtain the 10th of a microsecond or better.

So, they are complimentary systems.

DR. REDER:

Before I ask for the next question, I have one comment to Dr. Winkler's remarks. I would be more concerned with the short distances than with the long distances. There is no second order mode on Omega over long distances, but over short distances, from Washington to North Dakota, for instance, there is a possibility.

DR. WINKLER:

Exactly.

DR. REDER:

Another remark. I will come to you in a moment, I was thinking of you, Eric. One more remark to Andy's paper, and that is there are no SIDs at night. However, particularly North Dakota is quite susceptible to electron precipitation because of its location. Therefore, what you see at night is partially mode interference and the effects of electrons.

MR. SWANSON:

First, I should state that some of these more recent numbers I personally haven't looked into in detail since the measurements have been made. So, it is possible there is some, perhaps, epoch bias at the present time in North Dakota.

Ordinarily, one wouldn't expect this to happen. It might easily be off by a few microseconds, but anything much beyond that, I suspect not.

In any event, the predictions made here do include allowance for model structure, as well as our general estimate for the phase.

I will certainly admit, and I believe Andy has made it clear, too, that these are just four preliminary checks. They are certainly not exhaustive test programs.

Nonetheless, the four checks that have been made so far, show that the system is working, and in fact, it works on an absolute basis to a matter of a few microseconds.

DR. REDER:

Any other questions?

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THE CORRELATION OF VLF PROPAGATION VARIATIONS WITH ATMOSPHERIC PLANETARY-SCALE WAVES

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ABSTRACT

Variations in the received daytime phase of long distance, cesium-controlled, VLF transmissions are compared to the height variations of the 10-mb isobaric surface during the first three months of 1965 and 1969. The VLF phase values are also compared to height variations of constant electron densities in the E-region from Brown and Williams (1971) and to variations of f-min from Deland and Friedman (1972) which have been shown to be well correlated with planetary-scale variations in the stratosphere by Deland and Cavalieri (1973). The VLF phase variations show good correlation with these previous ionospheric measurements and with the 10-mb surfaces. The VLF variations appear to lag the stratospheric variations by about 4 days during the 1965 period, but lead the latter by about 4 days during the 1969 period.

The planetary scale waves in the stratosphere are shown to be travelling on the average eastward in 1965 and westward in 1969. The above correlations are interpreted as due to the propagation of travelling planetary scale waves with westward tilted wave fronts. Upward energy transport due to the vertical structure of those waves is also discussed.

These correlations provide further evidence for the coupling between the lower ionosphere at about 70 km altitude (the daytime VLF reflection height) and the stratosphere, and they demonstrate the importance of planetary wave phenomena to VLF propagation.

INTRODUCTION

Numerous observations support the view that ionization variations in the D and E-regions are coupled to metoerological variations in the stratosphere. Evidence for this coupling is the connection of ionospheric variations, which have been determined almost exclusively from ground-based MF or HF (>1 MHz) radio transmissions, to pressure or temperature variations in the stratosphere (Bowhill, 1969; Gregory and Manson, 1969; Schwentek, 1969; Thomas, 1971; Lauter and Taubenhiem, 1971). Brown and Williams (1971) have correlated variations in the height of a constant electron density surface in the E-region, estimated from ionosonde observations, with height variations of the 10-mb isobaric surface in the stratosphere. Deland and Cavalieri (1973) have further shown the electron density heights determined by Brown and Williams to be well correlated with planetary-scale fluctuations of f-min (the minimum frequency at which reflection from the ionosphere is recorded by an ionosonde). Deland and Friedman (1972) have shown these same f-min variations to be correlated directly with atmospheric pressure fields for the stratosphere.

Long distance VLF (3-30 kHz) transmissions have been used for many years to study a variety of ionospheric disturbances related to solar x-rays, solar energetic particles, trapped energetic particles, aurora, and magnetic storms (e.g. Bracewell et al., 1951; Crombie, 1965; Belrose and Thomas, 1968; Westerlund et al., 1969; Zmuda and Potemra, 1972; Potemra and Rosenberg, 1973). The longest time scale of these disturbances is about 10 days and is only observed during severe polar cap absorption events with trans-polar VLF transmissions or following large geomagnetic storms with midlatitude transmissions. Analysis of longer-period (>10 days) or seasonal ionospheric variations observed with VLF signals has been limited by the long-term stability of transmitter and receiver reference oscillators and are rare (e.g., Reder and Westerlund, 1970). Brady and Crombie (1963) corrected transmitter and receiver oscillator drifts by subtracting a parabolic variation of phase drift in order to study the effects of lunar tidal variations on the phase of VLF transmissions. The more recent use of cesium atomic standards for frequency reference at transmitters and receivers has enabled seasonal variations to be analyzed using VLF data with greater confidence (e.g., Noonkester, 1972). However, no connections have yet been made between disturbances observed with VLF transmissions and planetary scale fluctuations in the stratosphere. Since correlations have already been established between stratospheric phenomena and ionospheric variations determined from MF and HF transmissions, it seems reasonable that variations in VLF transmissions can be related to and be used to study the coupling between ionosphere and atmosphere.

Theoretical work by Charney and Drazin (1961) indicates that strong zonal winds in the winter months tend to inhibit the upward propagation of quasi-stationary planetary scale waves, however, more recently Dickinson (1968a, 1968b), Matsuno (1970) and Hirota (1971) with improved models have shown that the stratosphere and mesophere are likely to be permeable to these planetary scale fluctuations. Other studies by Boville (1966) and Deland and Johnson (1968) have shown that transient planetary scale waves moving westward on the average exist in the lower stratosphere and are likely to extend into the upper atmosphere with large amplitudes in winter (e.g., Deland, (1970)).

Eliassen and Palm (1960) have related the upward propagation of energy to the vertical structure of quasi-stationary planetary scale waves. Deland (1973) has shown that the theoretical results of Eliassen and Palm (1960) are also applicable to transient planetary scale waves. The results presented below are consistent with upward propagation of energy into the lower ionosphere.

In this paper, variations in the received daytime phase of a long-distance VLF transmission are compared with the height variations of constant densities from Brown and Williams (1971), the variations of f-min from Deland and Friedman (1972), and the height variations of the 10-mb isobaric surface from Deland and Cavalieri (1973), which were all observed during the first three months of 1965. Daytime VLF phase values are also compared to variations in the 10-mb iosbaric surface for the first three months of 1969.

VLF PHASE DATA

The paths of VLF transmissions monitored at the Applied Physics Laboratory (APL) and nearby at the U.S. Naval Observatory (USNO) in Washington, D.C. are illustrated in Figure 1 with projections of magnetic L shells on the ionosphere at 100 km altitude. The frequency, path length, highest geographic latitude, highest L shell (and corresponding invariant latitude) for each VLF path are listed in Table 1. The phase advance produced by a uniform 1 km lowering of the daytime VLF reference height is also listed in this table and was computed in the following manner.

VLF transmissions are often analyzed as waves propagating in the waveguide formed by the earth's surface and the lower ionosphere. The total phase delay τ between transmitter and receiver separated by a distance d_0 is $\tau = d_0/v_0$ secs., where v_0 is the VLF phase velocity for undisturbed conditions. Variations in the ionosphere over this path which result in a different VLF phase velocity v will be observed as a change in the phase delay at the receiver, $\Delta\tau$, and is expressed by the formula, $\Delta\tau = d_0(1/v - 1/v_0)$ secs. A uniform lowering of the effective VLF waveguide height, due for example to ionization enhancements, will increase the VLF phase velocity and cause the phase to advance (i.e. a negative phase delay) at the receiver measured with respect to the undisturbed value. The time scale of these disturbances is less than a few hours, so that their effects are not important to the present analysis of variations of a few days.

The VLF reflection height for undisturbed daytime conditions is usually taken as about 70 km (Potemra et al., 1970; Johler, 1970, Westerlund and Reder, 1973). Using phase velocity values for the lowest order VLF modes from Wait and Spies (1964) and Spies (private communication, 1964) which

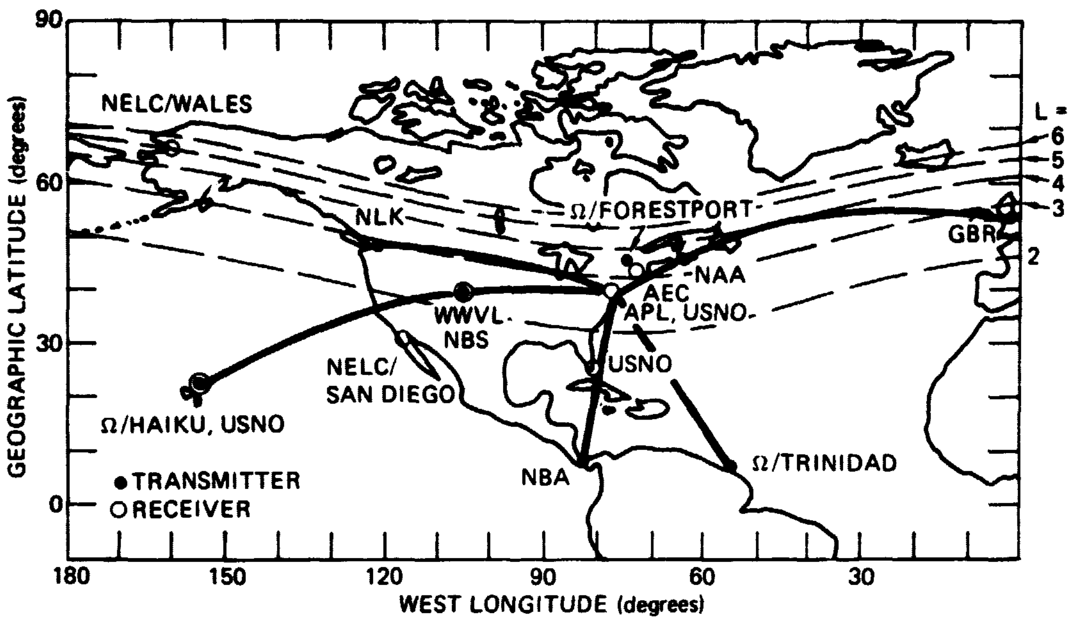

Figure 1. VLF Transmission Paths Monitored at APL and the U.S. Naval Observatory with Projections of Magnetic L Shells at 100 km Altitude (from Wiley and Barish, 1970).

Table 1

VLF Propagation Paths

Path	Freq. kHz	Distance, km	Highest Geographic Latitude	Highest L(A)	$\Delta\tau/\Delta h$ at 70 km μ sec/km
GBR-APL (Rugby, England)	16.0	5615	54.4°	4.0 (60°)	2.9
NLK-APL (Jim Creek, Wash.)	18.6	3730	48.2°	3.5 (57.5°)	1.8

employ the exponential conductivity model of the lower ionosphere, a uniform 1 km-lowering of the ionospheric reference height without a change of gradient will produce a 2.9 μsec (2.9×10^{-6} sec) advance in the phase of the GBR transmission as received at APL. The phase advance (or retardation) corresponding to a 1 km-lowering (or raising) of the effective height near 70 km for the NLK-APL path was computed in the same manner and is also listed in Table 1. These phase calculations may be applied to the VLF transmissions received at the U.S. Naval Observatory because this station is close (~30 km) to APL.

During the first three months of 1965 (the first period analyzed here) the frequency of most VLF transmitters was controlled by crystal oscillators which drifted in frequency and therefore in phase to such an extent that meaningful studies of long-period (>10 days) variations are difficult if not impossible. The 16 kHz transmission from station GBR in Rugby, England, was unique during this period since the frequency of this transmission was compared on a daily basis to a cesium atomic standard located nearby at the National Physical Laboratory, Teddington, Middelsex, England. The average frequency deviation of the GBR transmissions over a 24-hour period was measured and recorded (Pierce et al., 1960; Reder, private communication, 1973). The received transmission at APL was also compared to a cesium reference which is part of the receiving facility. The NLK transmitter oscillator was put under direct cesium control in May 1967. Before then the day-to-day variations in the NLK data (±10 μsec) were often very much larger than the GBR variations (±2-3 μ sec). This makes the use of the NLK data extremely difficult for a long-period analysis and may explain in part the poor correlations obtained using the NLK transmission data for 1965.

With transmitter and receiver oscillators controlled by cesium standards, the precision of the frequency measurement is better than a few parts in 10^{11}, so that the relative phase delay at APL or USNO can be determined with a precision less than a μ sec in a 24-hour period. Thus, variations in the ionospheric waveguide height that produce phase changes more than a few μ secs in a 24-hour period can be detected. Since a ±1 km uniform change over the GBR-APL path would produce a ±2.9 μ sec change in relative phase, we may expect to be able to detect height fluctuations of this magnitude.

The GBR transmitter oscillator was placed under direct control of a rubidium standard in 1967 which considerably reduced the longterm frequency drift (although not as effictively as by the cesium standard). A parabolic phase variation was subtracted to correct for this drift in the GBR-USNO phase data during the 1969 period presented here.

All the VLF data presented here were subjected to a five-day running mean.

The VLF phase variations may be considered as representative, approximately, of the variations of the reflection height averaged over the transmission path. For comparison with electron density variations calculated from the ionospheric soundings at Aberystwyth, and with meteorological data estimated for particular longitudes (see next section) we can consider the VLF phase changes to correspond to horizontally averaged observations over the midpoint of the path, that is about 40°W for the GBR path and 100°W for the NLK path.

METEOROLOGICAL DATA

The geopotential heights at various latitudes and levels had been subjected to longitudinal Fourier analysis previously in connection with another study (Deland 1973). Since the VLF paths are relatively long, and also because previous work has indicated that the largest scale variations extend upward to a greater extent than the smaller scales, we have calculated values of the geopotential height at a particular longitude by summing the contributions of the first three zonal wavenumbers 1, 2 and 3. These longitudinally smoothed values of geopotential height were then subjected to a longitudinal and time-lagged auto-correlation analysis ("auto" because it is the same variable at different places and times that is being correlated), the height fluctuations at four different longitudes being correlated with the fluctuations at zero longitude. Lag correlation coefficients were calculated for $y_\lambda(t + \tau)$ and $y_0(t)$ where y_λ and y_0 are the geopotential height values at longitude λ and zero, respectively, and τ is the delay in days at longitude λ relative to longitude zero. The results are presented in Figure 2.

The zero and 90°W longitude graphs for 1965 (Fig. 2a) are almost opposite in phase, so the fluctuations appear to correspond to a wavelength of approximately 180 degrees, that is, the three harmonics average out to essentially a "wave two" pattern. It is also apparent from all four graphs of 1965 that the best positive correlation is found for increasing lag as longitude λ increases corresponding to the composite wave moving eastward with an average speed of the order of 8 degrees of longitude per day.

In 1969, a comparison of the 45°E and 90°W graphs (Fig. 2b) indicates that the average half wavelength of the composite wave is of the order of 135 degrees, somewhat longer than in 1965. The composite wave for 1969 is apparently moving westward (increasing lag westward) with an average speed of about 15 degrees of longitude per day.

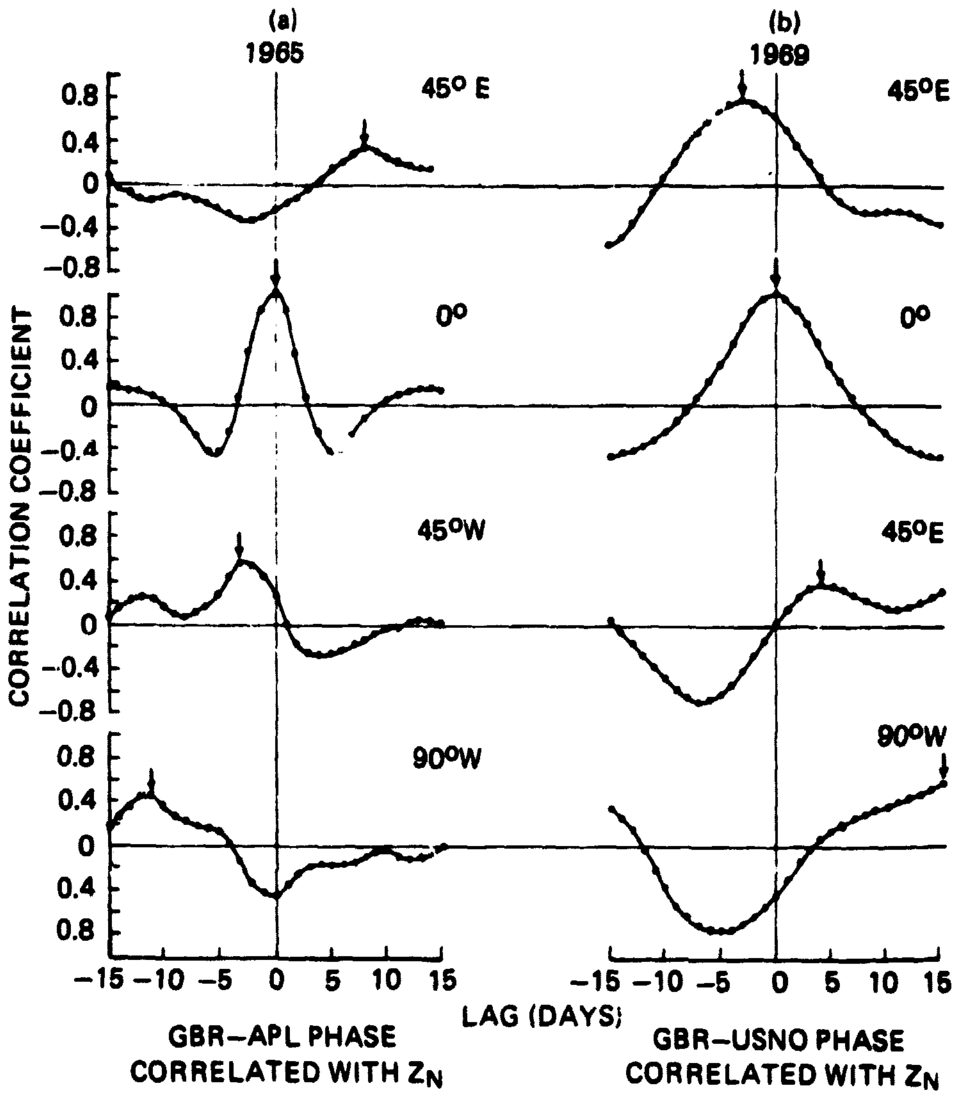

Figure 2. Auto-Correlations of the Variations of 10 mb Geopotential Height Corresponding to the First Three Harmonics Relative to Zero Longitude for the First Three Months in (a) 1965 and (b) 1969.

COMPARISON OF IONOSPHERIC AND METEOROLOGICAL DATA

The running 5-day average of the daytime relative phase delay for the GBR-APL path is plotted in Figure 3 for the first three months in 1965. The relative phase is measured in units of μ sec (10^{-6} sec). The effective reflection height, computed by the method described earlier, relative to a 70 km height, is also indicated in this figure. Also shown in Figure 3 are the variations of the

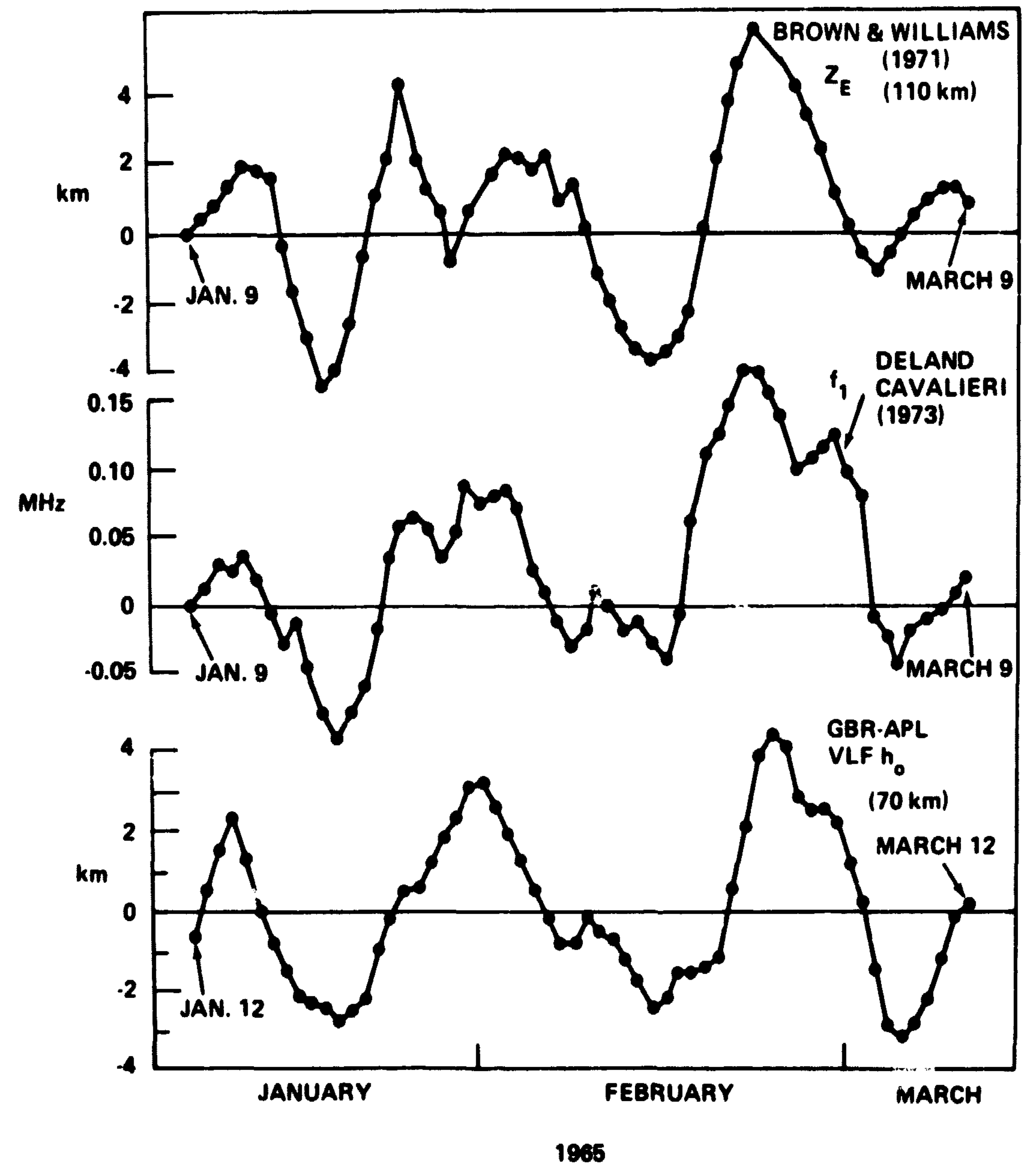

Figure 3. The Height Z_E of the Constant Electron Density Surface for N = 4.5×10^4 elec/cm^3 in the E-Region over Aberystwyth from Brown and Williams (1971), the Interpolated Values of f-min at Zero Longitude Corresponding to Zonal Wave Number 1 (f_1) from Deland and Friedman (1972), and the Running 5-day Average of the Daytime Relative Phase Delay of the GBR-APL Path for 1965.

interpolated values of f-min at zero longitude corresponding to zonal wave number $1(f_1)$ determined by Deland and Friedman (1972) and the height Z_E of the constant electron density surface for $N = 4.5 \times 10^4$ elec/cm^3 in the E-region derived by Brown and Williams (1971) from ionograms measured at noon at Aberystwyth (located near the GBR transmitter at Rugby). The three different ionosphere measurements shown in Figure 3 appear to be well correlated when the VLF data are delayed by about 3 days with respect to the f_1 and Z_E data.

The same GBR-APL phase variations are plotted in Figure 4 with the geopotential height corresponding to the sum of the first three Fourier harmonics computed for each day at 50°N geographic latitude and 90°W longitude. The "daily equivalent planetary amplitude" A_p (Rostoker, 1972) is used here as the daily over-all index of magnetic activity and is also plotted in Figure 4. The times of polar cap absorption events (PCA's) and geomagnetic storm sudden commencements (SC) are also indicated in this figure and their effect on VLF signals will be discussed later.

The running 5-day average daytime relative phase delay for the NLK-USNO transmission during the first three months of 1969 are plotted in Figure 5. The height of the 10 mb surface at zero longitude calculated from the first three zonal harmonics at 50°N geographic latitude is also plotted in this figure, but shifted to 4 days later with respect to the VLF data. The A_p indices and times of PCA's and SC's are plotted in Figure 5 on the same time scale as the VLF data.

In Figure 6 the results of a lagged cross-correlation between the VLF phase data and the 10 mb geopotential height data are presented for several longitudes for both periods analyzed.

DISCUSSION

The comparison of the GBR VLF phase fluctuations with the 90° W component of the 10 mb data for 1965 (Fig. 4) shows the two time series to be well correlated when the latter is lagged by about fourteen days. The correlation is 0.67 which is significant at the 0.025 level assuming 11 degrees of freedom for a sample of 56 data points using the "Student's" t statistic (but of course the choice of lag is also relevant in estimation of significance). There is also a good correlation between the VLF and the 10 mb data at 45°W longitude when the VLF is lagged by 9 days. The correlation is 0.65 at the 0.01 level assuming 12 degrees of freedom from a sample of 61. The best positive correlation at zero longitude is 0.36 at the 0.2 level with a lag of 4 days.

In Figure 6a the lag correlation coefficients mentioned above are marked by arrows at each longitude. The lag correlation curves for 45° E and 45° W are almost

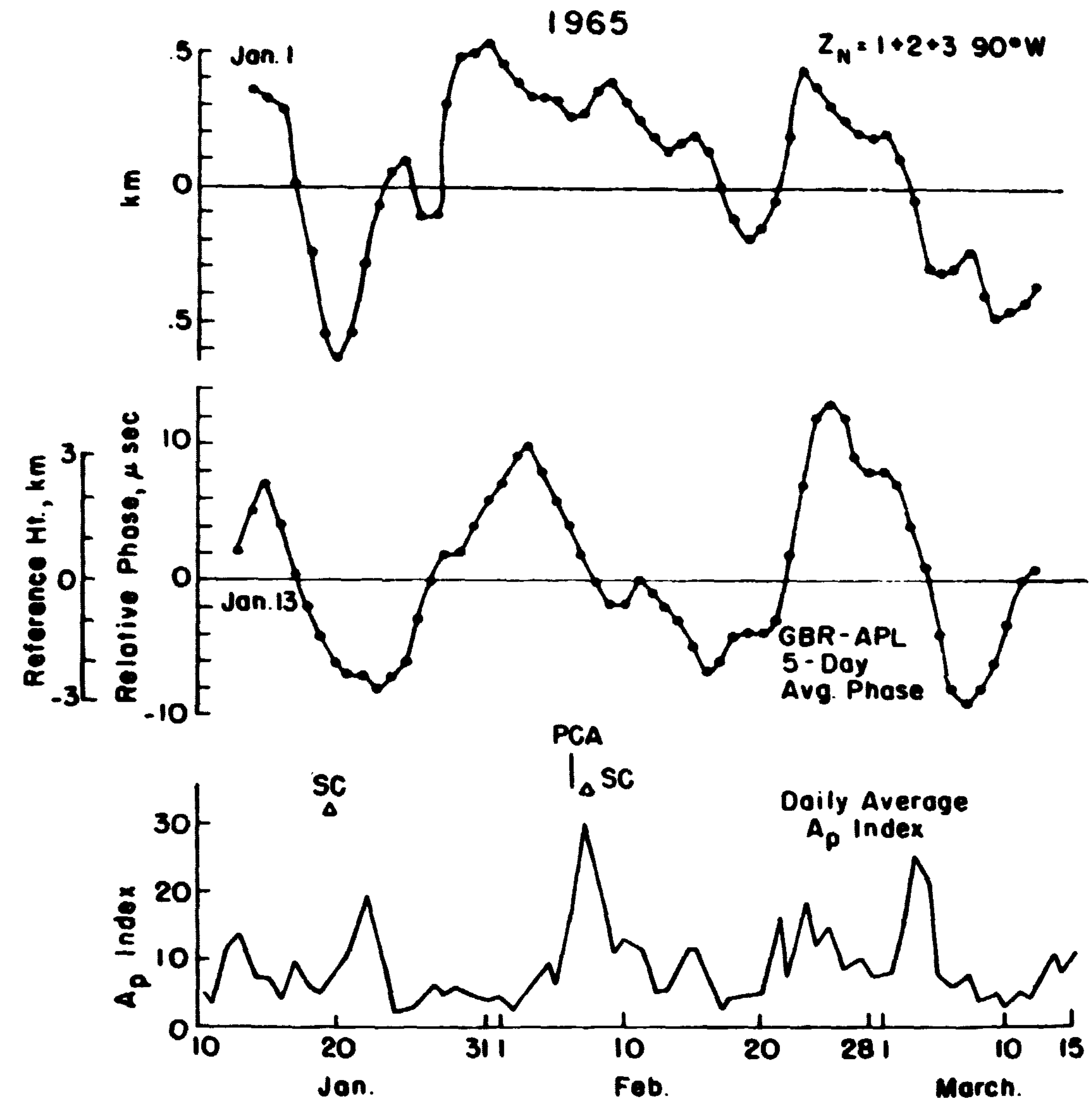

Figure 4. The 10 mb Geopotential Height Corresponding to the Sum of the First Three Fourier Harmonics at 50°N Geographic Latitude and 90°W Longitude, the Same GBR-APL Phase Variation from Figure 3, and the Daily Equivalent Planetary Amplitude A_p (Solar Geophysical Data, U.S. Department of Commerce).

180° out of phase corresponding to a wave two pattern (that is the VLF data are correlated with an average two pattern) in agreement with the auto-correlation of the 10 mb height data for 1965 (Fig. 2). It is apparent from an inspection of the correlation curves for all four longitudes that the VLF correlated fluctuations at 10 mb are travelling eastward (increasing lag eastward) with an average speed of approximately 8 degrees of longitude per day which is again in agreement with

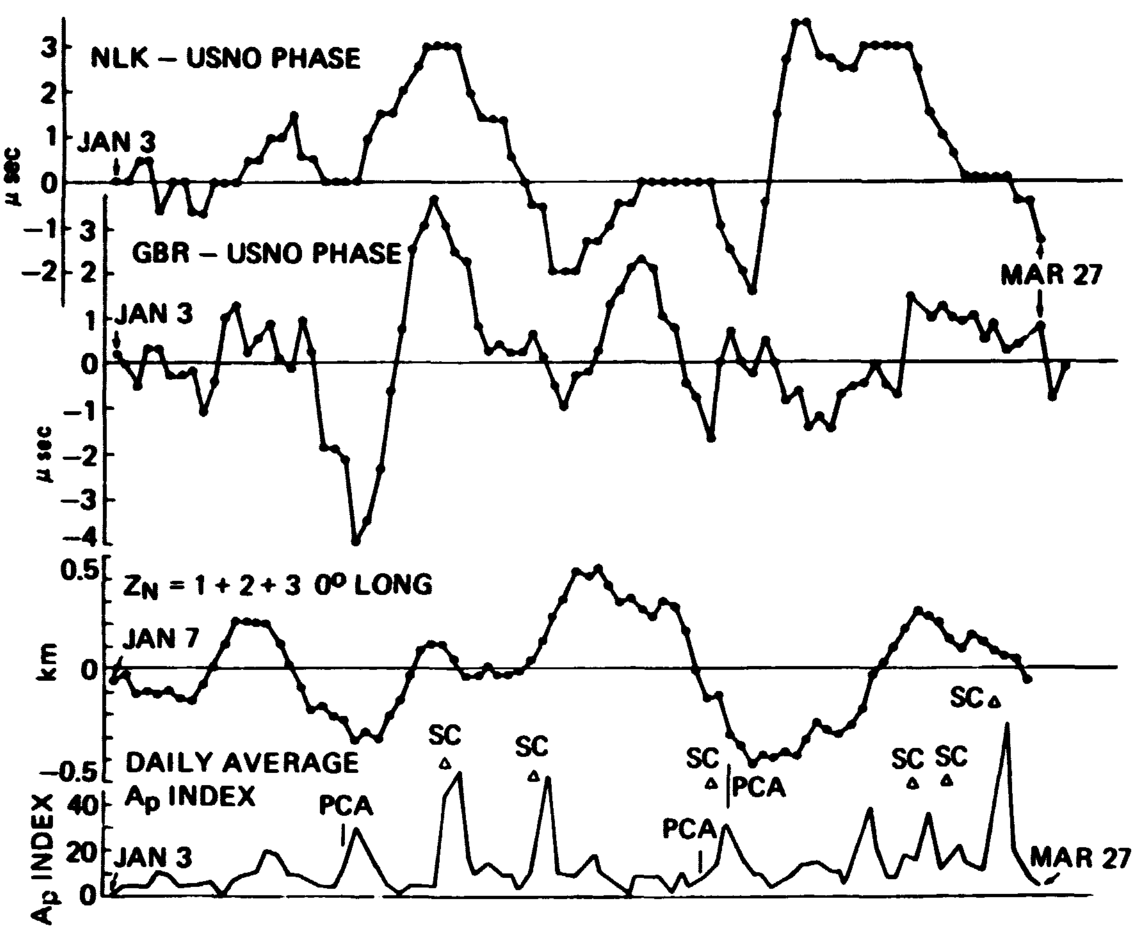

Figure 5. Running 5-Day Average of the Daytime Relative Phase Delay for the GBR and NLK Transmissions Received at the U.S. Naval Observatory, the Height of the 10 mb Surface Calculated from the First Three Zonal Harmonics at a 50°N Geographic Latitude and 0°Longitude, and Daily Equivalent Planetary Amplitude A_p for the First Three Months of 1969.

the speed of the wave at 10 mb. Therefore, from a comparison of Figures 2a and 6a, it may be tentatively concluded that there are fluctuations at 70 km moving eastward with approximately the same speed as those at 30 km (10 mb). Also, from Figure 6a, the correlation between the VLF data (for 0-75°W) and the 10 mb height data is greatest at zero lag around zero longitude and 45° E, indicating westward tilt with height. Since the waves appear to be moving eastward, the 3-day delay of the GBR-APL phase with respect to the f-min and z_E variations (which are dependent upon ionization changes at higher altitudes than the daytime VLF reference height) indicate an eastward tilt above 70 km.

In 1969 the phase fluctuations are leading the 10 mb geopotential height data (Fig. 5). The correlation of the VLF phase data when leading the 0°longitude

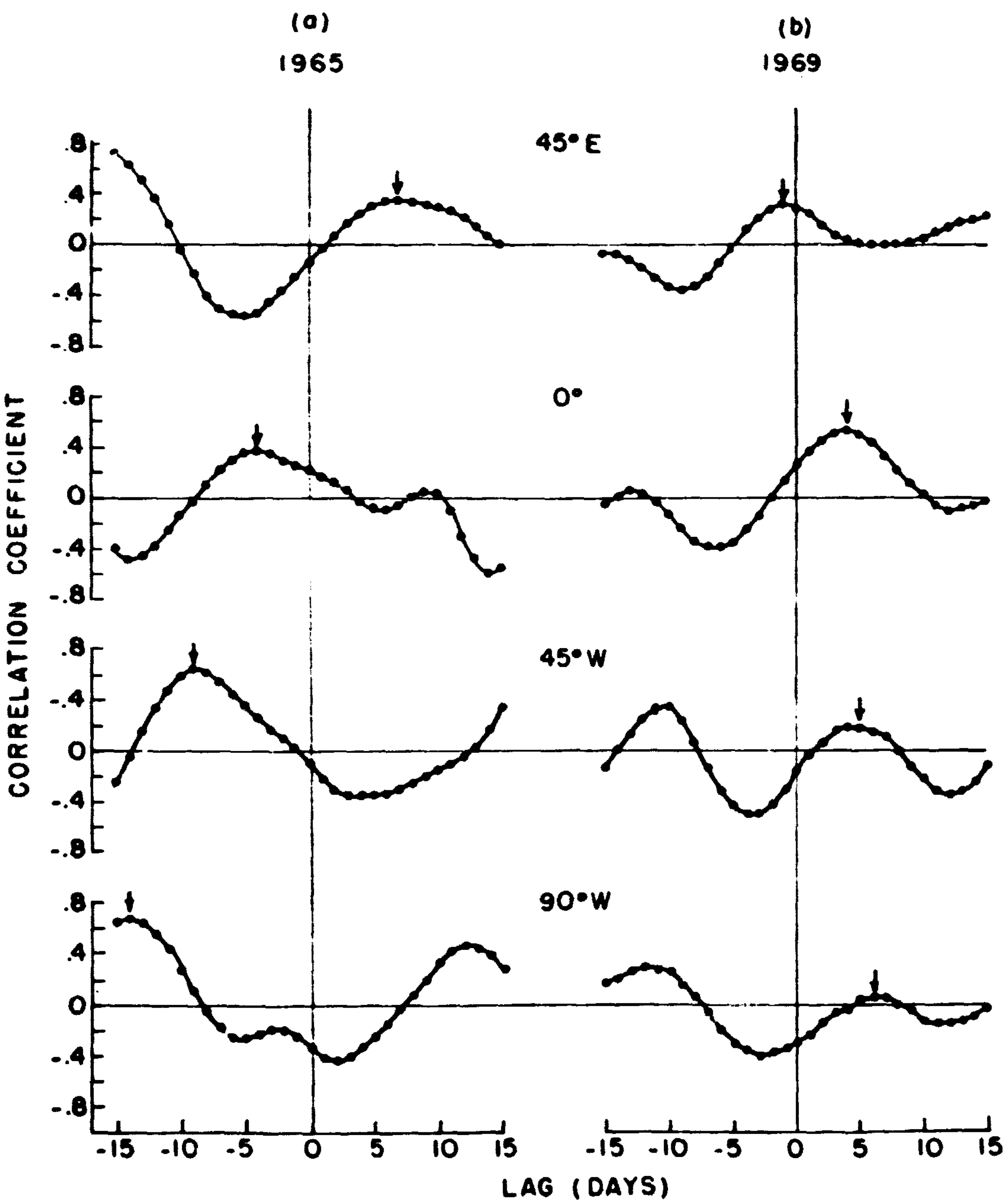

Figure 6. Correlations Between (a) the GBR-APL Phase Variations and the 10 mb Geopotential Height Data in 1965 and (b) the GBR-USNO Phase Variations and 10 mb Geopotential Height Data in 1969 for Several Longitudes.

geopotential height data by four days is 0.52 which is significant at the 0.025 level assuming 15 degrees of freedom for a sample of 76. The GBR fluctuations are almost in phase (time wise) with the geopotential fluctuations at 45°E (Fig. 6b). Inspection of Figure 6b shows that the variations appear to be dominated by a wave one pattern (the correlation nearly reverses from 45°E to 90°W) and that this pattern is moving westward (increasing lag westward) with an average speed of about 14 degrees of longitude per day, in agreement with the results at 10 mb for the same period. Since the VLF phase fluctuations are almost in phase with the geopotential fluctuations at 45°E, the wave apparently tilts westward with height. Summarizing the above, longitudinal phase relationships both in space and time presented in Figures 2 and 6 provide evidence of the existence of a westward tilted eastward travelling planetary scale wave during the 1965 period and a westward tilted westward travelling wave in 1969.

The longitudinal phase relationships discussed above for both periods analyzed were also present before smoothing of the VLF data, so these phase relationships are apparently real and are not due to averaging techniques.

Comparison of the phase fluctuations along the two paths analyzed (NLK and GBR) did not indicate any definite phase (longitudinal) relationship in 1965, which seems likely to be due to the severe frequency drifts of the NLK transmitter oscillator during that period.

In 1969 correlation of the NLK and GBR fluctuations computed over the whole period was weak. However, there appears (Fig. 5) to be a good correlation between the two paths for January and February. The reason for the poor correlation in March is not obvious, particularly since the entire 1969 period is marked by relatively high geomagnetic activity. A discussion of geomagnetic effects on VLF propagation is presented in the next section. The correlation between the phase fluctuations of these two indicate that the fluctuations at least during January and February were of large scale both in longitude and latitude.

The fact that the phase fluctuations along the GBR path correlate better with the 10 mb data than do the fluctuations along the NLK path may be due in part to the lower geographic latitudes of the NLK transmission path. Studies made with shipborne absorption experiments (Schäning, 1973) have suggested that there may be a geographic latitude "cut off" around 35°N - 40°N latitude for such events as variations of D-region absorption that are apparently due to planetary wave effects. Therefore, a southern boundary may exist (~40°N) south of which planetary scale wave transmission may be inhibited. Dynamical models (Dickinson, 1969; Matsuno, 1970) of upward transmission of planetary scale wave energy also indicate that such upward transmission should mainly occur in high latitudes. More significant correlations would then be expected at higher latitudes.

Deland and McNulty (1973) have derived an approximate relationship for the time and zonal average energy conversion from the zonal flow to a traveling planetary-scale wave:

$$\overline{C}_T = -\frac{U_p}{\sigma} \frac{k^2}{a \cos\varphi} \frac{Z^2{}_T}{2} \frac{\partial\lambda_T}{\partial p}$$

where

λ_T = the phase of the traveling wave
p = pressure
Z_T = the amplitude
φ = the latitude
σ = the hydrostatic stability factor
k = the zonal wave number
U = the eastward wind velocity
U_p = $\partial U/\partial p$

From this expression it follows that if the eastward zonal flow decreases with height (i.e. $\partial\lambda_T/\partial p > 0$) the waves must tilt eastward with height for the energy conversion to be positive. On the other hand if the zonal flow increases with height then $\overline{C}_T$ will be positive only with a westward tilt with height.

From observational studies Deland (1973) has found that in the lower stratosphere at mid latitudes the traveling planetary scale waves apparently adjust their structure relative to the zonal flow so that energy is converted from the zonal flow to the waves at the levels studied.

In view of the fact that in winter the eastward zonal flow increases with height from 30 km up to the stratopause and than decreases, it is not surprising to find that the VLF fluctuations are lagging behind both the geopotential data at 10 mb and f-min and E-region electron density isopleths for the 1965 period (see Fig. 3). Although the height of the stratosphere is taken to be at about 55 km at mid latitudes, various studies have shown that winter mid latitude west wind maxima vary greatly. Maxima heights as great as 70 km have been reported (Batten, 1961).

The results obtained from the above correlations seem to be consistent with the study made by Deland (1973). The tilt of the wave fronts of these transient planetary waves are such that energy on the average is converted from the zonal flow to the wave up to the E-region and possibly higher. Such an energy supply for the waves could compensate the losses due to radiational cooling, for example, as analyzed theoretically by Dickinson (1969).

PCA AND GEOMAGNETIC STORM EFFECTS ON VLF PROPAGATION

The phase of midlatitude VLF transmissions during daytime conditions is not often affected by geophysical disturbances in comparison to high latitude or nighttime VLF transmissions. The daytime phase is sometimes disturbed by 1-10Å x-rays during solar flares, but these effects usually last for less than 1 hour and cannot affect the slow planetary-scale variations analyzed in this paper. However, during PCA events, the sun can provide a sufficient number of energetic particles to penetrate down to a 70 km altitude and disturb VLF transmissions for long periods of time (e.g. 1 to 10 days). The excess ionization during PCA's is confined to the polar caps of the earth (>63° geomagnetic latitude) except during severe magnetic storms when these effects extend to lower latitudes (Zmuda and Potemra, 1972).

The only PCA event that occurred during the first 3 months of 1965 began on February 5, 1965 and was relatively minor (producing a peak 30 MHz polar cap riometer absorption of 1.8 db in comparison to 12 db for more severe events). Riometer measurements at several latitudes during this event by Bailey and Pomerantz (1965) indicate that ionization effects were negligible at or below L = 4 (the highest L shell reached by the GBR-APL path).

The comprehensive review of VLF and LF propagation disturbances at midlatitudes associated with geomagnetic storms by Belrose and Thomas (1968) indicates these disturbances are "most marked during twilight and night hours, and are usually absent at noon." The geomagnetic storm which accompanied VLF disturbances presented by Belrose and Thomas were characterized by a range in the daily equivalent planetary amplitude A_p = 100 to 150. The largest A_p value in the period 1 January to 20 March 1965, as shown in Figure 4, was equal to 31 following the storm sudden commencement (SC) during the PCA on February 5, 1965. Except for this minor PCA, the entire period during the beginning of 1965 can be characterized as magnetically quiet. It appears unlikely therefore, that the long-term variations in the GBR-APL phase shown in Figures 3 and 4 can be attributed to PCA or geomagnetic storm effects.

During the period 1 January to 27 March 1969, three minor PCA events occurred, which began on January 24, February 25, and February 27, with the peak 30 MHz riometer absorption equal to 1.7 db. These are indicated in Figure 5 and there do not appear to be any clear effects on the GBR or NLK-USNO phase variations. For example, the relative phase on both paths began to decrease on 20 January 1969 <u>preceding</u> the January 24 PCA and the phase delay increased after this event, instead of decreasing as would be expected for polar VLF transmissions during PCA events.

A large number of geomagnetic storm sudden commencements occurred during the beginning of 1969 and these are shown in Figure 5 with the daily planetary amplitudes A_p. The magnetic activity for the month of January 1969 is relatively low (maximum $A_p = 29$) when the GBR-USNO phase delay reached its most negative value during the entire period shown in Figure 5. Because of the number of SC's in February and March 1969, it is difficult to prove conclusively that none of the VLF variations shown in Figure 5 are associated with magnetic storm effects. However, the level of geomagnetic activity during this period (maximum $A_p = 62$ for February and maximum $A_p = 79$ for March) is only moderate in comparison to the larger geomagnetic storms that have been observed to produce daytime mid-latitude VLF disturbances (Belrose and Thomas, 1968).

CONCLUSION

Comparison of VLF phase measurements with stratospheric geopotential height data indicate the presence of traveling planetary scale waves in the ionosphere.

The use of long distance VLF transmissions as an ionospheric probe is usually limited by the fact that localized disturbances (small in spatial extent compared to the path length) are difficult to detect. But, as shown here, the VLF phase data can be very effective for the study of planetary-scale disturbances. Further, the VLF is affected by a smaller altitude range of ionization in the D-region, in comparison to MF or HF absorption measurements, and is therefore, a more direct measure of small changes (about ± 1 km) in the effective height of the ionosphere near a 70 km altitude.

For these reasons and as demonstrated here, stable-frequency VLF transmissions can serve as a useful tool for the study of stratospheric-ionosphere coupling. They should be especially useful in studying the vertical propagation of energy into the ionosphere in terms of the vertical structure of both the quasi-stationary and transient planetary scale waves.

The results presented in this paper appear to be consistent with requirements for upward propagation of energy.

It is hoped that further use of VLF transmissions in the study of transient planetary scale waves in the ionosphere will make possible the forecasting of meteorological effects on the ionosphere in the near future.

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QUESTION AND ANSWER PERIOD

DR. REDER:

Any questions, please?

MR. MERRION (Defense Mapping Agency):

I was wondering, what other implications would this have, other than for weather forecasting? Also is it possible to go backwards, do you think, to take the weather forecasts and predict something about your VLF transmissions?

DR. POTEMRA:

Absolutely. As a matter of fact, in response to your latter point there, that is exactly what we have been using.

At one point we weren't really convinced that the meteorological disturbances did have an effect on the ionosphere. There are many, many reasons why it should not, because there are various temperature minima as one plots temperature versus altitude.

And one would suspect that anything that happens on the ground would be insulated from the Earth's ionosphere that is so high up. There is no reason to expect why it should propagate upwards.

But we believe, by looking at the meteorological data first, and then correlating it with the VLF data, that there is a connection.

So, this is the direction that we have been going now.

I only mention that as a very, very low possibility of using the VLF to perhaps predict what is going to happen on the ground, because there is a great deal of interest; as you know, Walter R. Roberts is now advocating his theory that the interplanetary magnetic field can be used to predict weather, and things like this.

So, this is quite a controversial issue. But I think at the present point we can claim that by using the meteorological data, we can correlate it directly with ionospheric oscillations.

Now, as far as implication is concerned, I suppose if you are using the VLF as a time and frequency reference that you have to be concerned in the winter months as to long period stabilities and disturbances caused by the ionosphere, because some of these can come out to 20 microseconds or so.

But I am just not clear how this would work into a time and frequency network.

DR. REDER:

Coming back to your question, maybe that will be the only useful application of weather forecasting.

(Laughter.)

DR. REDER:

Any other questions? Yes, please.

DR. KLEPCZYNSKI:

I think there might possibly be another application. I haven't done any order of magnitude estimates on the back of an envelope yet, but if we have an idea from VLF how the atmosphere is acting, astronomers might be very interested in this because they might be able to get data on refraction.

DR. POTEMRA:

Oh, absolutely. If we look at some of the data that was presented on VLBI, for example those oscillations in the early morning hours seem to exhibit periods, I think, of 15 to 20 minutes. But in any case, it was reminiscent, not of planetary waves with 15 to 20 day periods, but of acoustic gravity waves that have been looked at in great detail. They have periods of 10 to 30 minutes, and they are often found after sunrise, because when the atmosphere gets a big blast of heat from the Sun it starts shaking. Also it is seen as the Sun sets, because that is when things cool down.

So, yes, I think that would be an important input to people for very long baseline interferometry.

DR. REDER:

I have a question, Dr. Potemra. Maybe I missed it when I was outside.

Isn't it so that this kind of an effect will be mostly seen on paths which are fairly high in latitude?

DR. POTEMRA:

Yes, I didn't mention that, but this is a latitude restricted phenomena, and we just can't get anything from high latitude paths, because they are very disturbed by the auroras, as you will know from your work, but there appears to be a lower latitude cutoff also, and this cutoff occurs at about a 40 degree north geographic latitude. For example, the paths that we have down to Panama or to Trinidad, that is around the Equator or the Southern Hemisphere, there appears to be no variations of this sort. Professor Deland has an explanation for this, and it has to do with the propagation of the atmospheric disturbances.

But they are definitely restricted at latitudes above 45 degrees north geographic. If one gets higher than that, for example, up to 60 or 70 degrees geographic; then we would like to talk about geomagnetic latitude; and then we would have to be more concerned about short period disturbances due to particle precipitation and things like this.

DR. REDER:

Any more questions on this paper?

MR. CHI:

In your data which was presented, apparently you have correlated the nighttime phase record with magnetic disturbances.

DR. POTEMRA:

Yes.

MR. CHI:

What other parameters have you identified, temperature or --

DR. POTEMRA:

Now, you are referring to the nighttime disturbances correlated with the magnetic activity, is that right?

MR. CHI:

Right.

DR. POTEMRA:

I went very quickly over that, because it is related to an analysis that we did about a year ago. I think Dr. Reder has quite a bit of experience in this area as well, but the situation is this, during the nighttime we very often see very small disturbances that are correlated with magnetic activity.

The question is why. Now, on one occasion, during a so-called magnetic substorm, measurements of precipitating electrons were made down at the South Pole, of all places, and also whistlers propagation, VLF emissions. These are long, very long frequency waves that propagate back and forth on the magnetic field lines.

They were also correlated with the onset of the same type of VLF disturbances, and on at least this one occasion we put together an argument that the VLF transmission phase disturbances were due to precipitating electrons that were being dumped out of the Van Allen radiation belt, and that these were due to these whistlers propagating back and forth, and that another manifestation of the substorm — now, it wasn't a big storm, a small storm — was the ground base magnetogram deflection.

Now, we have been trying to advocate the theory that when one sees these nighttime VLF disturbances, they are due to precipitating Van Allen electrons that are associated with magnetic disturbances.

Now, unfortunately, they occurred so often and it is very difficult to get all these things coordinated. But we think the evidence is very strong that this is the case.

Now, that has nothing to do at all with meteorological disturbances. I just wanted to point out that we have to sort out magnetospheric disturbances from meteorological disturbances, and one has to be very careful.

MR. CHI:

Did you correlate with respect to temperature, for instance?

DR. POTEMRA:

'n the metoerological disturbances, yes, we have done that as well because pressure and temperature would certainly work together, and there is an effect which has been long known, when one looks at absorption of HF radio waves, called the winter anomaly. During the winter months when the atmosphere cools down, they have observed for many, many years, 20 years, that the absorption, now, not VLF, the absorption disappeared as well. Not completely, but reduces, except on certain days, when the temperature increases on the ground for a few days — these are called stratospheric warmings — and the absorption also increases. This was first detected, I believe, by Professor Louckes in 1950 or so in Berlin, and it was called the "Berlin warming."

So, that is another manifestation, but VLF hasn't yet been used for this. But certainly temperature correlations have been made, yes.

DR. REDER:

Any other questions on this paper?

(No response.)

DR. REDER:

So, let's start now with our general discussion of all the papers which have been given up to now, and who wants to ask a question or comment or anything?

Yes.

MR. MONTGOMERY (WSM, Nashville):

For several years we have been running phase recordings on WWVB at Nashville, and we have noticed on a number of occasions that there will be a shift about noontime on certain days.

I was just wondering if anyone else has noticed this? This is a shift that looks like the start of a diurnal shift, but it is only for a short period.

DR. REDER:

Is anybody here from the Bureau of Standards, or from the power companies, somebody who uses WWVB?

(No response.)

DR. REDER:

May I ask you, Mr. Montgomery, when was this? When did you observe it?

MR. MONTGOMERY:

On a number of occasions in the past, but I don't have the data with me at present, but I can look this up. We have the records for the past three or four years.

DR. REDER:

And it happened at noontime, local noontime?

MR. MONTGOMERY:

Right, local noontime.

DR. REDER:

Well, was it an SID, maybe? How long did it last?

MR. MONTGOMERY:

A matter of an hour or so.

DR. REDER:

Well, it could be an SID.

Are there any other questions? Yes.

MR. MERRION (Defense Mapping Agency):

I have a question for Mr. Amlie of FAA.

I asked Dave Call this same question, but I guess I didn't get the intent of my question across.

The Air Force, or whoever is responsible for changing the name of that GPS so many times, is about to go ahead with the GPS — NAVSTAR system.

My question is not referred to the synchrodabs, but the astrodabs. Wouldn't it be reasonable to plan on using an astrodab system to be compatible with the GPS system, rather than as a synchronous orbit system?

MR. AMLIE:

Let's see, how do I handle that answer?

First of all, the astrodab really isn't real. You know, it is fashionable to have a satellite program, so we have one.

(Laughter.)

I am serious. I own an airplane, and my wife and I share a checkbook, and I simply couldn't afford the kind of avionics that is required, to participate in a satellite system.

The military have a need for global coverage, they have a need for secure criptographic navigation and communications. Their needs are entirely different from the civil community, and they are willing to pay, as all we taxpayers know. It is entirely different. So, I think it is not reasonable.

DR. REDER:

Yes.

MR. MERRION:

In reference to what you just said about general aviation, someone who is in operations thought that proximity warning devices are the ideal collision avoidance system, and wouldn't something in this area, say, in infrared sensors, wouldn't this be the . . . .

MR. AMLIE:

Again, it is a matter of economics. The system that was used at Fort Rucker by the Army was a short range system, because they had a severe problem with helicopter training. As you know, they have a couple of square miles and an enormous number of helicopters, and they had a problem, they had people killed in collisions.

The equipment they bought was very short range, it was $5,000 a unit. If you are to use it for fixed wing aircraft, it has to be, you know, much fancier, and the price goes up.

Our goal in the DABS operation is to have the entire avionics units under a thousand dollars.

DR. REDER:

Any more questions on anything?

DR. WINKLER:

I would like to make a comment though and that goes back to the slide that you just gave.

I think there is one more point in the considerations, and that is 99 percent of all general aviation is not interested to find their location in the middle of the Pacific. They want to have something to go here in the Continental United States.

Now, for those few who are in the middle of the Pacific, or who are bush pilots in Northern Canada or in Alaska, there are additional systems which are economical and which are on the market today. I wanted to mention that, and also that they do not only use Omega, which at the moment is kind of frustrated because of a lack of operational transmitters. I imagine, of course, that this will eventually be done. There are stations on the air which are entirely compatible with Omega. These are the high power VLF stations, and I hope to hear a little bit more about this this afternoon.

They are being used for navigation by a large number of aircraft, already going into many hundreds of users.

What general aviation can do, other people can do as well, and I think the application of precise frequency control of VLF transmissions, be that now Omega transmissions, or be that the communications transmissions, is something which is still an important item, and it is for that reason that I think that research on prediction of propagation phenomena must continue.

We have had this morning the correlation with atmospheric phenomena, and I think that is just one of the things which we have not yet completely under control, and I think until we are in a position to set up somewhere and to have a predicted, accurate time of propagation from a station for a specific frequency — we are still a little bit away from that.

Would you agree with that, Dr. Reder?

DR. REDER:

Yes.

MR. WILSON:

I am Robert Wilson, from Aerospace Corporation, from the division that is involved with NAVSTAR.

As sort of an instant lay expert, I have been studying a lot of data that has been produced by many people in the audience. I would like to know why I have seen a great deal of data plotted as a variance of $\delta f/f$, but essentially no data plotted as a variance of $\delta t/t$, which is of considerable more interest to us, for example, than the frequency variation.

DR. REDER:

Well, if you give me your address, we could send you, for instance, as far as VLF is concerned, data on phase as a function of time.

I understand there are some data, for instance, on the change of the total electron content which can be related to the change in the time delay of satellite signals to ground stations. I am sure they are available from many sources, perhaps Dr. Soischer or Mr. Gorman who is here. He can take your address and send you data on that.

DR. WINKLER:

You may not have zeroed in on exactly the sense of the question here.

Frequency and Phase, the two are related. The sigma of a time variation, of course, is related to sigma of frequency variations. It is very simple to convert one plot into the other, once you agree what you want to accept as a good statistical measure of time deviations.

One misunderstanding which I find most often in discussions about probable time deviations is the simple fact that the most likely position of your clock in any future moment will be with no time deviation. There is an equal probability for the clock to be late or slow (in relation to its extrapolated rate).

One has to keep that firmly in mind, that the most probable clock closure, or clock error when you resynchronize, is zero.

What we are talking about is the width of the distribution function of these clock errors when we make many synchronizations. This width is quite clearly related to the sigma/tau plots for frequency variations.

I would use the following measure $\delta_t(\tau) = \tau \cdot \delta_{\frac{\Delta f}{f}}(\tau)$ and apply an additional factor $\sqrt{2}$ in order to be conservative.

MR. WILSON:

Let me make the point that while these are convertible, it is not always easy to do, particularly for people who aren't experienced in the field of statistics.

Both for the Air Force and for engineers who are not experts in the field of frequency, and the field of time determination, it would be extremely convenient to have curves and data that show the way in which the errors in clocks over long periods of time will develop, and these simply don't seem to exist. At least we haven't been able to run them down.

Now, I understand from what you have said that this is available, and I will be glad to talk to you. But I did want to make that point, it is perhaps more a matter of laziness or inconvenience than the actual overall capability of being able to convert.

DR. WINKLER:

One source which is widely distributed and available is one of the older Hewlett-Packard catalogues. I don't know why HP, in the most recent catalogue has omitted the right-hand scale of the sigma tau plots. I think that they have been paying tribute to some perfectionist, because of the lack of standardization in sigma tau, or sigma subscript tau.

But I think it was a useful device, and maybe HP would like to respond to that question, why did you omit in your catalogue the right-hand side?

MR. BOURDET (Hewlett-Packard):

I think it was just a very simple economic move rather than anything else. We thought we could simplify the graph. We had to make it small in the catalogue and it was getting very confusing with so many lines.

DR. WINKLER:

Maybe, since this is a generally interesting question, I should reply to it more fully.

There is a considerable amount of information in the paper on characterization of frequency stability by Barns and co-authors, members of that committee, particularly see equation 39 on page 113 of the IEEE IM20 paper (May 1971).

In addition, there have been publications where direct measures in time have been cited, e.g. our paper in metrologia Oct. 1970 or Cutler & Venot, NEREM Record page 68, 1968. If you have a sigma tau frequency plot you add one to the slope, e.g. for a -1/2 slope in frequency you get a + 1/2 slope in time, etc.

DR. REDER:

Any more questions?

(No response.)

DR. REDER:

Well, let me ask you one question.

Is there anybody here who has personal experience with the problem of precipitation statics on antennas used in aircraft navigation? Anyone?

MR. AMLIE:

Well, I can give a sort of an answer. It is a problem, precipitation static has been a problem for a long time in aircraft. There are some excellent little plastic widgets with very sharp needles which seem to solve the problem, certainly on HF, VHF is not a problem. It is a little plastic widget that works fantastically well down to VLF.

DR. REDER:

Well, maybe you should also get in touch with your people at Atlantic City, because they seem to have a problem.

MR. AMLIE:

Maybe they don't have some of these gadgets. I have one on my desk I can give them.

DR. REDER:

Any more questions, comments?

(No response.)

SESSION VI

Chairman: R. L. Easton
Naval Research Laboratory

N75 11298

IONOSPHERIC EFFECTS ON ONE-WAY TIMING SIGNALS

H. Soicher
F. J. Gorman, Jr.
U.S. Army Electronics Command, Fort Monmouth

ABSTRACT

A proposed navigation concept requires that a user measure the time-delay that satellite-emitted signals experience in traversing the distance between satellite and user. Simultaneous measurement of the propagation time from four different satellites permits the user to determine his position and clock bias if satellite ephemerides and signal propagation velocity are known. A pulse propagating through the ionosphere is slowed down somewhat, giving an apparent range that is larger than the equivalent free space range. The difference between the apparent range and the true range, or the free space velocity and the true velocity, is the quantity of interest. This quantity is directly proportional to the total electron content along the path of the propagating signal. Thus, if the total electron content is known, or is measured, a perfect correction to ranging could be performed.

Faraday polarization measurements are continuously being taken at Fort Monmouth, N. J., using beacon emissions of the ATS-3 (137.35 MHz) satellite, which is in a geostationary orbit. The polarization data yield electron content values up to ~1500 km since the measurement technique is based on the Faraday effect which is weighted by the geomagnetic field. Day-to-day variability of the diurnal variation of total electron content values is present with differences of up to 50% or more not being uncommon. In addition, superposed on the overall diurnal variation are smaller scale variations of ~ 5 to 10% of the total content which are attributed to ionospheric density irregularities.

Future experiments planned for the emissions of the forthcoming ATS-F will permit Faraday rotation, dispersive phase, and dispersive group delay measurements. The latter two will give the integrated electron density to geostationary altitudes while the first will give the density integrated to ~ 1500 km. The difference—referred to as the exospheric content—will yield the currently unknown propagation time delay from ground to geostationary altitudes.

INTRODUCTION

A space-based radio navigation system could provide military and civilian users with precise three-dimensional position and velocity data.

The navigation signals contain data such as satellite identity, real-time ephemerides information, system time and other data. To determine his position and velocity, the user cross-correlates the coded time signal received from the satellite with the same coded time signal generated in his receiver. The relative phase, or equivalently the time displacement between the user's receiver and the incoming code, determines the range to the satellite. Simultaneous measurment of such relative phases from four different satellites permits the user to determine his range and his clock bias with respect to the satellite's position and clock respectively. In addition to such range measurements, corresponding range-rates are measured by the carrier frequency Doppler shift of each signal and the corresponding motion of the particular satellite as described by the ephemerides data.

The range from user to the various satellites is, of course, not the correct geometric range. A propagating navigation signal is slowed down by the ionosphere by an amount proportional to the total electron content along its path. The electron content may be measured in real time, provided the user has dual-frequency capabilities. However, substantial reduction in the cost of user equipment could be realized if the navigation system uses only one frequency. In such a case, the ionospheric time delay will have to be determined through empirical modelling techniques, based on existing and future global electron content data, and will be transmitted to the user for correction via the navigating signal. To calculate the true range, one must determine the group velocity of the signal along the path.

The transit time of a transionospheric signal from a satellite to a ground observer is:

$$t = \int_O^S \frac{ds}{v_g} = \frac{1}{c} \int_O^S n_g \, ds, \tag{1}$$

where ds is an element of distance along the signal's path and v_g and n_g are the group velocity of the signal and the group refraction index respectively, c is the speed of light, and O and S are the observer and satellite position respectively. In the high-frequency approximation, the group index of refraction is:

$$n_g = 1 + \frac{40.3\ N}{f^2}, \tag{2}$$

where N is the electron density per meter cubed, and f is the operating frequency in Hz. Equation 1 becomes:

$$t = \frac{1}{c} \int_0^S ds + \frac{40.3}{cf^2} \int_0^S N\,ds. \tag{3}$$

The first term in Equation 3 represents the free space signal transit time, while the second term represents the signal's excess time delay in the ionosphere. The excess time delay is inversely proportional to the frequency squared so that in the L band (the proposed navigation frequency is in the 1600 MHz band) it is very small. However, the precision required by the system is such that the ionospheric time-delay has to be accounted for.

The variation of the time delay with electron content for 1.6 GHz, 400 MHz, and 150 MHz is shown in Figure 1. At 1.6 GHz, the excess delay times are 0.524 nanoseconds and 52.4 nanoseconds for a total content of 10^{16} el/m^2 and 10^{18} el/m^2 respectively, which are the lower and upper bounds of the normal vertical ionospheric electron content. For an oblique signal path, the total content increases by an amount proportional to the additional path length (assuming spherical stratification of the ionospheric density distribution). At low elevations, i.e. below 10°, the slant total content exceeds the vertical content (i.e. elevation angle = 90°) by a factor of 3; while at 40° elevation, the slant content exceeds the vertical content by a factor of 1.5. Thus, for the vertical content at the upper bound and a low-elevation signal path, the total time delay introduced by the ionosphere is ~150 nanoseconds at 1.6 GHz.

THE FARADAY ROTATION

In the high-frequency and quasi-longitudinal approximations, the two magneto-ionic modes are nearly circularly polarized in opposite senses, thus a plane polarized wave traversing the ionosphere may be regarded as the vector sum of the ordinary and extraordinary components. Since the two components travel at different phase velocities, the plane of polarization rotates continually along the signal's path. The total rotation from the signal source to the observer is related to the total electron content by the expression:

$$a = \frac{k}{f^2} \int_0^S B \cos\theta\, N ds = \frac{k}{f^2} \int_0^S (B \cos\theta \sec\chi)\, N\, dh, \tag{4}$$

where $k = 2.36 \times 10^{-5}$, B is the local magnetic field flux density in gammas, θ is the angle between the radio wave normal and the magnetic field direction, and

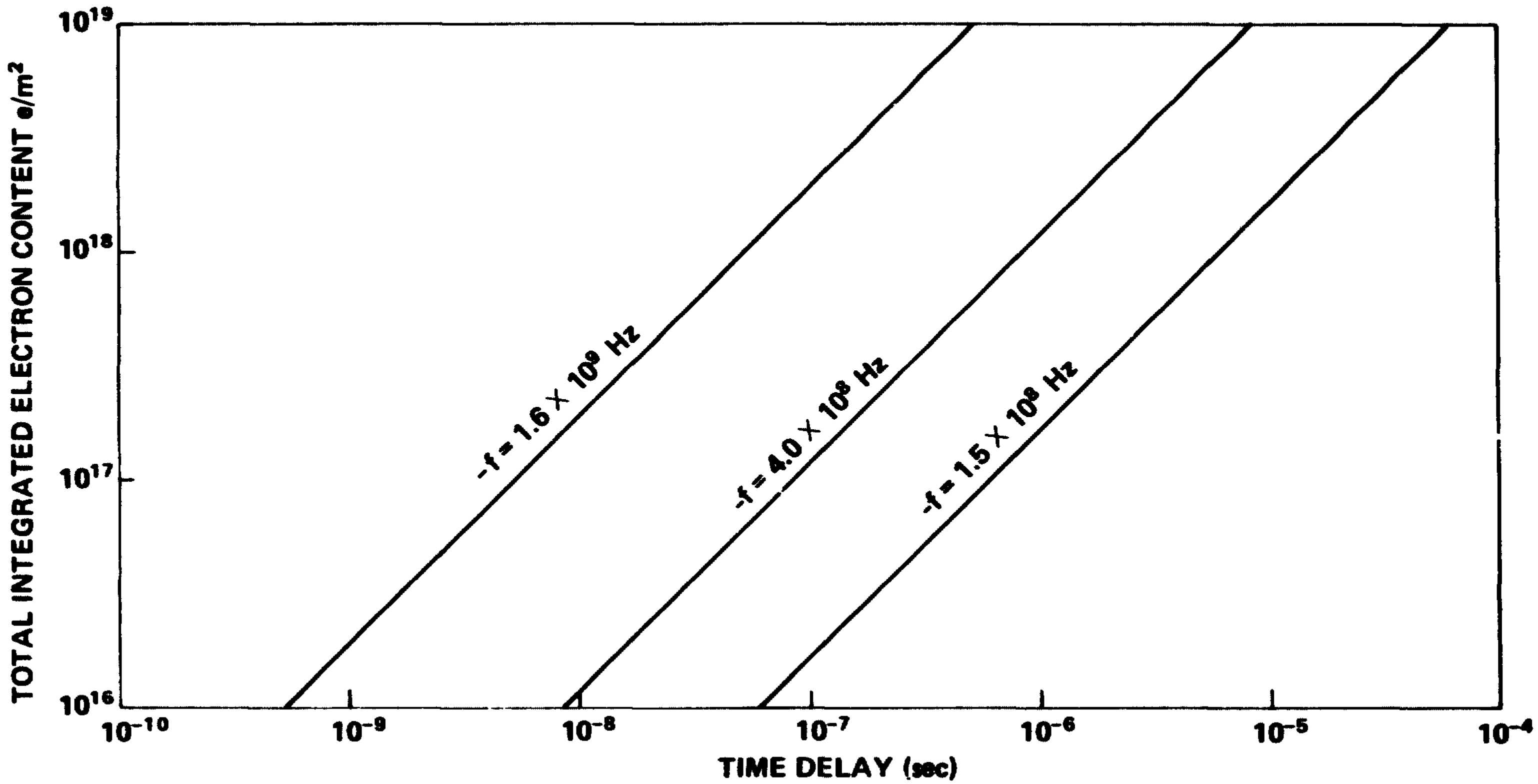

Figure 1. Ionospheric Excess Time Delay vs. Integrated Electron Content for 150 MHz, 400 MHz, and 1600 MHz Signals

χ is the angle between the wave normal and the vertical. Since B decreases inversely with the cube of the geocentric distance, and since the electron density decreases exponentially with altitude above F_2 max ($\sim$300 km), the integral is heavily weighted near the earth and is considered to provide electron content values below ~1500 km.

The term $M = B \cos\theta \sec\chi$ in Equation 4 may be taken out of the integral sign and replaced by its value at a "mean" ionospheric altitude. Equation 4 then becomes:

$$a = \frac{k}{f^2} \bar{M} \int N \, dh. \tag{5}$$

The correct conversion of polarization rotation data to electron content data depends on the altitude chosen for the calculation of $\bar{M}$. A method for arriving at such an altitude is shown in Figure 2. The height distribution of the electron density was obtained by converting the topside and bottomside ionograms recorded at close geographic proximity to Fort Monmouth into electron density profiles. Polarization-rotation data on 40 MHz was obtained from an overhead orbit of the S-66 satellite (nominal altitude = 100 km). The vertical component of the geomagnetic field (curve B) was derived from the spikes in the topside ionogram which measure the gyrofrequency at the satellite altitude. At lower altitudes, the field intensity was calculated from the reference at the satellite using the magnetic dipole approximation. Numerical, successive integration of the product $N \cdot B$ produced the curve of the polarization angle rotation Σa which ends with the total polarization angle observed at the ground ("measured" in Figure 2). The next procedure was integration of the bottomside and topside profiles to obtain $\int N \, dh$. Next, the magnetic field component, $\bar{M}$, was obtained from Equation 5 by inserting the measured total polarization angle Σa, and $\int N \, dh$ of the integrated profiles. The figure indicates that for the above example $\bar{M}$ corresponds to a local field value about 60 km above h_{max}. Figure 2 indicates further that 90% of the total polarization-angle rotation took place below 550 km.

THE DATA

The need for an empirical model of the global distribution of the ionospheric electron content for prediction purposes has focussed attention on the availability of such data on a global basis and on future requirements. The advent of beacon emissions from geostationary satellites has clearly facilitated data gathering at wide geographic areas, with the diurnal variation of content being obtained without contamination by satellite orbital changes. With low flying satellites, months of data from a particular station are necessary to obtain a diurnal variation. The

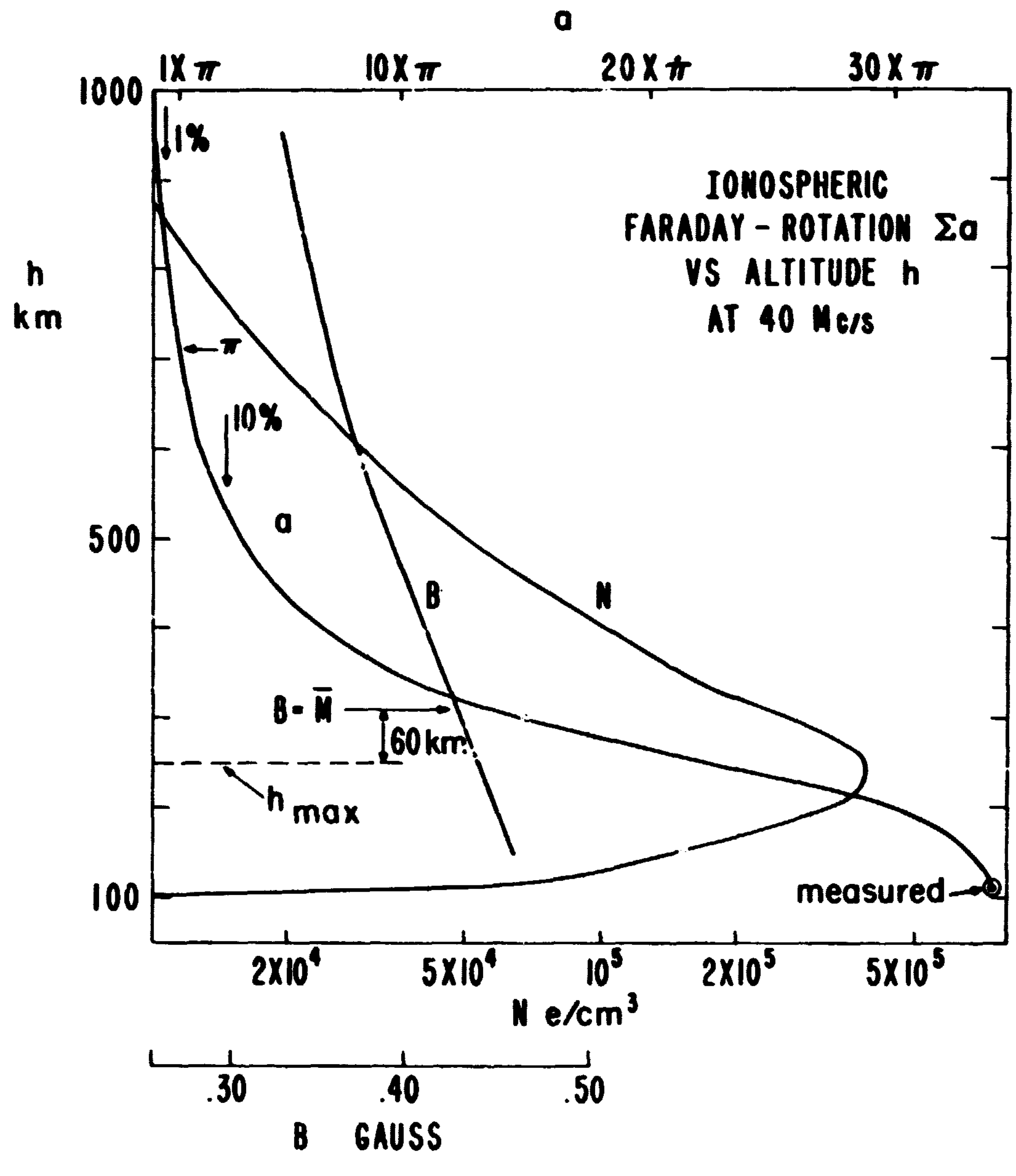

Figure 2. Calculation of the Faraday Polarization Rotation Angle Σa as a Function of Altitude Using the Actually Measured Electron Density Profile N(h), and the Geomagnetic Field Component B Obtained from Gyrofrequency Spikes in the Topside Ionogram.

day-to-day as well as the geographic and seasonal variability of the ionosphere is superimposed on the diurnal variation thus obtained.

Polarization rotation measurements are performed continuously at Fort Monmouth, N. J. (40.25°N, 74.025°W) utilizing beacon emissions of the ATS-3 (137.35 MHz). The subionospheric point (below 350 km along the path from Fort Monmouth to ATS-3) is located at 37.1°N, 73.6°W. For the purpose of this report, data observations for time periods between the 123rd and 178th days of 1973, i.e., May 3 to June 27, 1973, are presented. The data have been normalized to the vertical direction and, hence, represent the vertical total electron content. Representative diurnal variations are shown in Figures 3 through 5. The following observations are made with respect to the absolute values of the content (and, equivalently, of the ionospheric time delay):

1. The diurnal variation as well as the day-to-day variability of the total vertical content is evident. The lower and upper limits of the content are $\sim 0.2 \times 10^{17}$ and $\sim 3.0 \times 10^{17}$ respectively and correspondingly the ionospheric time delay is ~1 nanosecond and 15.7 nanoseconds. Differences of up to 100% can be observed in the figures.

2. For the reported data, buildup of ionospheric ionization started daily at ~0400 EST. For the time of year considered, the dawn buildup begins when solar illumination is at ~100 km (solar zenith angle = ~98°). Topside ionospheric densities have been reported to decrease with increasing solar illumination until about ground sunrise.[1] The discrepancy between topside density and total content could be explained by thermally induced particle fluxes from the topside ionosphere to the bottomside ionosphere during ionospheric sunrise and by the quicker buildup of the bottomside ionosphere.

3. The buildup phase of the diurnal variation is smooth, and its time slope is nearly constant. On most days, the sustained buildup phase ends prior to noontime, although the diurnal maximum is not reached until later.

4. The maximum of the content is variable in absolute value as well as in the time of occurrence. Such maxima usually occur after 1600 EST, and sometimes much later.

5. In terms of absolute values of the electron content, magnetic activity does not have a consistent effect on the content. Figures 3 through 5 show cases when magnetically disturbed days show depressed content values with respect to quiet days, and vice versa. Even data taken on consecutive disturbed days have totally different characters.

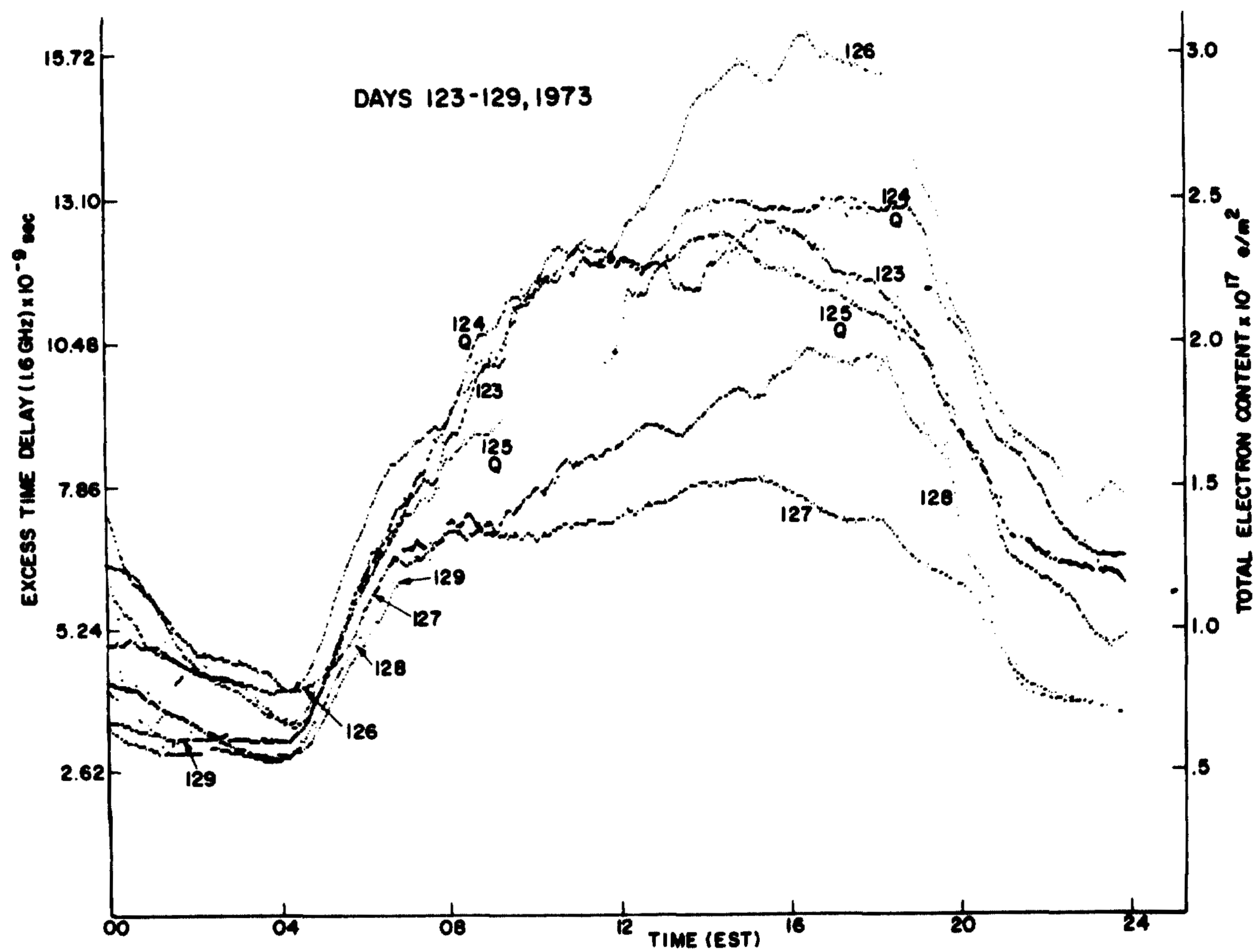

Figure 3. Total Integrated Electron Content Diurnal Variation for the Days 123 Through 129, 1973. (QQ, Q, D refer to Magnetically Extremely Quiet, Quiet, or Disturbed Days, Respectively).

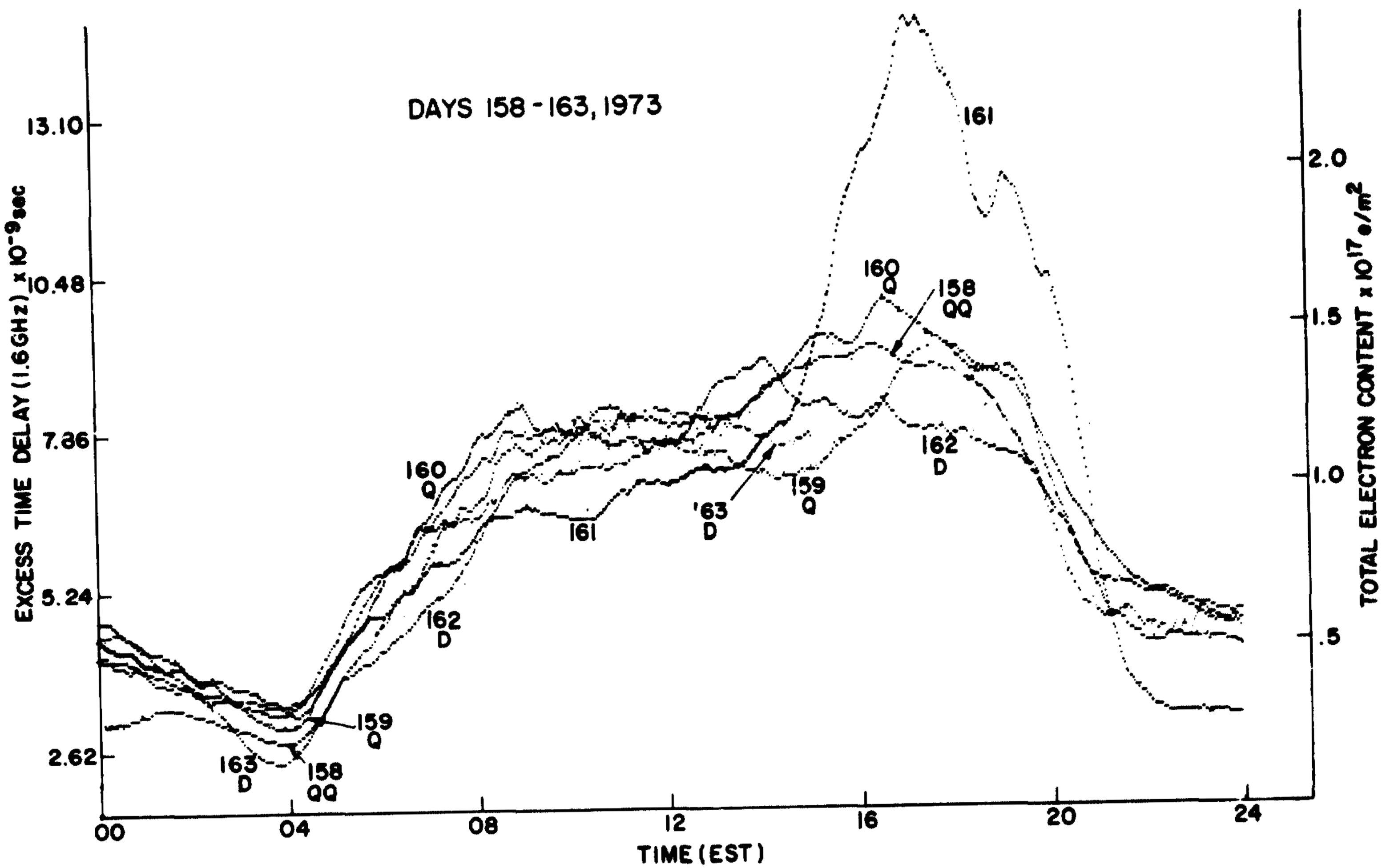

Figure 4. Same as 3, but for the Days 158 Through 163, 1973.

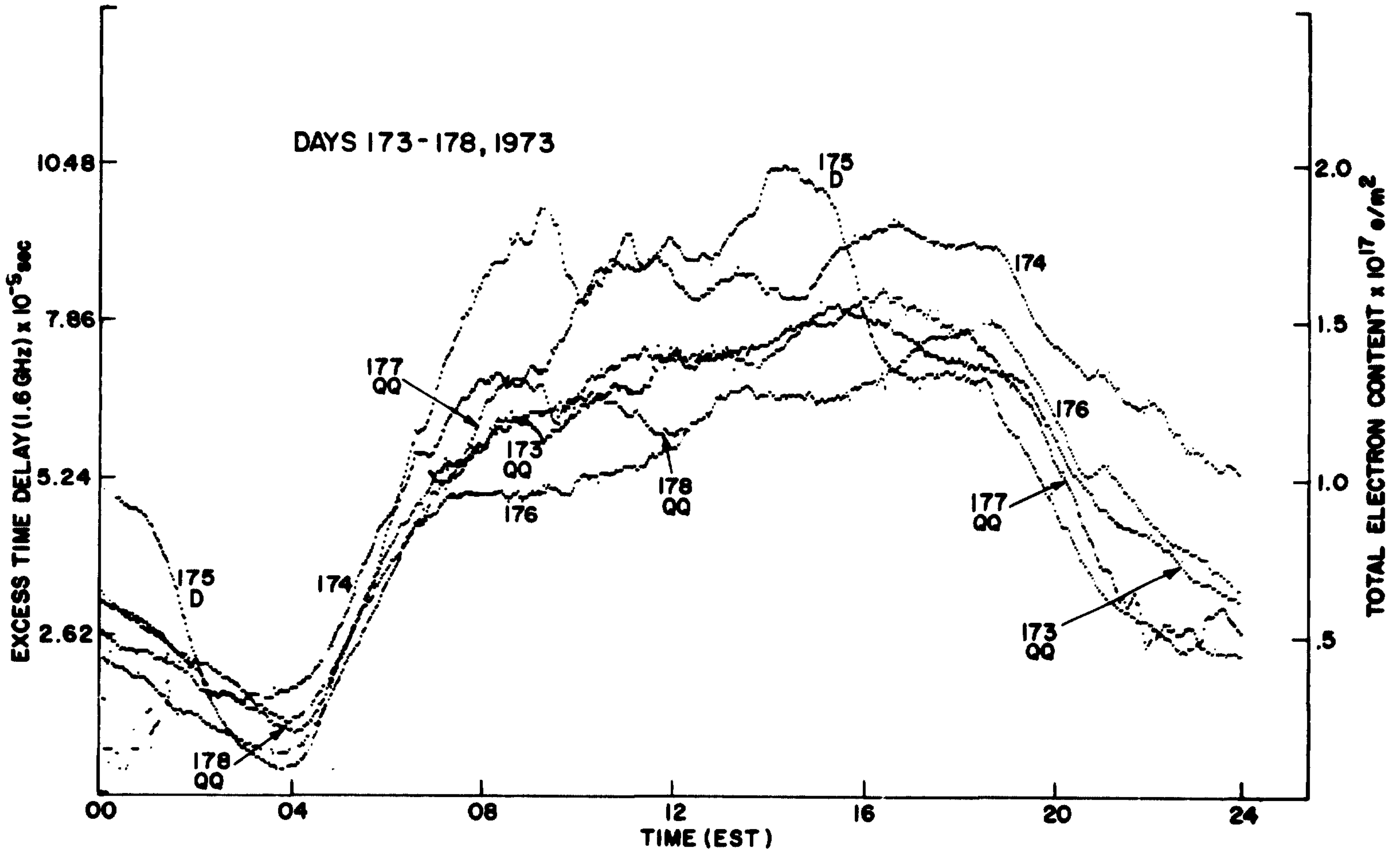

Figure 5. Same as 3, but for the Days 173 Through 178, 1973.

6. The sustained decay of ionization with the setting of the sun starts, in most cases, from the maximum absolute value of the content. As during the buildup period, the decay with time is smooth and has a constant slope. The decay slope is sharper than the buildup slope.

7. At night the content continues to decline until it reaches an absolute minimum, from which the buildup phase starts at sunrise. The minimum may be reached just before sunrise or it may be sustained an hour or so before sunrise.

8. Smaller scale variations are superimposed on the overall diurnal variation of the electron content as is evident from Figures 3 through 5. These variations are caused by ionospheric ionization irregularities along the signals' path. The irregularities are finite in extent and are known to be moving. Some of the irregularities are caused by ionospherically traveling internal gravity waves.[2] Their finite size means that two relatively closely-spaced ground stations monitoring the same satellite may observe different vertically normalized electron content values since one's path to the satellite goes through the irregularity while the other's does not.

The traveling ionospheric disturbance which cannot be predicted, except possibly statistically, constitutes a natural limit to the accuracy of any real-time prediction of the total integrated electron content. To ascertain the extent of this limit and its possible diurnal variation, the following procedure was used. Each day was divided into 6 four-hour intervals and the maximum deviation from the ambient content at any of the intervals was recorded. The bounds of the deviation ranged from no deviation to an $\sim$20% deviation. The deviations were then averaged for all the days and plotted in Figure 6. The following conclusions may be drawn:

a. Electron content deviations occur, on the average, at all diurnal periods with a maximum of 5.4% and a minimum of 2.8%.

b. On the average, the deviations are smallest during the sustained ionospheric buildup period (0400-0800 EST) and during the sustained ionospheric decay period (1600-2000 EST).

c. The greatest deviations occur during the day between the buildup and the decay. Nighttime deviations are also large.

d. From the viewpoint of prediction schemes, the daytime deviations pose a greater problem to accuracy, since the daytime content is larger than the nighttime content by a factor of 3 or so.

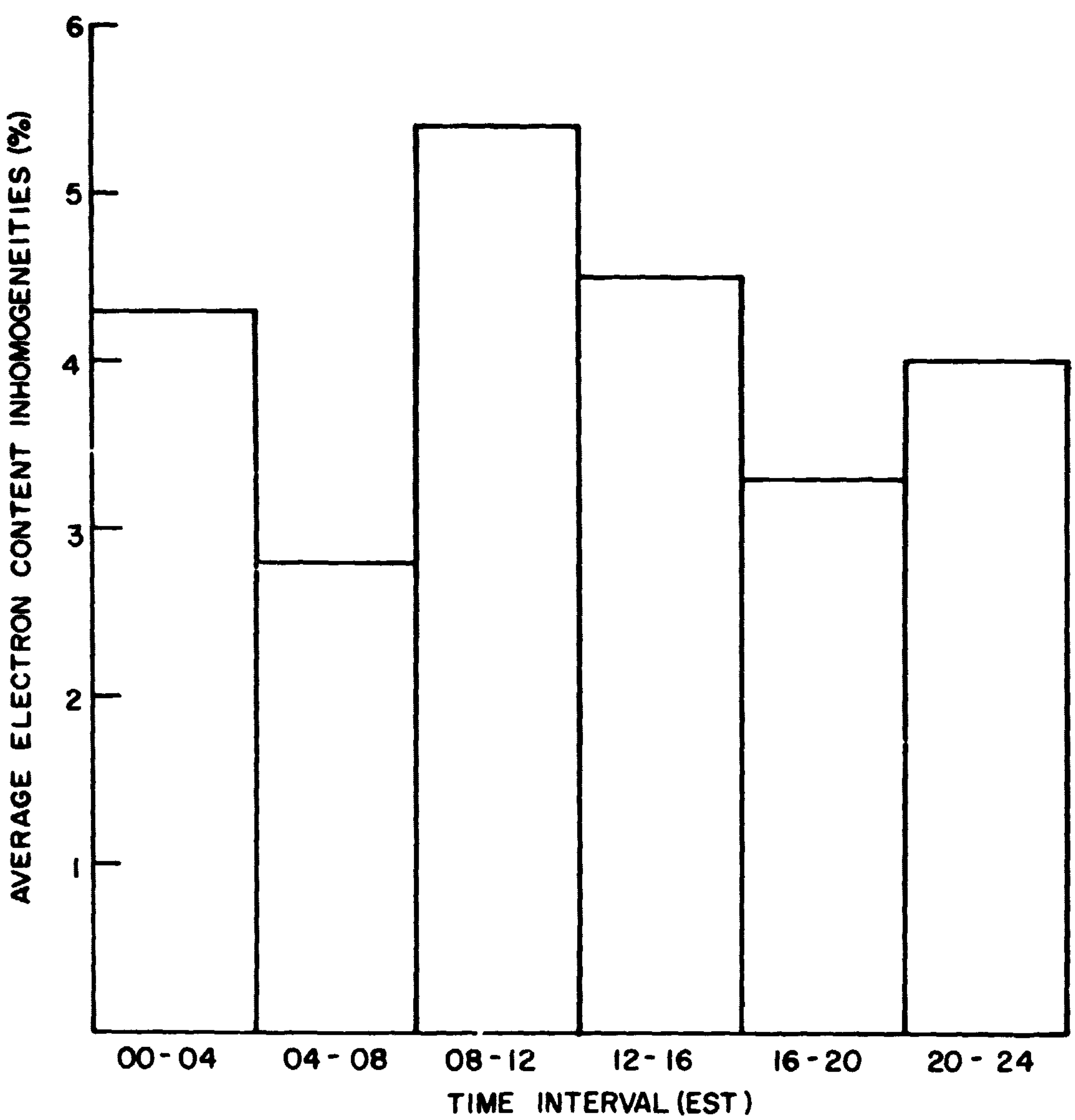

Figure 6. Ionization Irregularity in Percent of Ambient Content for Six Daily Time Periods

FUTURE EXPERIMENTS

The forthcoming launch of the geostationary ATS-F[3] will offer a unique and excellent opportunity to study the diurnal behavior of the total electron content at various geographic locations. Our group will perform two experiments. In one experiment, the polarization rotation of the 140 MHz beacon will be measured.

This will not be different from the experiments carried out to date utilizing other geostationary satellites. In a second experiment, continuous dispersive group delay measurements will be made on 140 MHz and 360 MHz, both of which will be complemented with ±1 MHz sideband emissions. With such a modulation on both frequencies, the distance between peaks of the modulation envelope is 300 meters in free space and very little different in the ionosphere. The modulation envelope travels at the group velocity and is retarded in phase by $\Delta P/300$ cycles at the modulation frequency where

$$\Delta P = \int_0^S ds - \int_0^S n_g \, ds = -\frac{40.3}{f^2} \int_0^S N \, ds. \tag{6}$$

At night (assuming $\int N \, ds \approx 10^{17} el/m^2$), $\Delta P \sim 200$ meters for the 140 MHz frequency and $\Delta P \sim 30$ meters for the 360 MHz frequency, i.e., phase reduction is <1 cycle for both frequencies. The modulation phase difference is thus obtained unambiguously and yields the absolute value of the total electron content. For other times of the day when the total content is larger, the absolute value could easily be derived from the nighttime values since the total content varies continuously with time.

Since the phase effect is independent of the terrestrial magnetic field, it gives the true electron content along the entire propagation path, as opposed to the content given by the polarization rotation effect which pertains only to a signal path portion of 1500 km from the earth's surface. The difference between simultaneous polarization and group-delay data will yield the currently unknown exospheric electron content, i.e., the content between 1500 km and synchronous altitudes.

SUMMARY

With stringent precision requirements, a navigation system which measures signal propagation time between high-altitude satellites and users at or near the earth's surface must take into account the excess time delay of the signal owing to the existence of free electrons along its path. The excess signal time delay is proportional to the total electron content along the propagation path. The upper bound for non-anomalous ionospheric conditions is ~150 nanoseconds for a highly oblique propagation path at a frequency near 1600 MHz.

For dual-frequency user-capability, the excess time delay may be measured in real-time and a correction applied to the apparent range. For single-frequency user-capability, the ionospheric time delay must be arrived at through empirical global prediction techniques based on existing and future electron content data.

The pertinent information will be transmitted to the user via the navigating signal. To date no truly global coverage of the total electron content exists. Most existing data are based on Faraday rotation measurements of the electron content in the earth's immediate vicinity only (i.e., up to ~1500 km). Future experiments will yield content values up to geostationary altitudes.

A limit to the accuracy of the prediction is set by superposition of the variations of ionization irregularities on the diurnal variation of the total electron content. The greatest average percent variation was observed during the day between the buildup and decay phases of the diurnal variation and amounted to ~5.4% of the ambient total electron content. Since the content is at its highest during the day, such percentage deviations cause relatively high absolute time delay deviations. Of course the complexity of the ionospheric processes and their interrelationships with many other geophysical phenomena will introduce additional uncertainties into the predictions.

ACKNOWLEDGMENT

The investigation reported in this paper has been supported by the U.S. Army Satellite Communications Agency, Fort Monmouth, N. J.

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QUESTION AND ANSWER PERIOD

MR. EASTON:

Any questions? No questions?

(No response.)

MR. EASTON:

Thank you very n.uch, Mr. Soicher.

N75 11299

A SYNOPTIC STUDY OF SUDDEN PHASE ANOMALIES (SPA's) EFFECTING VLF NAVIGATION AND TIMING

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ABSTRACT

Sudden phase anomalies (SPA's) observed on VLF recordings are related to Sudden Ionospheric Disturbances (SID's) due to solar flairs. This study presents SPA statistics on 500 events observed in New York during the ten year period 1961 to 1970. Signals were at 10.2 kHz and 13.6 kHz emitted from the OMEGA transmitters in Hawaii and Trinidad. A relationship between SPA frequency and sun spot number was observed. For sun spot number near 85, about one SPA per day will be observed somewhere in the world. SPA activity nearly vanishes during periods of low sun spot number. During years of high solar activity, phase perturbations observed near noon are dominated by SPA effects beyond the 95th percentile. The SPA's can be represented by a rapid phase run-off which is approximately linear in time, peaking in about 6 minutes, and followed by a linear recovery. Typical duration is 49 minutes.

INTRODUCTION

Periodically, portions of the 'surface' of the sun near sunspots are known to erupt or 'flare', thereby giving off large bursts of various forms of radiation. Flares producing sufficient amounts of energy in the X-ray portion of the spectrum are known to be the cause of sudden changes in the ionization of the earth's daytime D-region. This type of Sudden Ionospheric Disturbance (SID) may be evidenced as a Sudden Phase Advance or Anomaly (SPA) as observed on recordings of Very Low Frequency (VLF) radio signals received over long paths. The typically observed phase variation as a function of time is shown in Figure 1, including short term variations due to atmospheric noise; an idealized triangular waveform used as a theoretical model for the assumed variation is detailed in Figure 2.

This paper presents the results of a synoptic study of SPA's observed over North America from 1961 to 1970 as recorded on VLF signals propagating from the Omega Navigation System transmitter in Hawaii to an Omega receiving site at Rome, New York. Results of a shorter-term study from 1966 through 1970 over the path from the Omega transmitter in Trinidad to Rome also are presented. Parameters investigated include those noted on Figure 2, onset and recovery

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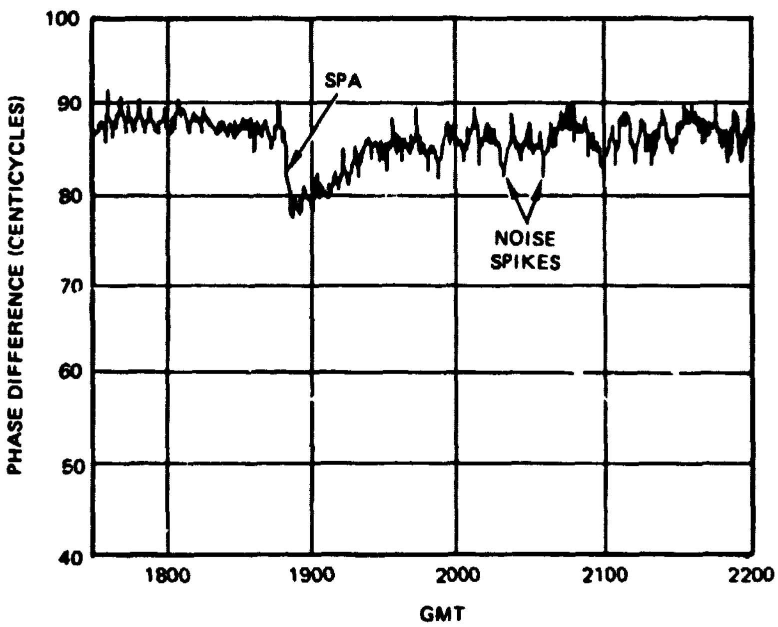

Figure 1. Typical VLF Phase Disturbance Caused by Solar X-ray Flare

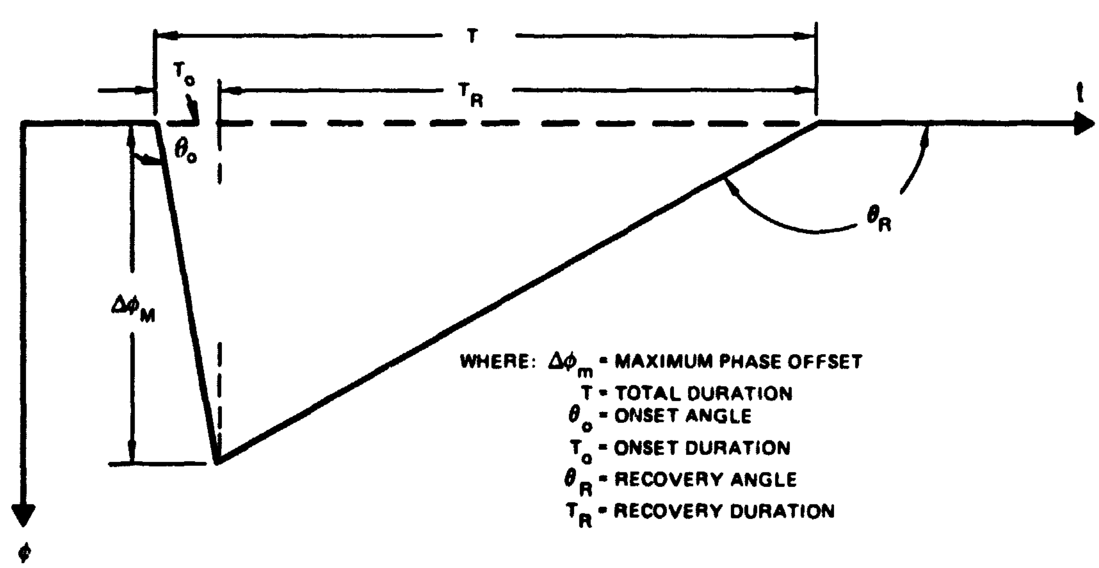

Figure 2. Idealized SPA Shape

rates, and cumulative disturbance probabilities. Distribution functions for the parameters were obtained together with interrelationships and behaviour with carrier frequency, sunspot number, solar zenith angle, and propagation path length.

An important feature of the present investigation is its restriction to synoptic data. No attempt has been made to relate results to particular geophysical morphologies or to direct data on observed solar X-ray flux. The approach taken was direct application to general error considerations for the Omega navigation system or other VLF navigation or communication system. For any particular specified application, especially one where the X-ray flux from the observed or anticipated flares can be determined, more complex analysis may be warranted. Additional information on the physics of solar flares especially their effects on solar flares can be found in References 1 through 4 of which Reference 4 includes an especially thorough study of one particular SPA for which the associated flux data was known. References 5, 6 and 7 provide additional information on the Omega system.

a. Propagation path length

b. Solar zenith angle on path

c. Sunspot number

4. 'Probability' curves giving the percentage of time that propagation was disturbed above a certain level.

Due to the scarcity of Omega data and the low level of solar activity during the early 1960's, most of the foregoing results are derived from 10.2 kHz signals over the Hawaii to New York path from 1966 to 1970. In general, all results in this paper are intended only as summaries of observed effects of SPA's on Omega signals and have not been related to possible physical or chemical aspects of flare effects. Additional information on the physics of solar flares[1,2,3,4], as well as the Omega System[5,6,7], is available in the literature.

DATA AND COMPILATION PROCEDURES

The major source of data for this study was the Omega VLF phase difference measurements at 10.2 and 13.6 kHz recorded on strip charts at the Rome Air Development Center (RADC),[8] New York through 1970. The data represent the observed phase difference between the long-path signals from Hawaii (7814 km) or Trinidad (3843 km) and the groundwave signal from the local Omega transmitter at Forestport, New York (36 km).

As the signals from all Omega transmitters were being maintained by synchronism either by a master-slave mode of operation or by cesium-standard clocks,[9] these recordings indicate the absolute effect of ionospheric variation on the behavior of the long propagation paths. Data were available essentially continuously from January 1966 and paritally from 1961 on 10.2 kHz.

Statistical data were obtained by manually scanning the recorded charts for SPA's and measuring observed times, rates and offsets. The time and phase offset determinations were straightforward; rates were indirectly determined by assuming the traingular shape of Figure 2 and obtaining the slope of the onset and recovery 'legs' of the triangle. The onset slope normally followed the recorded rapid shift exactly; the recovery slope was determined from an eyeball 'best-fit' line tangent to the half-magnitude point of the recovery period. Deviations from the assumed triangular shape were also tabulated for the larger events. Although all detectable events were noted, shape characteristics were compiled only for those events falling within a 'day window' centered about mid-path noon. This window varied seasonally from 4 hours in winter to 8 hours in summer and was typically about 2040 hours per year. This restriction was imposed to prevent the curvature in the diurnal phase variation during sunrise and sunset transitions from affecting the apparent phase rates-of-change and offsets caused by SPA's. Two other restrictions on the compilation of events involved very small (5 cec or less) and multiple SPA's. Disturbances of 5 cec* or less have been excluded from all analyses due to both the difficulty in detecting such events in the normal propagation noise and to the desire to limit the number of events to those exhibiting a shape sufficient for analysis on the scale of the phase recording charts. A 5 cec SPA amounts to less than 0.25 inch on the typical track of an Omega recording, so detection and/or analysis of smaller events was considered impractical.

Multiple SPA's; i.e., additional disturbances occurring before the initial event was recovered completely, were included in only those analyses for which the relevent shape characteristics could be determined reliably. As an example, these events were included in the probability of disturbance and cumulative analyses but not in any of the shape correlation analyses. The possible effects of inclusion or exclusion of multiple SPA's, as well as the other constraints, are discussed wherever applicable in the "results" sections to follow.

Before presenting any results however, the possible effects of equipment and the applicability of various types of units will be discussed.

*1 cec = 1 centicycle = 0.01 cycle. See following sections.

EQUIPMENT

In general, the receiving equipment at the Omega system monitoring sites was designed either for use in controlling the timing synchronization of the associated transmitters or for general navigation aboard relatively slow-moving vehicles. The receiver time constants (approximately 30-60 seconds) and tracking rates were, therefore, selected to adequately perform these system-oriented tasks with only secondary priority attached to the accurate representation of propagation anomalies. Abrupt phase changes were not expected during normal operation so that some smoothing over several 10-second transmission format intervals was not only acceptable but also desirable for noise-reduction purposes. None-the-less, the typical time constant was about one minute and the equipment was capable of slewing up to 10 cec per min, which the following discussion will show to be adequate for this study.

The distortion to input phase variations caused by the receiver can be assessed easily by considering two special cases; an abrupt received phase disturbance and a ramping one. In the case of an abrupt input phase shift greater than 10 centicycles (cec), the output would ramp at the maximum slew rate of 10 cec/min. In practice, a typical magnitude was 15 cec and the typical onset rate was 3.5 cec/minute so that the observed onset rate must be indicative of primarily the actual input phase rate. In the case of a ramped input phase variation, the observed steady state output will also ramp but delayed from the input by the one-minute time constant; within the first minute or so, there will be a slight non-linearity between the steady-state ramping and the actual onset. Presumably, this slight non-linearity will be difficult to detect due to normal noise effects on the phase recordings and the principal effect will be to delay the apparent onset time by about one minute rather than affect the observed duration or time to maximum onset. Thus the receiving instrumentation is not believed to have had a significant effect on the important statistics considered.

Some scatter must reflect inability to precisely scale the recorded data. All but a few months of data were recorded on linear chart paper having a phase scale of 1 cycle full-scale equal to 4.5" and a take-up rate of 3"/hr before 1966 to 3/4"/hr after 1965. The remaining data were recorded on curvilinear paper with a 4.5"/cycle phase scale and a 3/4"/hr take-up rate. The precision of the recorded phase and time readings were about 1 centicycle (cec) and 2 or 3 minutes at the slowest chart speed, respectfully. The precision of the slope measurements was about 1 degree. As the typical observed onset slope of SPA's was about 85° (approx. 3 cec/min), the rapid change in the tangent in this region will cause the rate uncertainty to increase directly with rate and become approximately 7 cec/min for 89°. Since the maximum receiver tracking rate of 10 cec/min corresponds to angle of 88.5°, the few observed rates in this region and the high associated uncertainty lead to the conclusion that the equipment was not a factor in limiting the recorded shape behavior of the SPA's. The two events in 1969 with angles of 89° supposedly are not possible, due to equipment limitations, but are most probably due to the measurement uncertainty.

PHASE ANOMALY SIGNIFICANCE AND UNITS

All primary statistics in this paper are expressed in units of the experimentally observed phase changes or rates over the propagation path being investigated. While lacking universality, the approach renders the statistics independent of assumed ionospheric models. To assist in making the results more meaningful, additional scales have been superimposed in which the observed variations are associated with "equivalent" changes.

Experimental measurements were made in angular units of centicycles (1 centicycle = 1 cec = 0.01 cycle). It is often common practice to draw an "equivalence" between phase and time by associating one cycle of the carrier with one period.[10,11] At 10.2 kHz this yields 1 cec $\sim 1\mu s$ while at 13.6 kHz, 1 cec $\sim 3/4\mu s$. A similar relation between phase and "equivalent" distance when ranging may be obtained by associating one cycle with one wavelength. The wave length at 10.2 kHz is 30 km so that 1 cec $\sim$0.3 km distance while at 13.6 kHz, 1 cec $\sim$ 0.23 km distance. (In the hyperbolic phase difference mode usually used with Omega, these distance equivalences are approximately halved so that 1 cec $\sim$0.15 km.) Associated rates follow directly: one centicycle/minute corresponds to a fractional frequency variation of 1.7×10^{-8} at 10.2 kHz and 1.3×10^{-8} at 13.6 kHz. Velocity equivalences when interpreted for radial ranging are 1 centicycle/minute $\sim$18 km/hr at 10.2 kHz or 14 km/hr at 13.6 kHz. Another association which is often made is that between phase variation and ionospheric height change. In the common calculation, the path length is divided by the time equivalent phase variation to obtain a velocity variation. The velocity variation is associated with an equivalent change in the height of the earth-ionosphere waveguide necessary to match the computed velocity variation. The difficulty with this method is that it assumes the phase shift is entirely due to an effective height change rather than changes in ionospheric electron density gradient or other process. Further, the calculation is valid only if the excitation factor remains constant. An additional complication, discussed in a subsequent section, is whether the calculation should use the entire propagation path length. Despite the limitations, "equivalent" height variations[7] have been associated with the data based on a partial relative velocity variation with height of 3.2×10^{-4} /km at 10.2 kHz and 1.9×10^{-4}/km at 13.6 kHz corresponding to equivalent height changes of 0.12 and 0.15 km per centicycle at 10.2 and 13.6 kHz respectively over the Hawaii-New York path and twice as much over the Trinidad-New York path.

RESULTS

Maximum Phase Offset Distributions

Figure 3 gives the number distributions of the maximum phase offsets produced by SPA's observed at 10.2 kHz on the Hawaii-New York path from 1966 through 1970. The data was quantized in 5 cec intervals, and include all observed events greater than 5 cec. Multiple SPA's have been included by considering the apparent additional offset produced by the subsequent events as being individual events. This procedure has had the most significant effect in 1967 and 1970 wherein the number of observed events has been increased by 20-25%. For other years the effects were 10% or less, and no significant effect on the overall distributions was found.

Several features are apparent from Figure 3. There are fewer SPA's and they are smaller during periods of lower solar activity (1966-1967) than near solar cycle maximum (1968-1970). The phase change typically peaks between 10-15 cec corresponding to ionospheric phase-height changes of 1.2 to 1.8 km. For SPA's greater than 5 cec, the average magnitude was 23 cec corresponding to height changes of 2.8 km. It is notable that in most years, fewer SPA's were observed with amplitude between 5 and 10 cec than were observed with amplitude between 10 and 15 cec. The distribution thus does not appear of the type where there is a very large probability of small events such as might be expected if SPA's were but rare manifestations of a phenomenon characteristic to normal ionospheric formation. Instead, the distributions suggest SPA's and the causual solar flares are specific identifiable events which tend to have typical magnitudes characteristic of the flare formation physics.

Onset Phase Rate-of-Change Distributions

The number distributions for the onset rate-of-phase-change for various years are shown in Figure 4. The distributions appear similar and essentially normal in each year differing primarily in the fewer events observed during lower solar activity in 1966. The median onset rate is 3.5 cec/minute which corresponds to a fractional frequency shift of 6×10^{-8} equivalent to a radial-range rate of 63 km/hr. The associated rate of lowering of the ionospheric phase height is about 0.4 kilometer per minute.

The observed onset rates are generally well within instrumental capabilities and thus are believed to indicate true ionospheric changes. The two extreme rates in 1969 may be the result of measurement uncertainty whereas the near absence of rates between 4 and 5 and between 6 and 7 cec/min is due to roundoff of the onset angle during scaling.

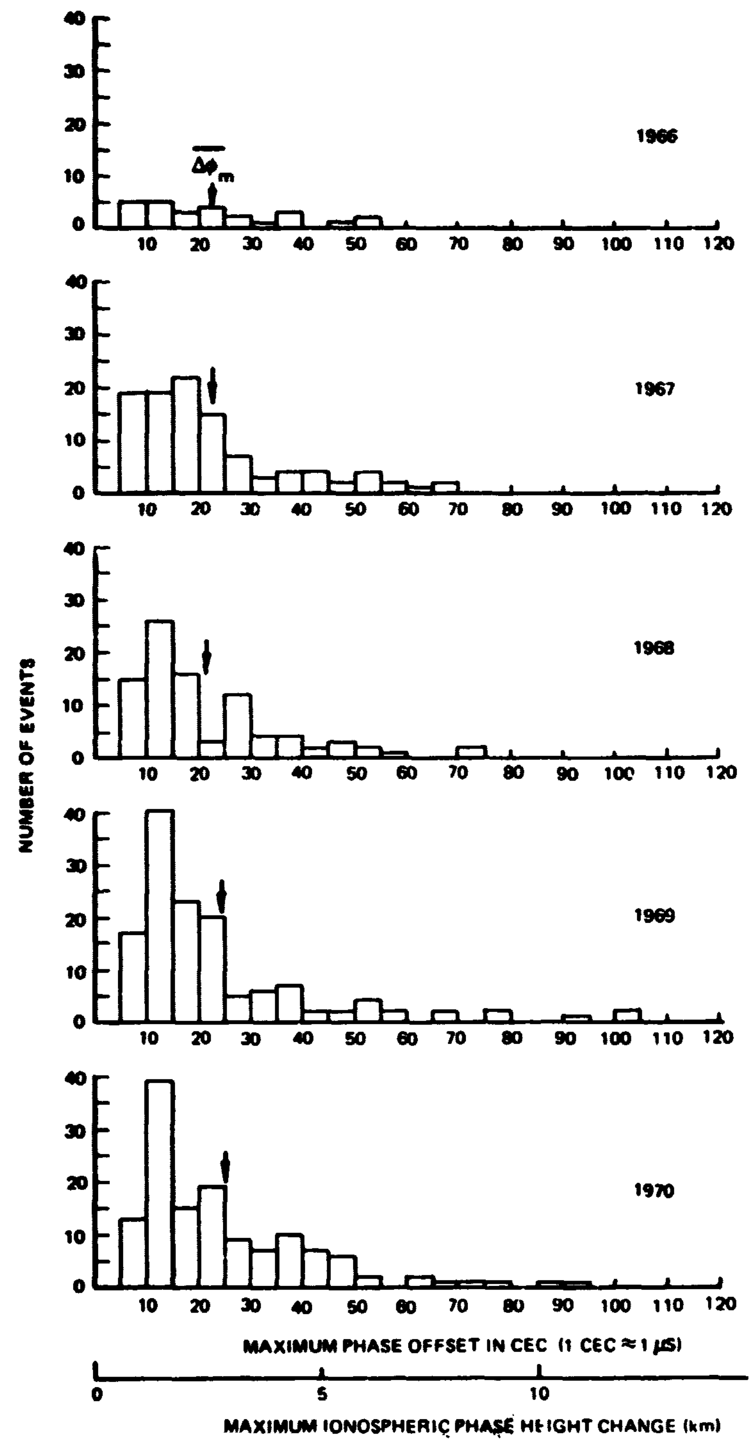

Figure 3. Maximum Phase-Offset Distributions Observed During SPA Events on Hawaii to New York Path at 10.2 kHz

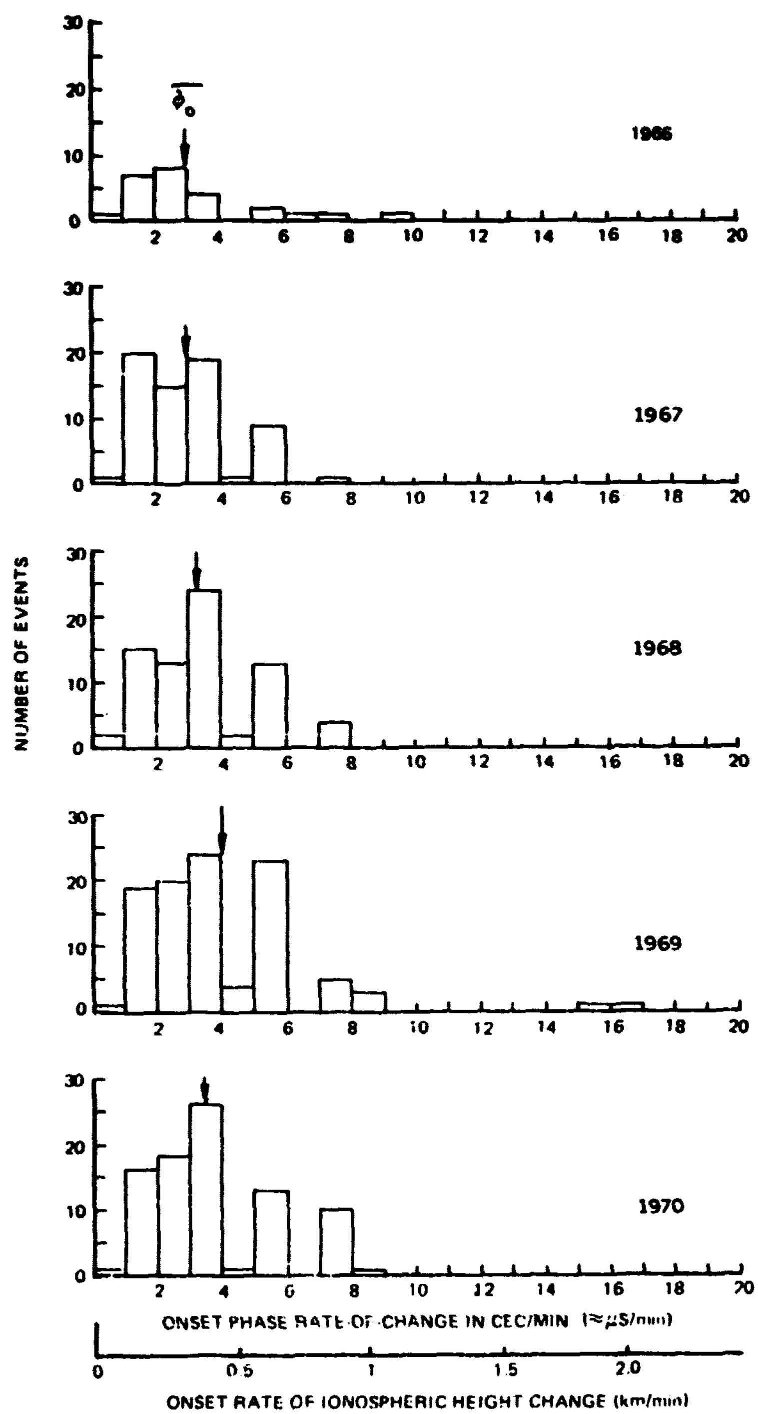

Figure 4. Onset Phase Rate-of-Change Distributions Observed During SPA Events on Hawaii to New York Path at 10.2 kHz

In this and the following 2 sections, multiple SPA's have been excluded because of the difficulty in determining the rates-of-change and duration of individual events in the disturbance.

Disturbance Duration Distributions

Figure 5 shows the number distributions for duration of SPA disturbances observed during the same data sample used to show amplitude distribution in the previous section. The plots indicate a peaking effect around 40 minutes or so with a decrease in frequency with length of disturbance. Except for the minor occurrance of a few longer SPA's in the latter years, there does not appear to be any significant variation of disturbance duration with sunspot number, which nearly tripled over the time span being analyzed.

As will be discussed in the following section on decay rates-of-change, the disturbance duration may have been significantly shortened by the modeling approximation used for the 'recovery' leg of the event. For a typical duration of 40 minutes, an error of 10% is significant but probably unimportant in a practical sense.

Recovery Phase Rate-of-Change Distributions

Figure 6 shows the number distribution for the decay rates-of-change of phase for the same data sample as previously shown. The peak occurrence is at 0.5 cec/min or less for each year and the distributions are not quite normal with the heaviest weighting occurring at the slower rates.

As noted in the data section, the decay rate was determined from an approximate linear fit to the normally exponential recovery exhibited by the typical SPA. An investigation of the possible errors introduced by this approximation indicated that the decay slope estimation usually was biased toward the early portion of the recovery period and therefore resulted in a higher indicated overall decay rate, and subsequently, a shorter indicated duration of the disturbance. This systematic error will not significantly affect the decay rate statistics, as long as they are understood to apply to all but the final portion of the recovery period. However, the duration statistics may be significantly affected as was discussed previously.

Disturbance Level Probability Analysis

A most useful statistic describing the effects of SPA's is the percentage of time that an Omega Phase track is likely to be disturbed above a given value. Such information may be extracted from historical data summarized according to time span and the percentage of time the observed disturbances exceeded various incremental levels. Assuming that the chronological variation of SPA occurrence

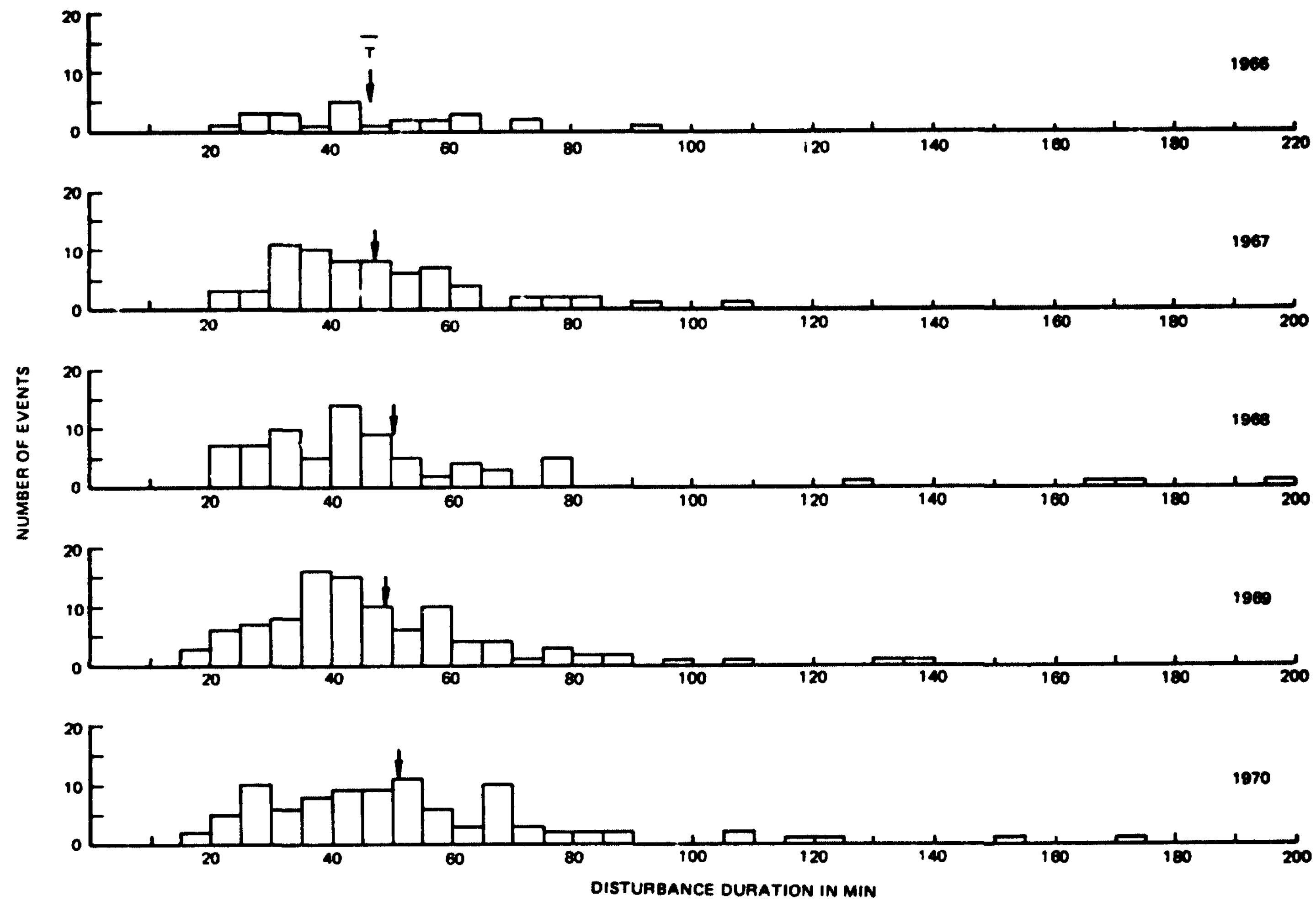

Figure 5. Disturbance Duration Distributions Observed During SPA Events on Hawaii to New York Path at 10.2 kHz

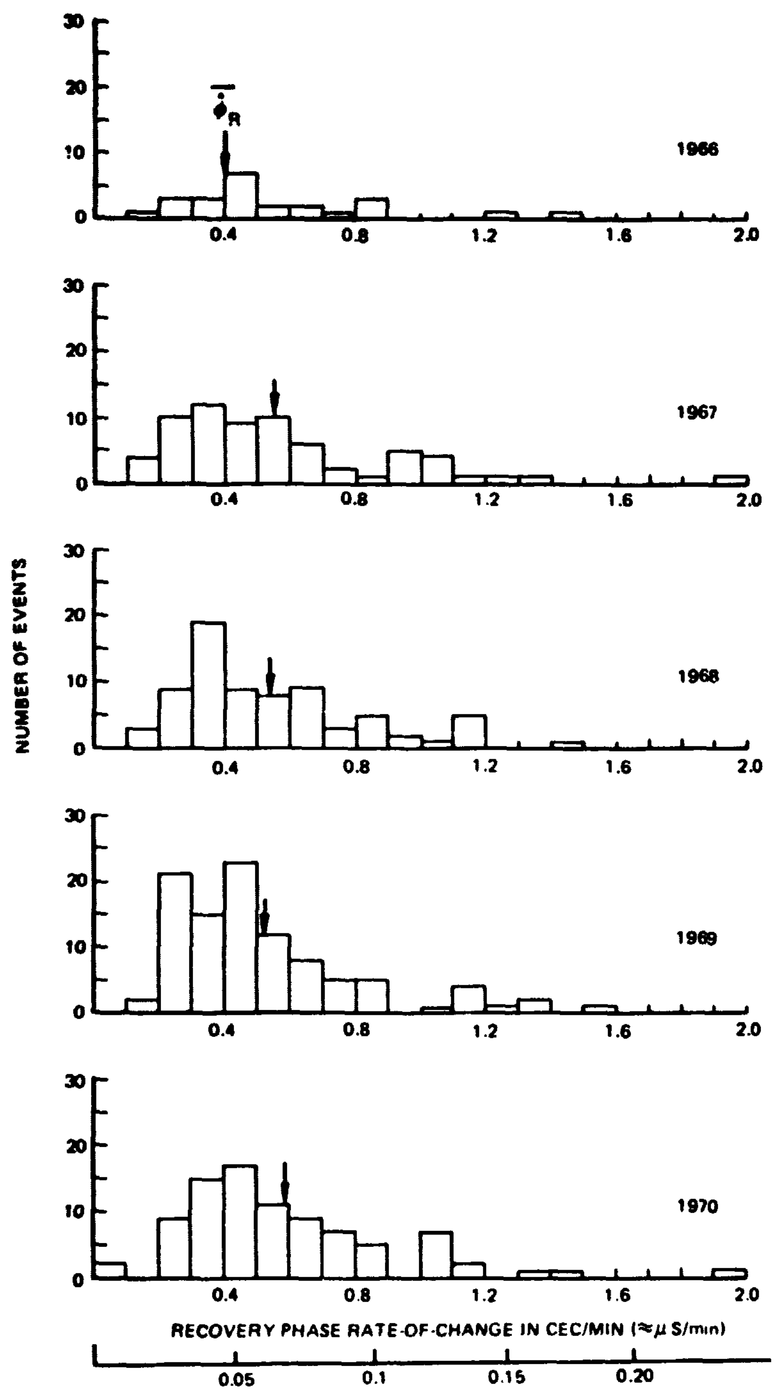

Figure 6. Recovery Phase Rate-of-Change Distributions Observed During SPA Events on Hawaii to New York Path at 10.2 kHz

can be related to some solar activity indicator (e.g., sunspot number), the historical statistics may be interpreted as the probability of occurrence of disturbances during any given period of solar activity.

The historical summaries may be obtained from the data compiled for this report by assuming SPA's to have the triangular shape of Figure 1 and a reference level $\Delta\phi_c$ as shown in Figure 7. The total duration T of the SPA is computed from the tabulated maximum amplitude $\Delta\phi_m$ and the onset and recovery angles θ_o and θ_R:

$$T = T_O + T_R = \frac{\Delta\phi_m}{\operatorname{Tan}\theta_o} + \frac{\Delta\phi_m}{\operatorname{Tan}(180 - \theta_R)} = \Delta\phi_m\left(\frac{1}{\operatorname{Tan}\theta_O} + \frac{1}{|\operatorname{Tan}\theta_R|}\right)$$
$$T = \Delta\phi_m\left(\frac{\operatorname{Tan}\theta_o + |\operatorname{Tan}\theta_R|}{\operatorname{Tan}\theta_o\,|\operatorname{Tan}\theta_R|}\right) \quad (1)$$

Using similar triangles, the duration T_c for which $\Delta\phi$ exceeds the reference level $\Delta\phi_c$ can be found from:

$$\frac{\Delta\phi_m}{T} = \frac{\Delta\phi_m - \Delta\phi_c}{T_c}$$
$$T_c = T\left(\frac{\Delta\phi_m - \Delta\phi_c}{\Delta\phi_m}\right) = T\left(1 - \frac{\Delta\phi_c}{\Delta\phi_m}\right) \quad (2)$$

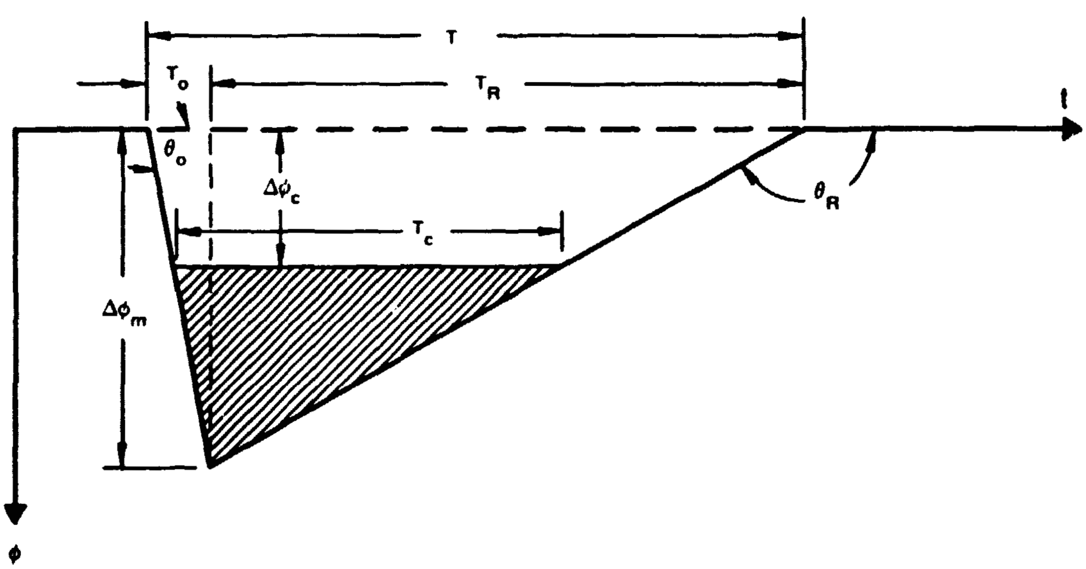

Figure 7. Idealized SPA Shape With Reference Level

As written, Equation 2 utilizes the amplitudes and rates of change obtained from the disturbances observed over a specific path under specific solar illumination conditions. When Equation 2 is divided by the total time available ΣT_0 for detecting SPA's, the result is the percentage of time that the observed disturbances exceeded the specified reference level:

$$T_c(\%) = \frac{\Sigma T_i \left(1 - \dfrac{\Delta\phi_c}{\Delta\phi_{m_i}}\right)}{\Sigma T_0} \tag{3}$$

If $T_c(\%)$ is thought of as a percentage probability of occurrance, the notation can be changed to read:

$$P(\Delta\phi > \Delta\phi_c) = 100\, T_c\, (\%) = 100 \frac{\Sigma T_i}{\Sigma T_0} \left(1 - \frac{\Delta\phi_c}{\Delta\phi_{m_i}}\right) \tag{4}$$

Figure 8 gives plots of P for the years 1966 through 1970 over the range of applicable reference levels. The relative position of the curves tends to follow the variation of solar activity over this period, except for 1967, which appears more active than expected. This may have resulted from the procedure used to normalize the observed disturbed time to the total time available for observation. This normalization assumes a random distribution of SPA activity throughout the year and neglects any compression of activity into specific months or even weeks, which is typical of recent solar activity levels. As 1967 had significantly less observed time then other years, any error introduced by the normalization would be greater for that year. In addition, 1967 contained a greater number of multiple SPA's, which amounted to a significant proportion of the already very small percentage of disturbed time. After consideration for the high sensitivity of the computation in the region of low percentages, the overall result is in good agreement with that expected from the sunspot number variation during this period. The following section discusses the correlation of SPA activity and the yearly average sunspot number.

Frequency of SPA Occurrence with Sunspot Number

Figure 9 shows the observed variation of SPA occurrence with the National American sunspot number, R_A[12]. The plotted data points have been determined from measurements at 10.2 kHz on the Hawaii to New York path and include all events greater than 5 cec as observed in a typically 6-hour duration 'window' near mid-path noon. The points shown for N_{24} are an extrapolation to the event levels expected under the condition of continuous solar influence over 24 hours. The curve for N_{12} is a similar extrapolation to a typical 'daylight' condition of 12 hours somewhere on the globe.

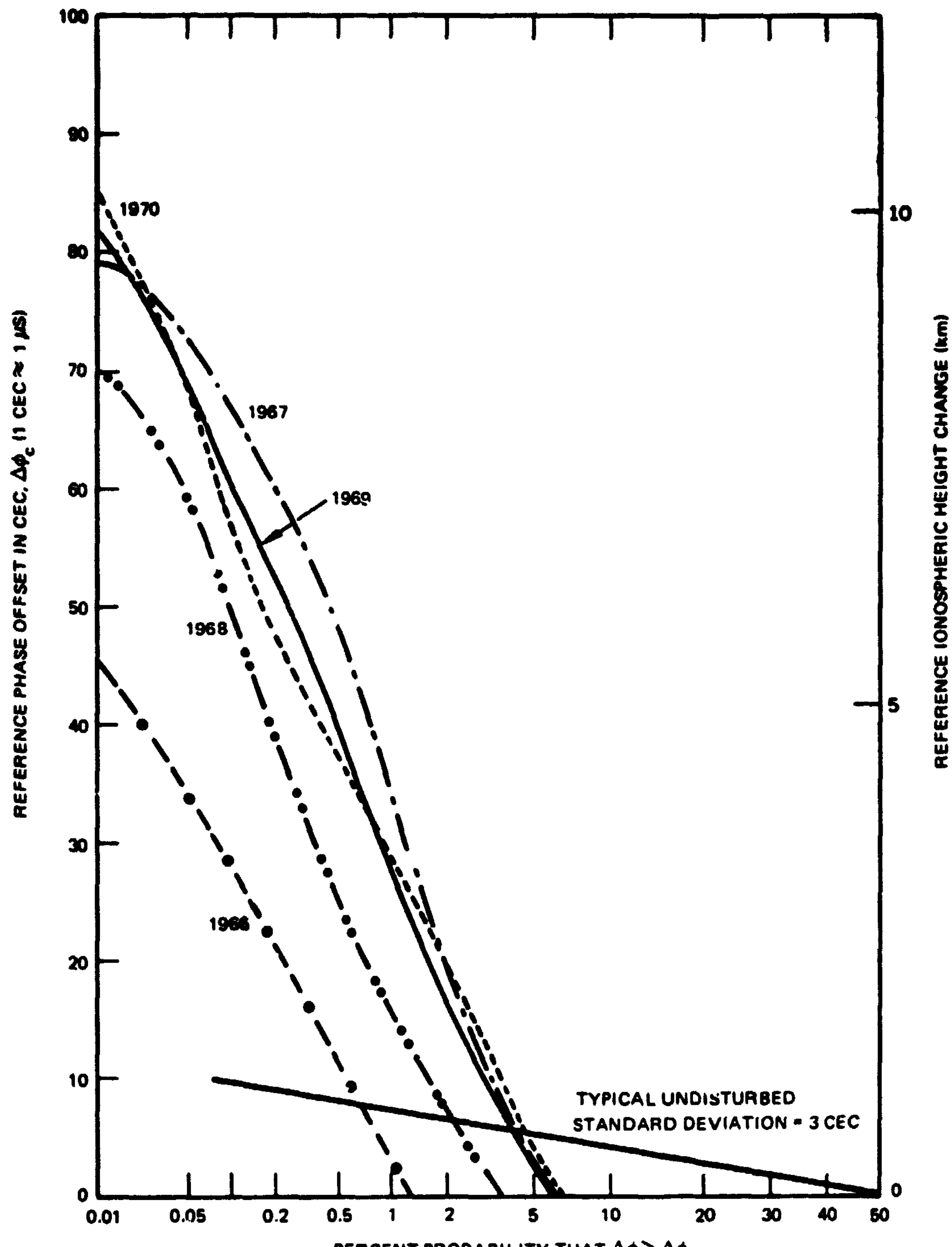

Figure 8. Percent Probability of Disturbance Level Occurrence for Observed SPA Events on Hawaii to New York Path at 10.2 kHz

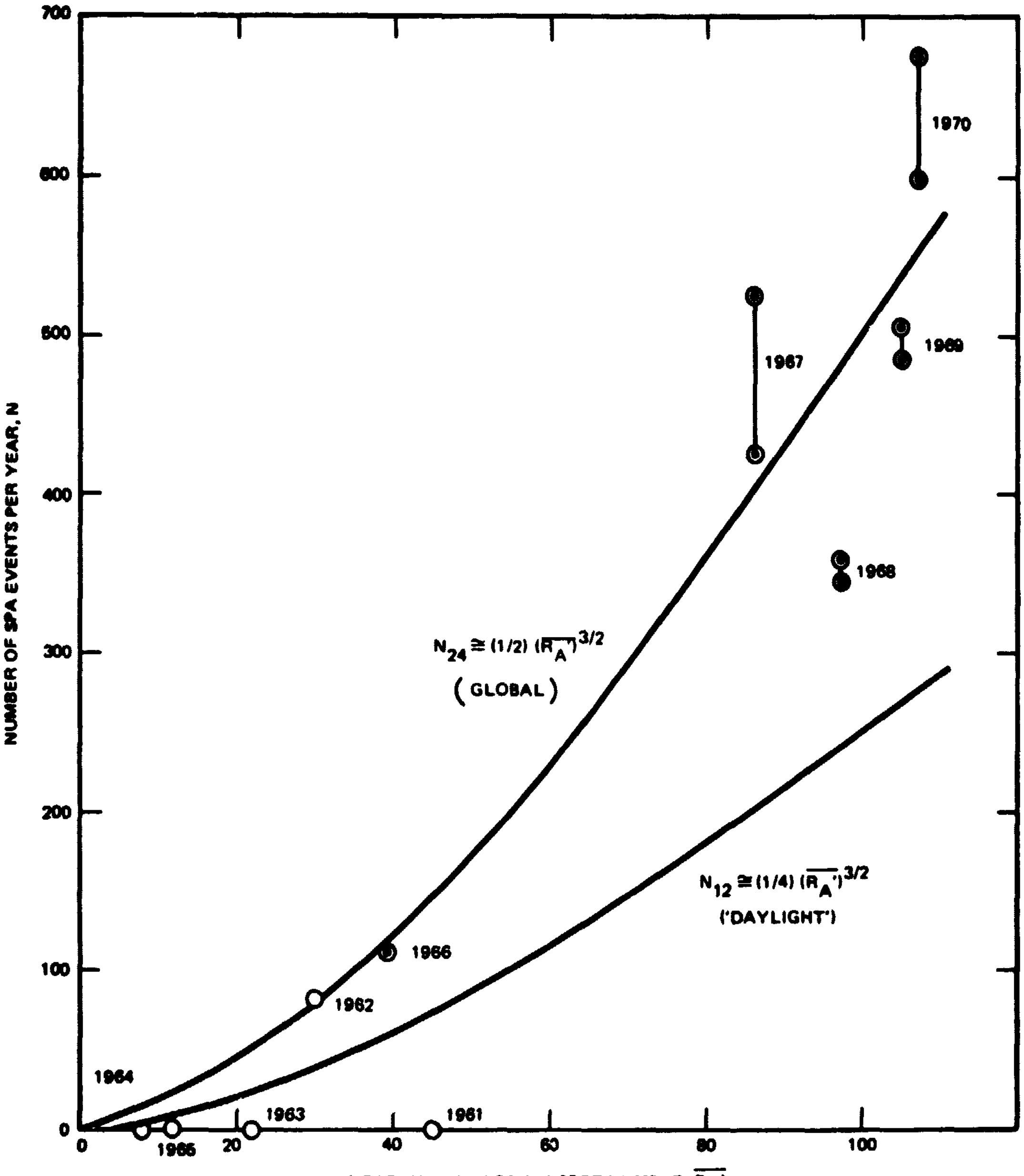

Figure 9. Variation of SPA Occurrence With Sunspot Number

The effect of multiple SPA's is shown by the double values plotted for certain years. The upper point includes all events discernible within the duration of the multiple disturbances; the lower point assumes each multiple event to be only a single disturbance. The largest effect is in 1967 which exhibited about 20% less observation time but proportionally more multiple events than other years.

The distribution functions of Figure 3 suggest that perhaps the event levels might be about 10% higher, if small comparatively unimportant events of less than 5 cec also had been included.

The empirical functions drawn on Figure 9 are simple approximations to the regression curve determined for the midpoints of the indicated range of events for the years 1966 through 1970. The midpoints were used as a compromise between the possible ways of counting multiple events. Data from 1961-1965, shown as open circles, were excluded from the fitting analysis because of the brief transmission schedule relative to the latter years and also the complexity in detecting the occurrence of events. For all years, the data were obtained by normalizing the observed number of events by the ratio of the total hours of recordings actually searched (500-2000 per year) to the number of hours available for observation (approx. 8800 and 4300 for the 24 and 12-hour functions).

The data indicate that a 'yearly average' sunspot number near 85 the frequency of occurrence of SPA's over the entire globe is statistically about one per day. There is also the suggestion of a non-linear relationship between SPA occurrence and sunspot activity with the occurrence nearly vanishing during years of low sunspots.

During 1961 there were 500 hours of transmission near noon while there were 750 hrs in 1962, 700 in 1963, 600 hrs in 1964 and 1000 hrs in 1965. Thus 1961-1965 probabilities are less statistically certain than those based on the nearly continuous transmissions schedule maintained in latter years. This is especially true for 1961 when there were no hours of simultaneous monitoring at both ends of the path. It was also more difficult to measure SPA's during 1961-1965 since the Omega system was not operated in the modern "absolute" configuration where each station operates directly from cesium standards but rather in the older system configuration wherein some stations were operated as "masters" and others as "slaves", which functioned to approximate in-phase reflectors of the master signals delayed by retransmission location in the 10-second time-sharing commutation pattern. During much of the early period a station in the Panama Canal Zone was operating as master with both Hawaii and New York operating as slaves. SPA's for the Hawaii to New York path were derived from measurements of the New York - Canal Zone master-slave pair near Hawaii and of the Hawaii - Canal Zone pair near New York. Propagationally, the former measurement includes transmission from the Canal Zone to Hawaii (CH) thence from Hawaii to New York (HN) measured with respect to transmission from the Canal Zone to New York (CN): Measurement #1 represents CH + HN - CN. Similarly, Measurement #2 represents CN + NH - CH. Thus the sum of the two measurement represents HN + NH, i.e., roundtrip propagation between Hawaii and New York. Since checks during other transmission periods indicate SPA's are similar in either propagation direction, the derived roundtrip is thus representative of the

Hawaii - New York measurement obtained directly in later years. Measurement of the multiple records is, however, awkward and subject to higher uncertainty than the direct measurement.

Variation of SPA Magnitude with VLF Frequency

The frequency dependence of SPA magnitudes is of interest both to the study of ionospheric behavior and for navigation using the Omega System. This behavior was investigated at the carrier frequencies of 10.2 and 13.6 kHz for both the Hawaii to New York and Trinidad to New York paths. Data were compiled for approximately 50 SPA's in each of the years 1967, 1969 and 1970 for the HA-NY path and a total of 50 SPA's for the years 1967 and 1970 on the TD-NY path. The events used were selected randomly from the total set and were determined mainly by their availability as individual events at both carrier frequencies.

Preliminary checks indicated that onset times and general shapes were the same for both frequencies for both paths being considered. The maximum phase offsets then were used to determine the average and best-fit linear estimate of the slope of the $\Delta\phi_{13.6}$ versus $\Delta\phi_{10.2}$ function, with the comparisons being given in Figure 10 and summarized in Table I. The results indicate to a high degree of confidence that the relative SPA magnitude effects at 13.6 and 10.2 kHz are directly proportional, with the indicated proportionality constant of 0.75 being equal to the ratio of the carrier frequency wavelengths:

$$\Delta\phi_{13.6} = 0.75\,\Delta\phi_{10.2} = \left(\frac{\lambda 13.6}{\lambda 10.2}\right)\Delta\phi_{10.2}\ \text{(Cycles)}$$

which is as expected if the phase height variations estimated from data at either frequency are to be the same. Since no data at other frequencies were used, the applicability of the wavelength-ratio proportionality to other frequencies is unknown.

Correlation of SPA Shape Characteristics

Figures 11 through 13 show the functional interdependence of the various shape characteristics of the SPA's being studied. The plots are presented in a format intended to represent both the predictive as well as physical aspects of these relationships; i.e., how well one can predict the maximum phase offset from the observed run-off rate, or the disturbance duration or decay rate from the observed maximum offset. These relationships have been approximated by best-fit (least-squares) lines through the origin and with arbitrary intercept. The resulting slopes and correlations are tabulated in Table II; ordinate intercepts are shown on the figures. The 'true' best-fit line was computed to show both the correct sample correlation, r_B, and the discrepancy with the line through the origin.

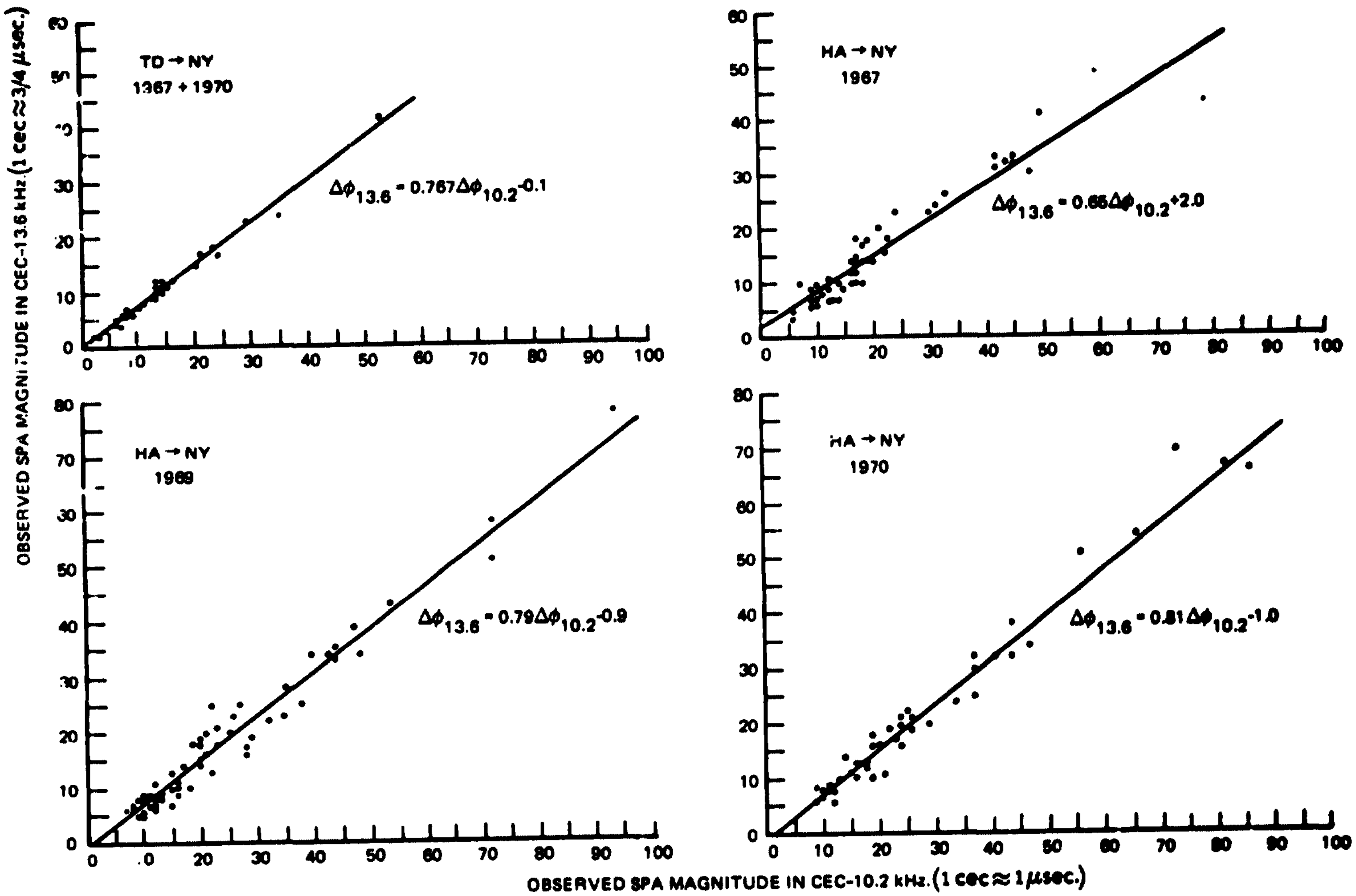

Figure 10. Frequency Correlation of Maximum Phase Offsets for SPA Events Observed Simultaneously on 10.2 and 13.6 kHz

Table I

Summary of SPA Magnitude Variation at 10.2 and 13.6 kHz

PATH	YEAR	SAMPLE SIZE	$\Delta\phi_{10.2}$ AVERAGE	$\Delta\phi_{13.6}$ AVERAGE	SLOPE AVERAGE	SLOPE LINEAR FIT	INTER-CEPT	SAMPLE CORRE-LATION
TD → NY	1967 1970	47	11.8	9.0	0.763	0.77	-0.1	0.99
HA → NY	1967	48	20.0	14.9	0.745	0.65	2.0	0.96
	1969	59	22.5	17.1	0.750	0.79	-0.9	0.98
	1970	41	26.3	20.4	0.775	0.81	-1.0	0.99
			AVERAGES		0.758	0.75	0.0	0.98

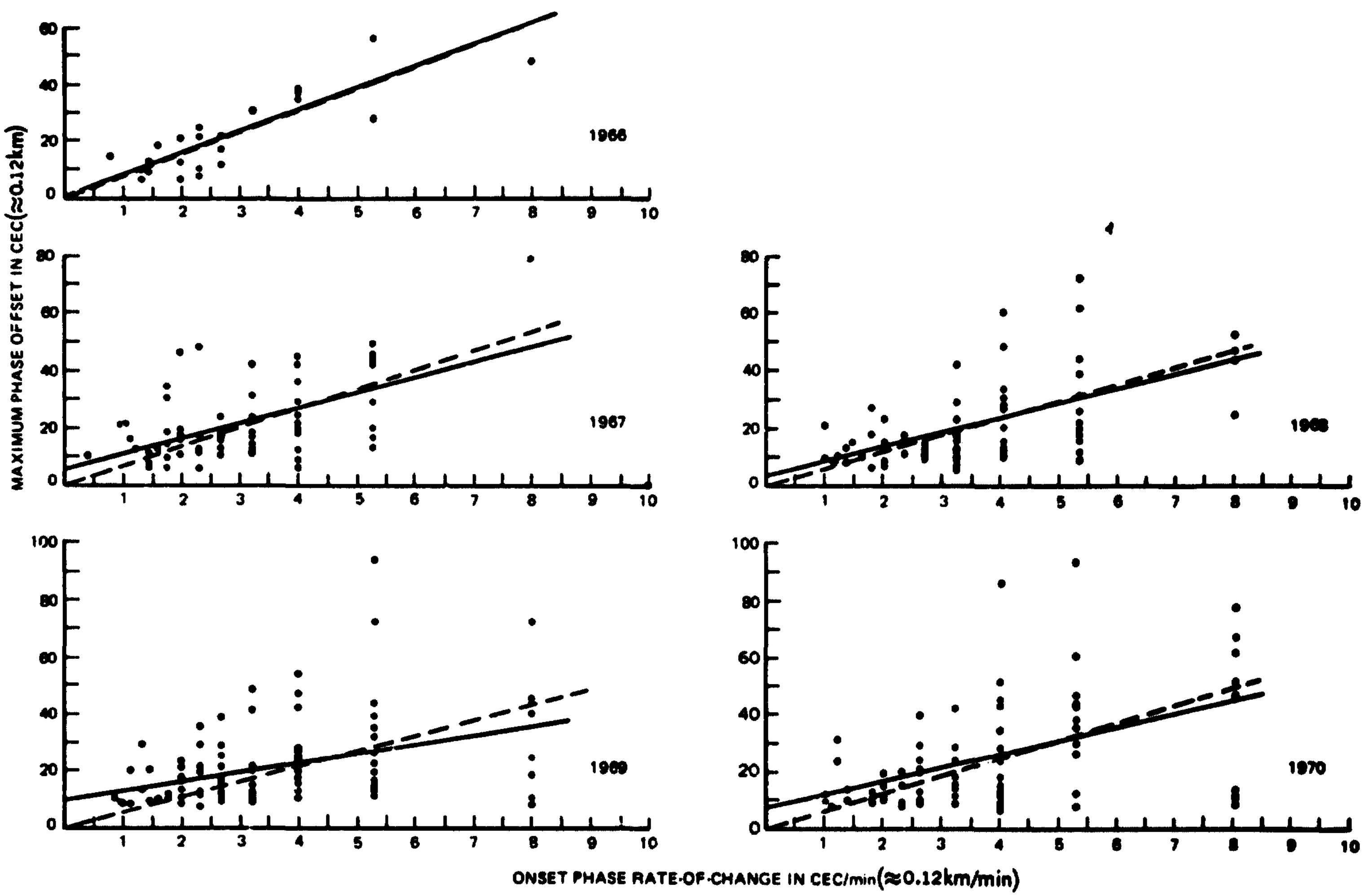

Figure 11. Maximum Phase Offset vs. Onset Phase Rate-of-Change for SPA Events on Hawaii to New York Path at 10.2 kHz

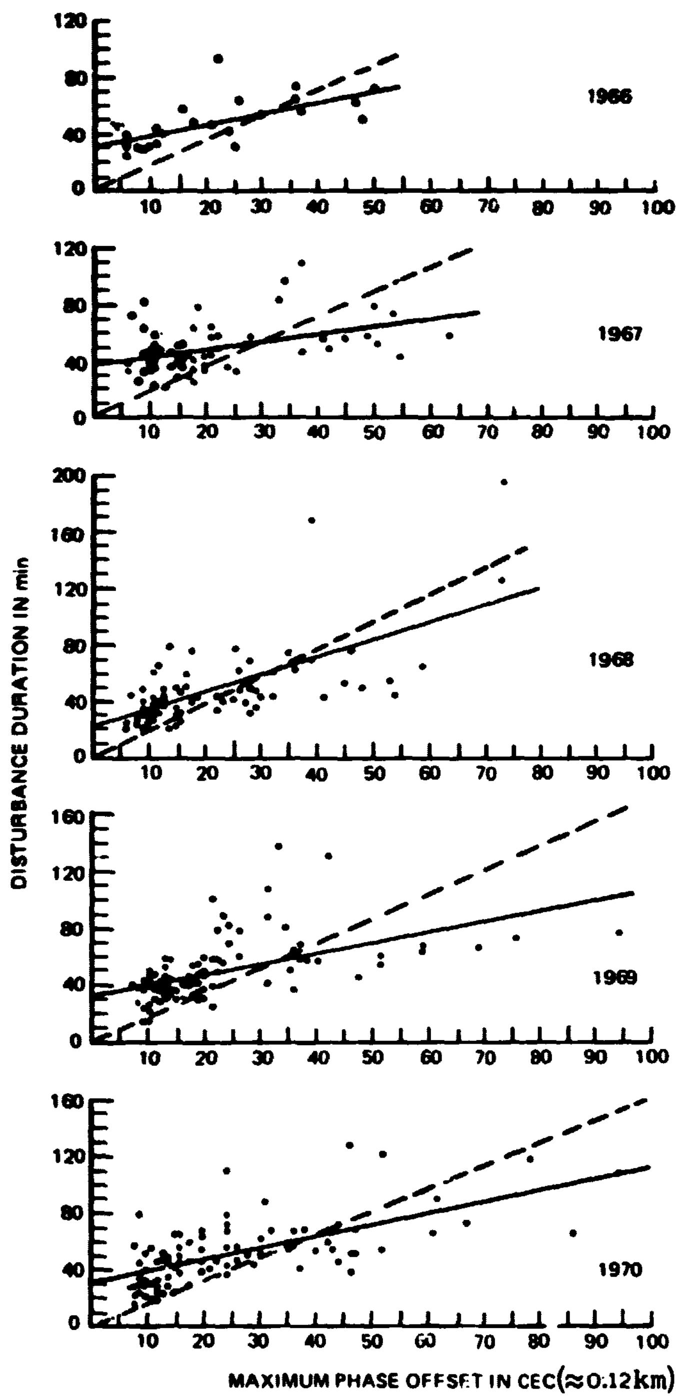

Figure 12. Disturbance Duration vs. Maximum Phase Offset for SPA Events on Hawaii to New York Path at 10.2 kHz

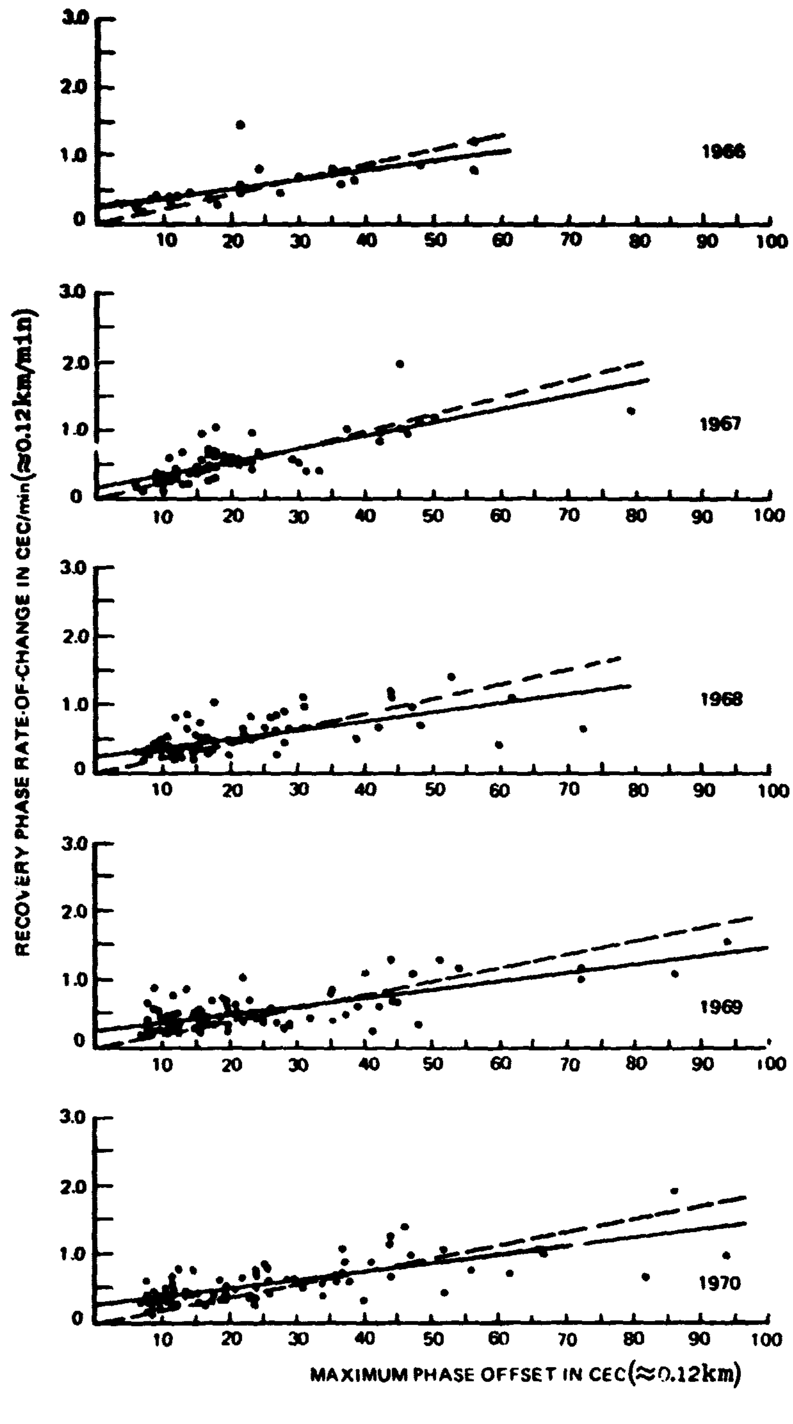

Figure 13. Recovery Phase Rate-or-Change vs. Maximum Phase Offset for SPA Events on Hawaii to New York Path at 10.2 kHz

Table II

SPA Shape Correlation

YEAR	NO. OF SPAs	MAXIMUM PHASE OFFSET VS. ONSET RATE-OF-CHANGE $\Delta\phi_M \sim T_o\dot{\phi}_o$			TOTAL DURATION VS. MAXIMUM PHASE OFFSET $T \sim (1/\dot{\phi})\Delta\phi_M$			RECOVERY RATE-OF-CHANGE VS. MAXIMUM PHASE OFFSET $\dot{\phi}_R \sim (1/T_R)\Delta\phi_M$		
		$\hat{T}'_o$ (MIN.)	$\hat{T}_o$ (MIN)	r_B	$\hat{\dot{\phi}}'$ (CEC/MIN)	$\hat{\dot{\phi}}$ (CEC/MIN)	r_B	$\hat{T}'_R$ (MIN.)	$\hat{T}_R$ (MIN.)	r_B
1966	24	7.7	7.6	0.84	0.57	1.30	0.64	47.0	71.9	0.69
1967	68	6.7	5.4	0.56	0.57	1.95	0.42	40.8	51.3	0.79
1968	76	5.9	5.0	0.59	0.53	0.82	0.65	46.3	78.1	0.65
1969	99	5.4	3.2	0.38	0.58	1.33	0.53	51.6	82.0	0.72
1970	92	6.2	4.7	0.51	0.62	1.24	0.65	52.4	80.0	0.74

Notes: See Figure 2 for definition of terms. Primes indicate quantities determined by regression through origin (dashed lines in Figures 9-11). The quantity $\hat{\dot{\phi}}'$ is the reciprocal of the estimated regression slope of T on $\Delta\phi_M$ and similarly for $\hat{\dot{\phi}}$, $\hat{T}'_R$ and $\hat{T}_R$.

All correlation coefficients are significant in the statistical sense that the respective quantities are positively correlated at the 95% confidence level. However, no estimated correlation slope is sufficiently high to allow explanation of even half of the observed scatter, although about half of the statistical variance can be explained in estimating recovery time. Presumably, other unobserved geophysical variables such as the energy spectrum of the associated flares or ionospheric chemistry variations are significant in determining the interrelationships. This statistical explanation associated with the correlation slope is in addition to causual explanation in the sense that when an event is recognized, the mean future condition is expected. Specific relations are discussed in the following paragraphs.

Maximum phase offset as a function of onset phase rate-of-change is shown in Figure 11. Although the indicated correlations suggest slightly shorter onset durations in periods of higher sunspot activity, the yearly average onset durations so computed yield a standard deviation of only 0.8 cec about an overall average of 6.4 cec. The apparent quantatization of rates is due to the measurement of onset slopes to the nearest degree.

Total duration as a function of the maximum phase offset is shown in Figure 12. The relationship is primarily causual; i.e., when an SPA has occurred, the duration will be typically about 45 minutes (see Fig. 5). There also is a tendency for larger SPA's to last longer. The median overall rate is 1.3 cec/min corresponding to 0.77 minutes per centicycle of observed phase perturbation, or equivalently, about 6 minutes duration per kilometer of effective ionospheric height change. There appears to be no significant difference between years of high and low solar activity.

Recovery phase rate-of-change is related to maximum phase offset in Figure 13. The indicated correlations are higher than for the two previous functional relationships and are sufficient to permit explanation of half of the variance in recovery rates in t rms of maximum offset. The indicated recovery time is consistant with previous results (see Fig. 5) showing the range for typical-to-average total duration to be about 40-50 minutes. There appears to be no significant difference between years of high and low solar activity.

Spatial Variation: Normalization of SPA Magnitude for Solar Zenith Angle

Previous sections have discussed the statistical occurence and distribution functions of SPA characteristics over a single path at one frequency and the interrelationship between SPA's at 10.2 and 13.6 kHz. Spatial effects on observed SPA magnitude will now be studied through the use of Rome, New York phase recordings of 10.2 kHz transmissions from both Hawaii and Trinidad. An initial scanning indicated that the onset times and durations of events observed near noon were simultaneous to within the minute or so accuracy of the instrumentation and that the shapes were approximately similar. Detailed attention was then directed to the interrelationship between peak amplitudes and illumination conditions along the two paths.

Previous studies of diurnal phase variation at 10.2 kHz have shown that phase varies approximately proportionally to the normal component of solar flux near noon (although slightly modified by historical dependence).[13] Normal diurnal variation near noon is approximately as though the effective phase height were negatively proportional to the incident solar flux (cosine of the solar zenith angle) and the nominal phase velocity were varying negatively proportional to the phase height with no variation in the phase of the excitation factor associated with coupling-propagated energy into or from the earth-ionosphere waveguide. The foregoing arguments are consistent with experimental phase variation resulting from normal solar radiative flux variations producing ionization changes in the D-region near noon. We now ask whether these features are also appropriate for abnormal solar radiation such as produced by solar X-ray flares. The raw measurements were correlated to obtain the assumed linear proportionality between maximum phase offsets on the two paths: $\Delta\phi$ Trinidad - New York = 0.44 ($\Delta\phi$) Hawaii - New York-0.2 cec. The raw measurements also were normalized by division by the respective path average cosines of the solar zenith angles and essentially the same result was obtained from the correlation both numerically and in quality of fit. Apparently the zenith angle criterion is a poor method of normalization. A further comparison was made by correlating measurements where the average solar zenith angle over both paths was much the same so as to reduce complexity by minimizing differences in path illumination conditions. In this case, a coupling proportionality constant of 0.39 was obtained compared with 0.44 obtained earlier.

The constant of proportionality between the magnitude of SPA's observed over the Hawaii - New York path and those observed on the Trinidad - New York path may be estimated theoretically. For the two paths in question secondary velocity variations, such as with path azimuth, are not expected to be large nor is the excitation factor expected to vary significantly for illumination near noon.[14] Thus the coupling constant should be proportional to effective path length ratio. The actual total path length ratio is 0.49 = (3843 km/7814 km) but propagation theory developed for the Omega signals[15] recognizes a region of excitation or de-coupling from the earth-ionosphere wave guide of 680 km (6.1° of arc on the earth's surface) at each end. Thus the effective path length is 2 x 680 km shorter than the geometric path length and the effective path length ratio for the two paths studied is (3843 - 1360 km/7814 - 1360 km) = 0.39, which was the experimental ratio obtained when data were selected so as to minimize differences in illumination conditions. Thus the experimental results are consistent with present theory on the spatial aspects of VLF propagation including the effective path length concept but are not consistent with zenith angle normalization. A possible explanation may be that the phase received is not linearly related to the normal component of X-ray flux over a path due either to ionization equations governing the relationship between effective phase height and input energy or a non-linearity between effective phase height and velocity. In practice both may be present to some degree. Certainly, theory indicates marked non-linearity in the relationship between phase height and velocity for heights between 60 and 70 km, the range needed for the larger SPA's. Non-linearity between ionospheric phase height and input flux is also believed likely. Although beyond the present scope of effect, it would appear possible to deduce the relationship between ionospheric phase height and high level solar flux input through further analysis of SPA's. Further analysis using the methods suggested here together with the more elaborate methods of Reference 4 appears particularly inviting.

CONCLUSIONS

The foregoing synoptic study of 500 SPA's observed between 1961 and 1970 in New York yields the following description of a typical SPA. A rather abrupt phase variation occurs reaching a maximum offset in about 6 minutes with the total duration of the event being about 45 minutes. Typical maximum offsets are about 15 cec at 10.2 kHz on the Hawaii - New York path corresponding to 15 microseconds or ionospheric phase height changes of 1.8 km. Typical observed phase rates of change during onset were 3.5 cec/minute corresponding to frequency shift of 6 x 10^{-8} or a rate-of-change of ionospheric phase height of 0.4 km/minute; recovery rates of change are 0.5 cec/minute corresponding to a frequency variation of 4 x 10^{-9} and ionospheric height change rate of 0.06 km/minute. SPA's are observed simultaneously over the different paths and at the two different frequencies investigated. The occurrence of SPA's is related to sunspot activity with about one per day being observed somewhere on earth when the sunspot number is about 85. The probability of a SPA occurring nearly vanishes during very low sunspot activity. Although sufficiently rare that SPA-associated phase variations exceed nominal propagationally-induced phase scatter only about 5% of the time even during high sunspot activity, SPA's are of practical as well as geophysical and astrophysical interest. VLF navigation, timing, and communications systems are expected to work safely, accurately, and reliably most of the time. It is primarily during unusual conditions that additional attention is needed to avoid false readings during these anomalies.

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QUESTION AND ANSWER PERIOD

QUESTION:

I see the great correlation with sunspot activity in many other fields of science, but I see a weak point, and ask you what significant data do you have of any activity that takes place on the other side of the Sun?

MR. SWANSON:

The solar forecasters do take into account and often will, say, call for a higher probability of activity, say, 12 or 13 days after activity was last observed on the ground — the spot group then reappearing on the other limb.

For the type of use that I have made of it here, I don't know if it is all that fair to tie it to a sunspot number directly, or whether it should be into the phase of a basically 11 year solar phenomenon. I wouldn't argue that.

Really, in the short run, it is clear that if you know the types and spots and whether or not they are there, or whether the evolution of spots on the Sun in the past few weeks has gotten them to be there, you can be far more deterministic about it. These reports are issued regularly, incidentally, both by Boulder and by the Cheyenne mountain forecast. It is still, I am afraid, somewhat of a black art, but it is getting more refined.

DR. WINKLER:

It appears to me that for practical application, time service, for instance, the probability measure is of relatively little importance. All you can say is next week it is going to be bad, and you will probably have a number of disturbances, but you will still be unable to say when they will come and how large they will be.

What is your opinion about comparing or correlating the various frequency difference, or phase differences, with the view toward telling the operator at the moment that he has a disturbance of so many microseconds? That is really going back to Pierce's composite phase technique.

MR. SWANSON:

The correlations there are high, but not entirely perfect. I think it is worth a try. Let's face it, this is what we do. We shouldn't lose sight of this, it is an accepted technique and has been for years. If you want to adjust a frequency standard or something of that sort, you start making a phase track as a function of your local clock, and you do this more or less in the daytime. If there is a sudden phase anomaly, the track makes an obvious runoff, and you say, oh, there was a Sudden Phase Anomaly. You wait for an hour and it goes away, and you are back to measuring again.

This is perfectly valid. Really that technique has basically the navigational counterpart which is to get a good dead reckoning of where you are going. We know from these distributions that when the event occurs the runoff would be fairly rapid. Your integration time is most likely on the order of a minute anyway.

So, we are talking here of only a couple of integration times before we are beginning to get a good estimate that there has been an event. This is a very realistic environment.

So, both the auto-correlated property, or sudden failure of it, is a good indication of an SPA as well as the inner comparison in the event at several frequencies. I think most of the time we avoid these because they are so obvious. The danger is mostly if you are using an automatic system or something of that type.

DR. REDER:

We had made some studies of finding out whether we can predict or whether we can say from a measurement, let's say on NPM at 23.4 kilohertz, whether we can say—at Fort Monmouth—what it would be on 10.2, Haiku, Hawaii, which is the same path.

And we are very happy because everything seemed to work out very fine. Unfortunately, I made some mistakes, and when I applied it to Trinidad at Fort Monmouth, it didn't work at all.

MR. SWANSON:

We did check the simultaneity of events on the Haiku to Rome, and also Trinidad to Rome path.

DR. REDER:

No, I am not talking about the simultaneity. This works fine. The problem was can it predict the size of the maximum phase, and this is the problem.

MR. SWANSON:

That very subject is in the paper. I didn't go into it here, partly because of the complexity. It is not as easy as you might think. It does not go strictly in a linear way with zenith angle, as the normal diurnal change would, near noon. Nor does it go strictly with the path length, apparently.

Well, one would think the process perhaps is more easily explained than it is. I think there are some reasons that it doesn't work quite the way you would like it to.

DR. REDER:

Yes, but Eric, the problem is it doesn't even work always on the same path, at the same time. That is the problem.

In other words, NPM to some location and Haiku to some location. We have three frequencies, 10.2, 13.6, and 11-1/3 kHz. Sometimes it will work very well using some kind of ionospheric model, and then comes an SID and it doesn't work at all.

Apparently, it means that it has a lot to do with the spectrum of the solar atmosphere, and that we have to take it into account.

MR. SWANSON:

I am sure this is an element. I think it is probably also true that over any of these long paths there is quite an array of the solar zenith angles, and I think, as you get more of a flare flux, the depression of the ionosphere, if you will, and the phase response to this depression, both will become non-linear.

So, now you say, I want a zenith angle, and what are we talking about. If we are talking about the average, we know that is wrong all of a sudden. It is a non-linear effect here. I have my own speculative feelings that one might be able to pull inversions, and deduce the relationship in essence between say velocity or effective phase height and the zenith angle, the flux component, by running studies of this sort.

In this regard, there is also the alternative approach of going directly to the aeronomy models using flux input on a particular flare, such as are available from the Solarad system.

DR. REDER:

Eric, it is a great pleasure to notice that whenever you don't know an answer you rely on non-linearity. Welcome to the club.

MR. SWANSON:

I am giving two approaches. I don't know how the non-linear lies, but I do know there are two. If you take even a simplistic model such as Wait published years ago, and look at the partial of the velocity with respect to the nominal height, as the ionospheric height levels go down toward 60 kilometers, it becomes a much wider spread in velocity than is true about, say, near 80. 70 to 80 is maybe half the velocity change than 60 to 70 is.

I think that the other half of the coin is what happens to the aeronomy given the flux coming in, and I suspect that is non-linear also.

MR. EASTON:

Thank you very much, Eric.

C-V

RESULTS OF THE LONG RANGE POSITION-DETERMINING SYSTEM TESTS

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ABSTRACT

The Long Range Position-Determining System (LRPDS) has been developed by the Corps of Engineers to provide the Field Army with a rapid and accurate positioning capability. The LRPDS consists of an airborne Reference Position Set (RPS), up to 30 ground based Positioning Sets (PS), and a Position Computing Central (PCC). The RPS transmits a PN modulated VHF carrier which is received by the PS units. The units measure the range changes to the RPS over a given data gathering period and transmit the range change information to the PCC via RPS sequentially. The PCC calculates the position of each PS based on the range change information provided by each Set. The positions can be relayed back to the PS again via RPS. Each PS unit contains a double oven precise crystal oscillator. The RPS contains a Hewlett-Packard Cesium Beam Standard. Frequency drifts and off-sets of the crystal oscillators are taken in account in the data reduction process. A field test program was initiated in November 1972. A total of 54 flights were made which included six flights for equipment testing and 48 flights utilizing the field test data reduction program. The four general types of PS layouts used were: Short Range; Medium Range; Long Range; Tactical Configuration. The overall RMS radial error of the unknown positions varied from about 2.3 meters for the short range to about 15 meters for the long range. The corresponding elevation RMS errors vary from about 12 meters to 37 meters.

INTRODUCTION

The Long Range Position-Determining System (LRPDS) has been developed by the U. S. Army Engineer Topographic Laboratories to provide the Field Army with a rapid and accurate positioning capability. Specific objectives of LRPDS are: (a) Provide combat survey throughout an Army Corps area; (b) Provide multiple positioning capability within a required area; (c) Accomplish survey and positioning missions in a required time frame.

SYSTEM DESCRIPTION

The LRPDS consists of a Position Computing Central (PCC), an airborne Reference Position Set (RPS), up to 30 ground based Positioning Sets (PS), and a Maintenance Set. The PCC controls the complete mission and calculates the locations of all PS. It consists of a transmitter-receiver unit, a computer, a mission control and monitor unit, communication equipment and other auxiliary equipment. The PCC is housed in a truck mounted van. The airborne RPS consists of a transmitter-receiver unit, a data processing unit, a cesium clock (H. P. H0I-5062C), a control and monitor unit, and an altimeter. During the ranging period of a mission the RPS transmits ranging signals to the PS. During the data transmission periods of the mission the RPS receives commands from the PCC or functions as a relay between PCC and PS. The PS consists of a transmitter-receiver unit, a crystal oscillator, a data processor, a data display unit, and a battery. The PS extracts ranging data from the ranging signal, stores the ranging data, and transmits the ranging data upon completion of the ranging period to the PCC for data reduction. The Maintenance Set is housed in a truck mounted van and contains instrumentation and facilities to support field maintenance of the LRPDS equipment. The LRPDS operates on a single carrier frequency which can be tuned between 260 MHz and 440 MHz in steps of 10 MHz. The carrier is bi-phase modulated by a pseudo noise (PN) code having a code length of $2^{13}-1$ bits or 245.73 Kilometer. The RF output of the transmitter of the transmitter-receiver unit can be set for one watt or five watt. The acquisition threshold of the receiver of the transmitter-receiver units is -113 dBm and the signal acquisition time is less than 10 seconds. The receiver employs code tracking for coarse ranging and carrier tracking for fine ranging. The resolution of the system is about 12 centimeter. The overall range error caused by the equipment is less than 1.5 meter.

SYSTEM OPERATION

A typical LRPDS mission consists of five phases: (a) Preparation and initialization; (b) Ranging; (c) Data collection; (d) Data reduction; (e) Data transmission. During preparation and initialization all messages and commands necessary to execute a mission are put together in proper sequence and transmitted to the RPS and stored in the processing unit. The messages and commands are transmitted to the PS according to mission schedule. In the second phase the RPS transmits ranging signals and commands to the PS which in turn extract and store the ranging data. The ranging data are obtained by measuring the time of arrival of the ranging signals from the RPS over preselected sampling periods. The measurement M taken over one sampling period t consists of several components which are shown in Figure 1. All components of the equation shown in Figure 1 including the measurement M have the same physical quantity of length.

$$M = \Delta R + at + bt^2/2 + N_R + N_o + P\Delta R$$

ΔR = Range Change

a = Frequency Offset

b = Frequency Drift

N_R = Receiver Noise Error

N_o = Oscillator Noise Error

P = Propagation Scale Factor

Figure 1.

ΔR is the range change between PS and RPC occurring during one sampling period. Frequency offset a and frequency drift b are considered as being constant during the ranging period and are determined and accounted for in the data reduction process. Receiver noise error and oscillator noise error are included in the overall range error caused by the equipment. The propagation scale factor takes in consideration the existence of the atmosphere. The factor is estimated and improved in the data reduction process. During the data collection phase the ranging data are transmitted in a preselected sequence from the PS to the PCC via RPS. The ranging data are processed and computed to PS location coordinates by the PCC during the data reduction phase. During the data transmission phase, messages and location coordinates are transmitted from PCC to the PS via RPS as required. Figure 2 shows a typical operational layout for LRPDS.

SYSTEM FLIGHT TESTS

The field test program was initiated in November 1972 and completed in January 1973. The primary purpose of the flight tests was to evaluate the accuracy of the system in actual field use. Four general types of Positioning Set layouts were used:

a. Short Range — Nine position sets uniformly distributed in a 30 km x 30 km area with the tenth PS located at various positions outside this area ranging from 10 km to 30 km from the perimeter.

b. Medium Range — Nine to ten position sets distributed through a 60 km x 60 km area. The tenth set during some tests was located in the vicinity of the PCC.

c. Long Range — Eight to nine position sets distributed throughout a 60 km x 60 km area with one or two position sets located at positions 180 km in distance from the center of the 60 km x 60 km area.

d. Tactical Configuration — Eight to nine position sets placed in a 60 km x 60 km area with six of the sets placed in the top third of the area.

The test area used included part of the Casa Grande and Arizona Test Range. Twenty-five presurveyed sites in a 60 km x 60 km area were used as position set locations. The survey of the PS locations was accomplished by a super first order survey method which kept the survey errors of the positions down to a few centimeters. In addition to these sites, two sites located in the Yuma Test Range near Stoval were used to evaluate the long range capability. The PCC was located at the Motorola Plant in Scottsdale during all the tests. Figure 3 shows a map of the general 60 km x 60 km area with the site locations.


LRPDS OPERATIONAL SET-UP
AN/USQ – 56
(SURVEYING-POSITIONING SYSTEM)
UNKNOWN STATIO
KNOWN STATION

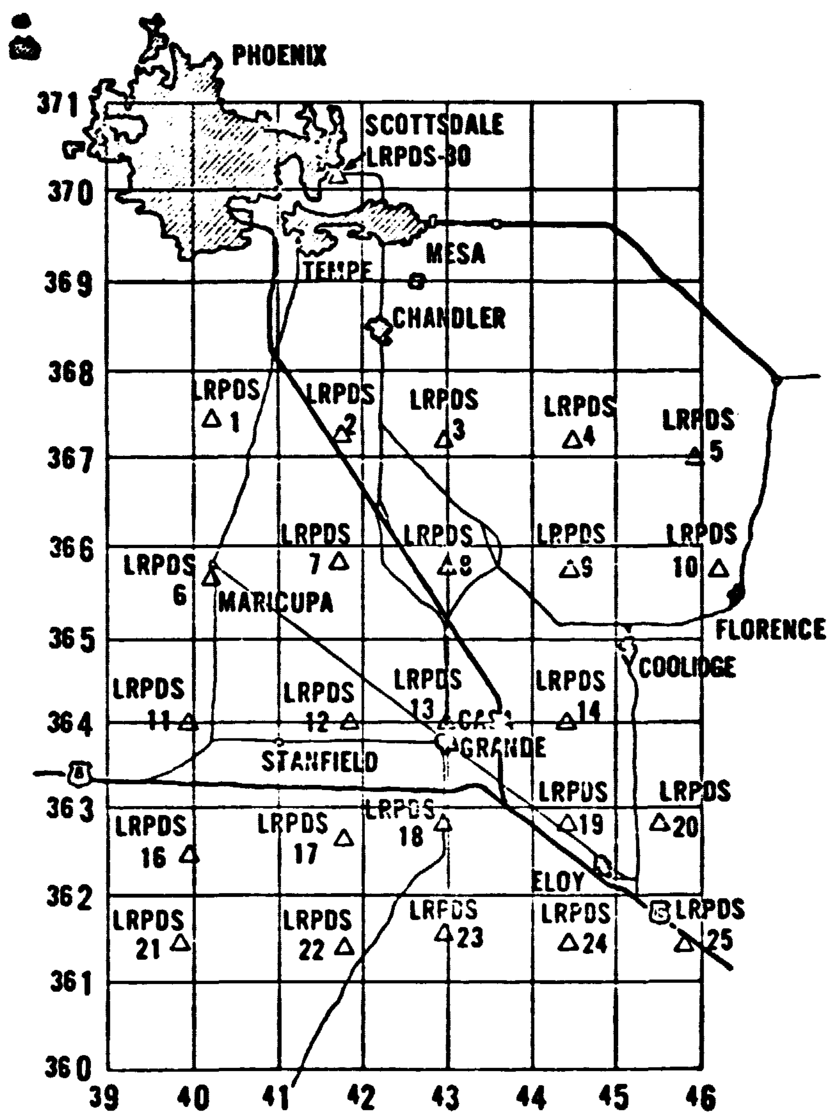


Figure 3. LRPDS Site Locations

A total of 52 flights were conducted including 62 missions for a variety of purposes. Of these, 15 missions were evaluated for Short Range Tests, 15 for the Medium Range Tests including the Tactical Configuration, and four for Long Range Tests. The other missions were devoted to Equipment Check Flight Tests.

A number of flight patterns were used throughout the tests. In each case each flight pattern generally consisted of one loop at one altitude followed by a second nearly identical to the first but at a different altitude. Figure 4 shows a flight pattern

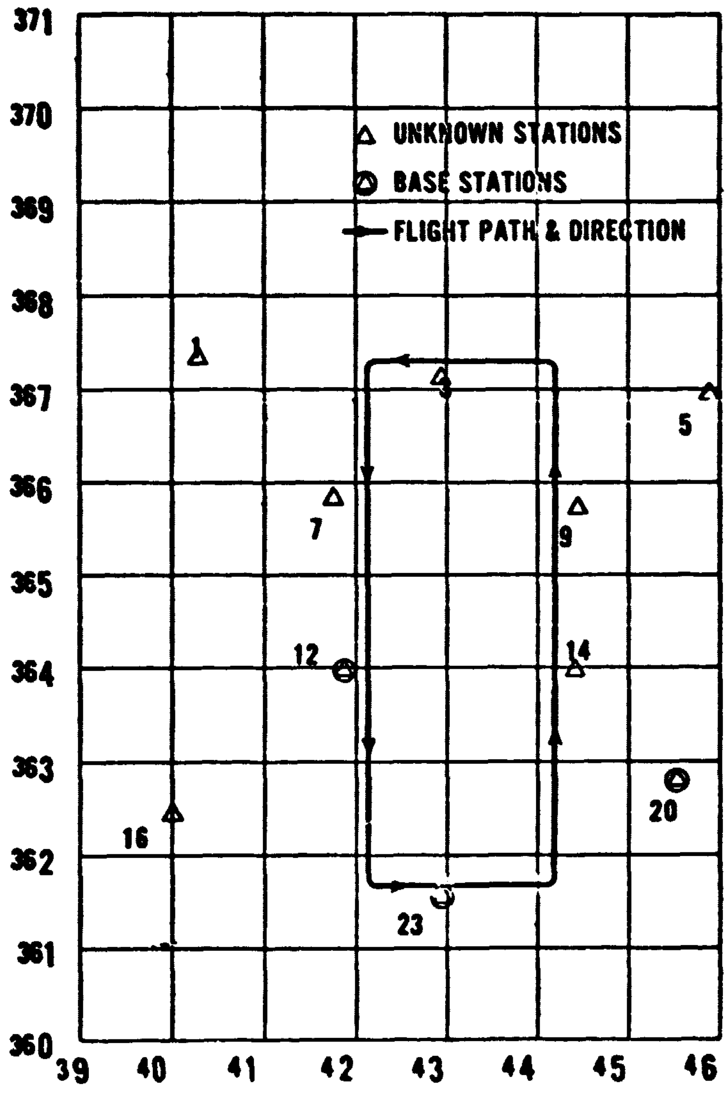


Figure 4. LRPDS Station and Flight Geometry

having a favorable geometry relative to the indicated ground stations. Figures 5 through 7 show some of the results of the Short Range Tests. The numbers in the figures are the easting, northing, and elevation errors of the positions measured by LRPDS with reference to the positions determined by survey. The positioning errors are measured in meters. Figures 8 through 10 show some of the results of the Medium Range Tests. Figure 5 through 10 show also the mean and root mean square of the errors of the individual stations.

FLT NO.	SITE NO. 2	3	6	7	12	13
7	2.9	3.1	- .8	2.1	1.0	
8	.1	1.2	.2	- .2	-1.2	.1
10	- .6	-2.9	1.0	-1.1	-2.0	-4.2
12	- .6	1.3	- .2	.4	.3	1.4
13	- .6	.0	.1	- .3	- .7	- .2
14	- .7	- .3	.0	- .3	- .2	.4
37	.1	.8	-1.4	- .0	.0	- .6
RMS	1.2	1.8	.7	.9	1.0	1.8
MEAN	.1	.5	- .2	.1	- .4	- .5

Figure 5. 30 km x 30 km Area Easting Errors

FLT NO.	SITE NO. 2	3	6	7	12	13
7	-2.2	-4.5	- .3	-2.4	.2	
8	- .1	.2	- .1	- .6	1.9	- .4
10	- .7	-1.4	- .8	- .2	.2	2.9
12	- .3	1.2	.8	.2	.5	- .7
13	-2.9	1.4	.6	.1	.9	- .6
14	-3.4	- .5	.3	- .3	- .5	- .6
37	-4.1	-4.5	1.4	.4	4.6	4.1
RMS	2.5	2.5	.7	1.0	2.0	2.1
MEAN	-2.0	-1.2	.3	- .4	1.1	.8

Figure 6. 30 km x 30 km Area Northing Errors

FLT NO.	SITE NO. 2	3	6	7	12	13
7	-20.8	-7.8	-1.9	-7.5	-7.6	
8	6.7	5.2	10.5	5.1	- .2	-4.3
10	11.5	-7.3	11.9	16.8	5.5	4.4
12	-12.3	.6	5.7	- 1.2	1.5	7.7
13	7.9	.7	.9	4.1	6.1	- .4
14	5.3	5.5	14.6	8.1	-3.0	-6.6
37	-14.2	-31.9	33.7	23.9		-26.5
RMS	12.3	13.0	15.3	12.1	4.8	11.9
MEAN	- 2.3	- 5.0	10.8	7.0	.4	- 4.3

Figure 7. 30 km x 30 km Area Elevation Errors

FLT NO.	SITE NO. 1	3	5	6	7	8	9	14
19	-5.7	1.3	-2.0		3.0		.5	- .6
20	-1.7	1.2	.6		.6		2.3	2.0
21	8.3	8.6	8.9		6.9		7.7	5.1
29	2.4	3.6	1.4	2.1		2.7		2.5
30	- .3	- .3	-4.3	.2		- .3		-1.9
32	.6	- .4	.9	1.1		- .1		
33	-1.5	2.5	5.8	4.1		1.8		
RMS	4.0	3.7	4.4	2.3	4.3	1.6	4.3	2.8
MEAN	.3	2.4	1.6	1.9	3.5	1.0	3.5	1.4

Figure 8. 60 km x 60 km Area Easting Errors

FLT NO.	SITE NO. 1	3	5	6	7	8	9	14
19	4.7	.7	- 5.1		- .1		- .3	- 2.0
20	2.2	.3	1.4		.9		1.3	1.3
21	.9	- .9	- 6.2		.7		-1.9	- 4.1
29	2.1	-1.4	- 3.9	.4		- .6		.7
30	2.4	- .8	- 5.3	- .3		- .7		- .5
32	- .8	-2.7	.1	-1.2		-2.0		
33	1.6	- .4	1.5	-3.5		- .6		
RMS	2.4	1.3	4.0	1.8	.6	1.1	1.3	2.2
MEAN	1.9	- .8	-2.5	-1.1	.5	-1.0	- .3	- .9

Figure 9. 60 km x 60 km Area Northing Errors

FLT NO.	SITE NO. 1	3	5	6	7	8	9	14
19	11.1	-2.3	26.1		.6		-27.6	-20.9
20	.2	7.7	21.5		-4.9		7.5	4.6
21	23.5	-3.3	19.5		-10.7		-13.8	-11.0
29		8.2	7.2	7.5		15.5		9.1
30		-1.8	-2.0	-4.7		2.1		11.1
32		2.9	-32.5	3.4		9.2		
33	1.7		13.9	8.8		8.8		
RMS	13.0	5.1	20.1	6.5	6.8	10.1	183	12.5
MEAN	9.1	1.9	7.7	3.8	-5.0	8.9	-11.3	- 1.3

Figure 10. 60 km x 60 km Area Elevation Errors

The horizontal errors of the positions determined by the Short Range, Medium Range, and Tactical Configuration Tests are plotted in Figures 11 through 14. Figure 11 shows the results of the Short Range Tests including 7 flights and 6 positioning sets on unknown locations. The geometry of the flight patterns of these flights with respect to the locations of the ground stations was favorable and therefore, the position errors were relatively small. The circular probable error (CEP) of the errors plotted in Figure 11 was 1.9 meter and the probable error (PE) of heights was 8.2 meter. Figure 12 shows the results of all Short Range Tests including 15 flights and 8 positioning sets on unknown locations. The 15 flights used flight patterns of various geometry. The errors were accordingly larger than the errors obtained by using good flight geometry. Figures 13 and 14 show the results of the Medium Range Tests. Figure 13 represents the results of flight patterns with good geometry and Figure 14 the results of all flights of the Medium Range Tests.

The Long Range Tests could only provide the easting and northing components of the location position. A simulation of the Long Range case had shown that the height error will always be exceedingly large because of the altitude limitation of the aircraft. The mean and the root mean square of the easting errors were 29 meter and -28 meter respectively. The mean and the root mean square of the northing were 16 meter and 13 meter respectively.

CONCLUSIONS

The LRPDS performance exceeds the stated objectives and requirements for this system. As a result, the LRPDS utility for tactical surveying is greatly enhanced.

The aircraft flight patterns were not critical to system accuracy. It is necessary to fly two normally closed loops at two relatively different altitudes to obtain best results. The flight path control and general shape did not seem to be important. Deviations of 10 to 15 km appeared to have little effect.

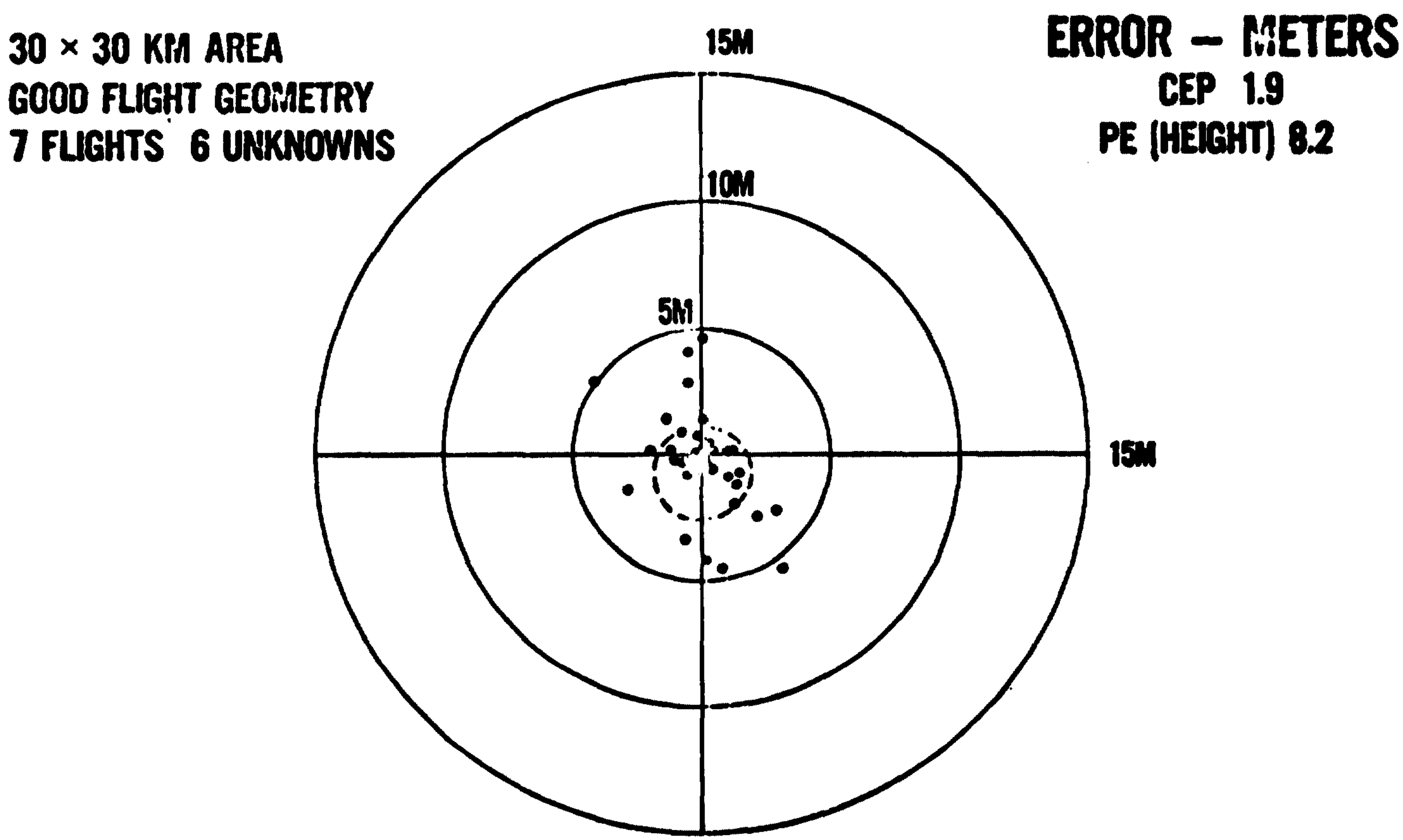
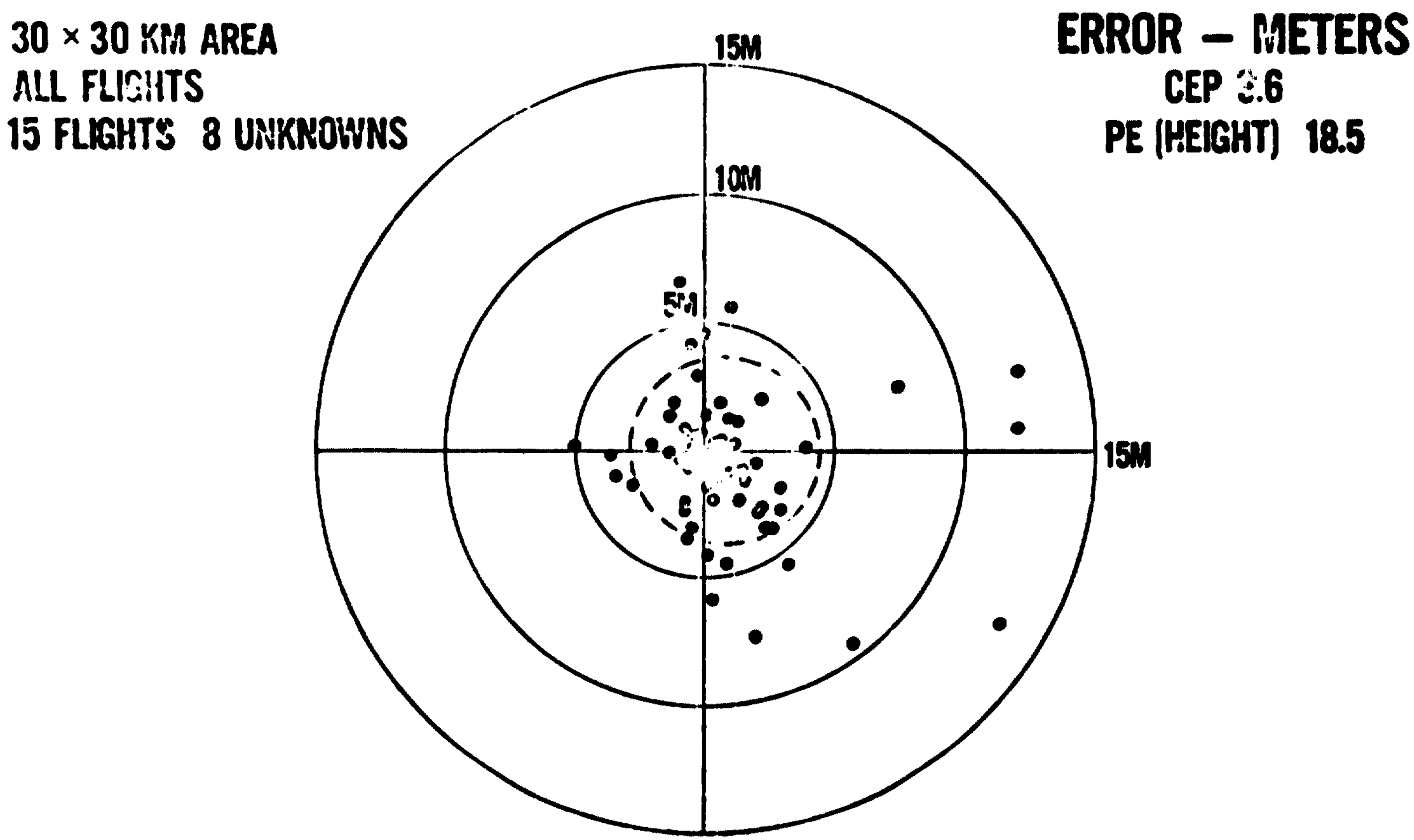
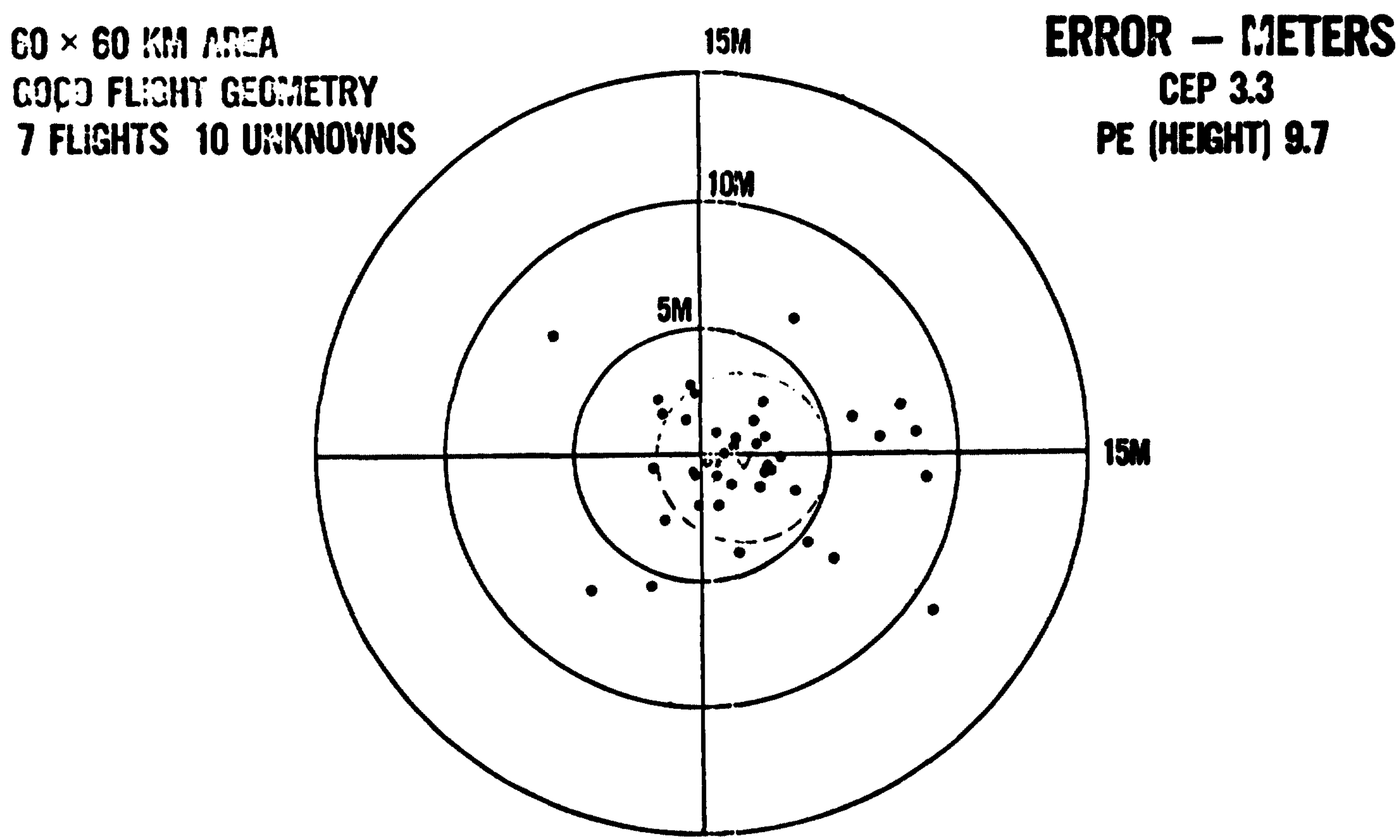

30 × 30 KM AREA
GOOD FLIGHT GEOMETRY
7 FLIGHTS 6 UNKNOWNS
ERROR – METERS
CEP 1.9
PE (HEIGHT) 8.2
15M
10M
5M
15M

Figure 11.



30 × 30 KM AREA
ALL FLIGHTS
15 FLIGHTS 8 UNKNOWNS
ERROR – METERS
CEP 3.6
PE (HEIGHT) 18.5
15M
10M
5M
15M

Figure 12.



60 × 60 KM AREA
GOOD FLIGHT GEOMETRY
7 FLIGHTS 10 UNKNOWNS
ERROR — METERS
CEP 3.3
PE (HEIGHT) 9.7
15M
10M
5M
15M

Figure 13.

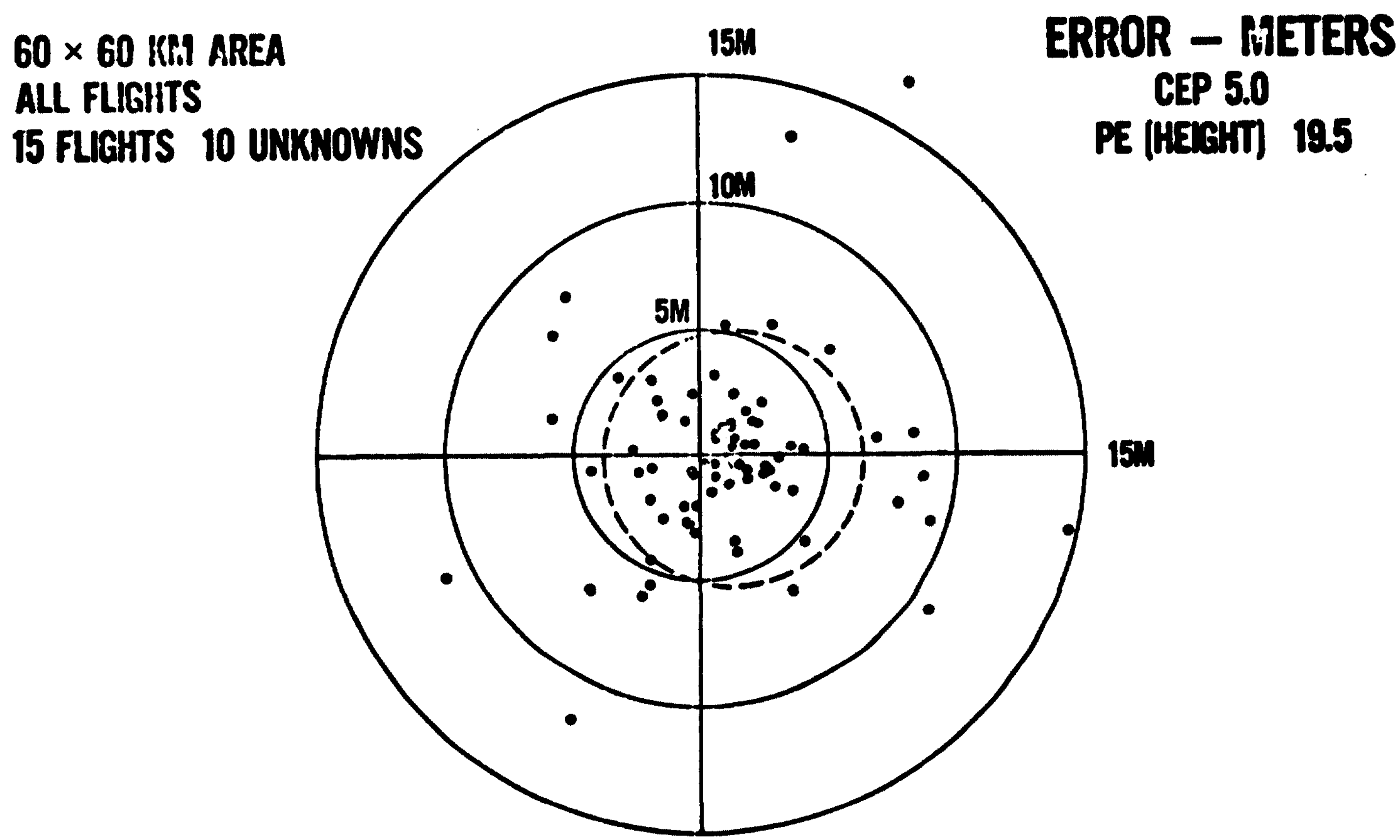

60 × 60 KM AREA
ALL FLIGHTS
15 FLIGHTS 10 UNKNOWNS
ERROR – METERS
CEP 5.0
PE (HEIGHT) 19.5
15M
10M
5M
15M

Figure 14.

QUESTION AND ANSWER PERIOD

MR. LIEBERMAN:

How do you get that field unit into enemy territory? That field unit that you showed with the helmet in it.

DR. ROHDE:

How do you get this into enemy territory?

MR. LIEBERMAN:

Yes.

DR. ROHDE:

On backpack by a soldier.

(Laughter.)

DR. ROHDE:

I mentioned in the first report on the LRPDS the weight. As a matter of fact, you need two people, because each backpack unit weighs 30 pounds, and so that two people are required to carry it.

So, I will say, this might not be a forerunner of NAVSTAR, but it shows, you know, the direction. And, of course, NAVSTAR has much tighter requirements on weight.

MR. LIEBERMAN:

Do you have a beeper in there?

DR. ROHDE:

I beg your pardon?

MR. LIEBERMAN:

Didn't you just have a beeper out in the ocean when they come down?

DR. ROHDE:

A beeper for what?

MR. LIEBERMAN:

To give the position.

DR. ROHDE:

That would be nice, but you know, you have to measure something. In order to measure something, you need some energy.

Now, I am glad to discuss this later. Maybe you have a very good idea which we could incorporate.

MR. POTTS:

Dr. Rohde, I have several questions.

On your artist's depiction of the deployment of the system, it indicated that you have three base stations in the friendly territory with your aircraft flying over friendly territory. And then your remote stations in enemy territory.

Yet your test data now showed the aircraft flying over the remote positions? Is that a valid test?

DR. ROHDE:

Now, let me see, these test data which I have shown give only the results if we would use this as a survey system.

But I have indicated in my abstract that we have actually four different areas. We have the 30 by 30 kilometer areas; we have the 60 by 60 kilometer areas; we have the long range operational area; and we have the tactical combat area.

I have not addressed the long range and the tactical combat areas.

MR. POTTS:

On several slides you indicated a circular error probability which ranged from about two to five meters, or something like that.

DR. ROHDE:

Yes.

MR. POTTS:

And then there was a height error. I guess the PE, is that probable error?

DR. ROHDE:

Probable error, yes.

MR. POTTS:

What is the significance of that? Is that an error in the location, altitude?

DR. ROHDE:

Right. Maybe I should have said that all the sites have been very carefully surveyed with conventional survey methods, and these positions were very accurate. And what we have measured with these positions sets are the deviations from these survey measurements.

DR. WINKLER:

Dr. Rohde, your system strikes me as a very straight-forward and surprisingly common sense approach to a problem which is quite general.

Now, there is one point, however, which I did not quite understand, and that is the role and the requirements of the crystal oscillators in each individual user location.

Isn't it possible by increasing the number of base stations to create the necessary redundancy so that you really don't need any high performance crystal oscillators at these stations?

I mean, this is the essential point, why is it necessary to have a high precision frequency control here in that system, when by providing redundancy you can avoid it?

DR. ROHDE:

I would say at this point we have enough problems with our data reduction, and what you suggest only would increase the data reduction on the computer, the position computer control.

DR. WINKLER:

Yes, of course.

DR. ROHDE:

And we have not entirely solved or debugged our present data reduction schemes. But we have thought about providing the base stations with cesium clocks, for instance, and then seeing if we could relax the requirements on the positioning sets.

This would be particularly interesting, perhaps, because at this time the requirement on the positioning sets is set up, and we don't move it. So, in other words, during an observation period, the positioning sets should not be moved around, because of the stability requirements.

DR. WINKLER:

Yes, but I am concerned really with the problem, how shall we strike that engineering compromise, speaking on the one hand possibly using a larger number of high precision oscillators under very strenuous conditions, or on the other hand using a little bit more computation.

In my judgement and I have considered that in many systems, the balance should always be with more computation.

DR. ROHDE:

Right, but this would require a considerably larger computer, because our present computer just barely can do the work within the allocated time. So, either we have to increase the emission time, which is undesirable from the military point of view, or we have to have a larger computer, and so far I don't know exactly what computer we could recommend. However, computer development is very fast, and we have to keep looking at these things. As a matter of fact, we have right now a test in our laboratories to re-examine the entire computer portion, which we literally underestimated. Everybody was concerned about the crystal oscillator, or the oscillator's period, but we found out that the oscillator period problems could be solved. We had many more problems with the computer system, or with the entire software and data reduction.

MR. WILSON:

I just wanted to know, what was the approximate frequency?

DR. ROHDE:

The system operates on a single frequency, and the frequency can be tuned between 240 and I guess 400 megahertz in steps of 10 megahertz, so that the number of users which are adjacent can use the system without interfering with each other.

MR. BRUHL:

Dr. Rhode, I am Keith Bruhl.

Have you, perchance, considered re-transmission of either Loran-C or three frequency Omega for this type of application?

DR. ROHDE:

One of the problems with Loran-C, and Omega, is that you have at least ground wave propagation, and I have shown you these results, in the desert of Phoenix.

If you would use the same system, maybe, in a jungle area, the results might not be as good, and in the framework of another project—I guess it is NAVSTAR—we are working on a program to determine close to ground wave propagation effects, such as foliage penetration, multi paths and so on.

But one of the problems with Loran-C, is the unknown of the propagation close to the ground. Suppose you measure a position repeatedly. If you take a standard deviation, it might be very good. Of course, I don't know if you measure this over a longer period of time, you might perhaps find out that after a rain or so, if you look for a diurnal variation, a seasonal variation, that your standard deviation will increase.

But by the same token, you may measure repeatedly, but you may measure repeatedly wrong.

MR. BRUHL:

That is, of course, true.

What you would have in your favor if you used Omega, would be that you would be retransmitting in base band on the UHF carrier to a translator and back to the base station. This is very similar to the system that the Coast Guard is now evaluating.

DR. ROHDE:

Would you expect that you could position a point to something better than 10 meters?

MR. BRUHL:

If it was premapped, yes. If the area has been premapped before by coordinates.

DR. ROHDE:

Yes, but if you don't have the time to do that?

MR. BRUHL:

You are quite right. I think there are ways around this. In other features, it is extremely lighter in weight, and you have a lockup a lot longer, in about 30 seconds.

DR. ROHDE:

I guess one of the reasons to overcome these problems, among others, is the embarking on the NAVSTAR program where you have consistently relatively high elevation angles. Maybe next time, if we get the modulation receiver, and we make reasonable experiments, we can report about this, too.

CMDR. POTTS:

Dr. Rohde, I didn't plant Keith Bruhl back there. I am glad he opened up Loran-C. I don't want to sound like a salesman.

We had a chain, and still do have a chain over in a jungle area, and we used it for quite a number of years, and got quite a lot of data on the baseline and between stations for about 200 miles, and the users were happy and reported repeatability in the order of 60 feet.

DR. ROHDE:

Yes, I guess you want me to—oh, I am not going to interrupt you.

CMDR. POTTS:

The absolute accuracy, of course, is a function of the conductivity of the soil, the way it was propagating. There is no question about that.

In your system there, where you are talking about a 200 kilometer distance, in enemy territory, and where the Loran-C transmitter baselines could be significantly shorter, I don't think you are going to have any trouble at all getting a 10 meter accuracy. Not only that, I was struck by the vulnerability of your system, in that the users are, first of all, radiating the signals, and second of all, you have got the aircraft up there which is also vulnerable.

DR. ROHDE:

I would agree that if you go to 200 kilometers that the results which can be obtained with Loran-C may approach the results which you may obtain with LRPDS under certain conditions. We have to look, of course, at all the parameters.

I guess what you are referring to is the maps which were made for Vietnam.

MR. POTTS:

No, I was referring to the users' experiences in the studies they were doing, and most of them are in the literature.

DR. ROHDE:

Yes. We have also looked into, of course, Loran as a potential positioning system, but for survey application, techniques, field artillery surveys, the accuracy is insufficient.

You have seen the accuracy we obtained in a typical area where we were conducting surveys, which is 30 by 30 kilometers, and you have seen that the horizontal position accuracy is in the order of a few meters, better than three meters.

MR. POTTS:

I quite agree with you, without precalibration, we couldn't do that with a normal Loran-C system with long baselines.

MR. WILSON:

I was just going to make a comment on the use of Loran-C versus the 400 megacycle system. Isn't one of the big problems here jamming?

I think Loran-C would be much easier to jam than the 400 megacycles system.

DR. ROHDE:

Yes. Of course.

As far as I know, Loran-C has a CW or pulse type modulation. So, it is more easily jammed. Also the enemy should not make use of our systems.

MR. WILSON:

Loran-C is a pulsed system, that is phase-coded. As a matter of fact, about 13 years ago the Army did extensive tests on the vulnerability of the Loran-C. I can state without worrying about going to jail that it is not very vulnerable.

We are more of an interference to ourselves when we position one chain near another and are not careful of rate selection.

DR. ROHDE:

Yes, certainly maybe we could at another time discuss this in more detail. We are always open to additional suggestions.

MR. EASTON:

Thank you very much, Dr. Rohde.

N75 11301

THE COLOR BAR PHASE METER—A SIMPLE AND ECONOMICAL METHOD FOR CALIBRATING CRYSTAL OSCILLATORS

D. D. Davis
National Bureau of Standards, Boulder

ABSTRACT

Comparison of crystal oscillators to the rubidium stabilized color burst is made easy and inexpensive by use of the color bar phase meter. Required equipment consists of an unmodified color TV receiver, a color bar synthesizer and a stop watch (a wrist watch or clock with sweep second hand may be used with reduced precision). Measurement precision of 1×10^{-10} can be realized in measurement times of less than two minutes. If the color bar synthesizer were commercially available, user cost should be less than $200.00, exclusive of the TV receiver. Parts cost for the color bar synthesizer which translates the crystal oscillator frequency to 3.579 MHz and modulates the received RF signal before it is fed to the receiver antenna terminals is about $25.00. A more sophisticated automated version, with precision of 1×10^{-11} would cost about twice as much.

N75 11302

A TIME REFERENCE DISTRIBUTION CONCEPT FOR A TIME DIVISION COMMUNICATION NETWORK

H. A. Stover
Defense Communications Agency

ABSTRACT

Starting with an assumed ideal network having perfect clocks at every node and known fixed transmission delays between nodes, the effects of adding tolerances to both transmission delays and nodal clocks is described.

The advantages of controlling tolerances on time rather than frequency are discussed. Then a concept is presented for maintaining these tolerances on time throughout the network. This concept, called time reference distribution, is a systematic technique for distributing time reference to all nodes of the network. It is reliable, survivable and possesses many other desirable characteristics. Some of its features such as an excellent self monitoring capability will be pointed out.

Some preliminary estimates of the accuracy that might be expected will be developed and there will be a brief discussion of the impact upon communication system costs.

Time reference distribution is a concept that appears very attractive to the author. It has not had experimental evaluation and has not yet been endorsed for use in any communication network.

BACKGROUND

Time division multiplexing and/or switching which is often desirable in a digital communication network presents timing problems. These are problems of a type not experienced in analog networks using frequency division multiplexing and space division switching.

For time division multiplexing and switching in a digital communications system, each bit from an incoming bit stream must be available to fill its time slot when it is needed. In an ideal system, exact time would be available at every transmission node and there would be known, fixed delays between nodes. Under these conditions, the system could be designed so that each bit arrives at the time division multiplexer or switch at the desired moment.

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However, in the real world this ideal situation does not exist. There are variations in transmission delay between nodes. These can be allowed for by using "elastic" storage buffers between the receivers located at each node and the associated time division multiplexing or switching equipment. Bits which arrive too soon are stored in these buffers until they are needed. The buffer storage also serves as a reservoir to supply bits when incoming bits arrive late. At any given data rate each bit of buffer storage represents an increment of time tolerance.

If, in addition to variations in transmission delay between nodes, there is a tolerance on time at each node, the buffers may be enlarged to also accommodate the nodal timing errors. Technology is presently available, MOS microcircuit first-in first-out (FIFO) serial buffers used by the computer industry, that can economically provide hundreds of microseconds of variable delay storage. A bit read into the input of these devices propagates by itself to the unfilled bit location nearest the output. When data is read out, the remaining stored data automatically shifts toward the output. The input and output clocks are independent. Unless timing is used for functions other than keeping the bits in the proper sequence, the acceptable timing tolerance for the communications system is limited only by the acceptable number of bits of buffer storage and the data rate, i.e., the acceptable variable time delay of the buffers.

A tolerance on nodal frequency (instead of on nodal time) is equivalent to a tolerance on the rate at which an error in time may accumulate. A frequency tolerance will permit a boundless time error; therefore, the interval of time over which an error is permitted to accumulate must be specified. The amount of buffer storage required by the communications system is determined by the accumulated time error rather than the rate at which it accumulates. As a result, whenever a frequency tolerance is specified, a reset interval must also be specified. For a system which is to be in continual use over a long period of time, it is preferable to control time rather than frequency.

One presently planned communications system (TRI-TAC) will employ a tolerance on frequency rather than time. In this system an atomic standard is used at each node to maintain the required frequency tolerance. Buffer storage sufficient for a 24-hour period is provided. The buffers are dumped and reset as required.

Another technique not requiring a tolerance on time is called mutual synchronization, in which each node adjusts its own frequency to reduce the timing error between itself and some average of the rest of the network[1,2,3]. Removal of any node of the network still leaves a synchronized network, but a transient disturbance in one part of the network will propagate to other parts of the network. Any one clock can perturb the system frequency.

A technique called pulse stuffing[4], which does not require synchronism, has been developed for point-to-point time division transmission. In pulse stuffing, multiple asynchronous signals are padded with dummy pulses to bring them to a common bit rate for time division multiplexing. After multiplexing at this common rate, transmission of the combined signals and demultiplexing at the receiver, the dummy pulses are moved to return each signal to its original asynchronous rate. Although this pulse stuffing technique appears economical for point-to-point applications, it does not appear economically attractive for a time division switched network. If a large number of channels are combined synchronously at the transmitting end, the pulse stuffing technique is an attractive method of multiplexing many of the resulting higher rate channels. The cost of stuffing is shared among all of the individual channels that are synchronously combined to form the higher rate input to the pulse stuffing equipment. The signals that are originally synchronous at the input of the point-to-point transmission system remain synchronous at its output. In a switched network each member of a group of synchronous channels at a single origin may have a different destination. Each might be grouped with signals originating from other points in the network so that members of the new group will not be synchronous. They no longer will be able to share the same pulse stuffing and destuffing equipment. Pulse stuffing on an individual channel basis thus becomes necessary in an unsynchronized switched digital network. This implies expense.

Perhaps the most obvious of all synchronizing methods is a master-slave technique in which all nodes of the network are slaved, either directly or through intermediate nodes, to a single master clock. The reliability of this technique and its survivability in a military environment have been questioned. However, several commercial communications systems plan to use it[5, 6].

From this background discussion it can be seen that a close time tolerance at every node of a digital communications network employing time division multiplexing and/or switching would be desirable if an economical, reliable and survivable method could be found. The Time Reference Distribution technique is offered as a possibility. After the technique has been explained some of its advantages will be listed. Some of the listed advantages result from maintaining a close time tolerance.

TIME REFERENCE DISTRIBUTION

The Time Reference Distribution technique[7] for digital communications network timing provides an accurate clock at each node. Accuracy is maintained by occasional correction of nodal clocks using time reference information transmitted over every link of the network in such a way as to be independent of transmission delays. Since a timing path is associated with every communications link, the only way for any node to be isolated from timing information is for it to have no communications with the remainder of the network.

For the Time Reference Distribution technique, all nodal clocks are rank ordered, i.e., sequentially arranged in order of priority. Time reference information is passed in both directions over every link. Time comparison signals to be used for time difference measurement can be superimposed on the data stream or its carrier by a special modulation technique. Alternatively, the frame synchronization code may be used for this purpose. In addition to these basic time comparison signals, four types of data are transferred from each node to the node at the other end of each link. These data are:

1. The time difference between the local clock and the clock at the other end of the link as observed at the local clock (this time difference includes transmission delay).

2. The rank of the node used as the master time reference for the local clock.

3. The merit of the transmission path over which the time reference information is passed from the reference clock to the local clock.

4. The rank of the local clock.

The first datum, i.e., the clock difference information, is used to make the time reference "independent" of transmission delay. Each node measures the time difference between its own clock and that at the other end of each link. This measurement is transmitted to the other end of the link so that both measurements are available at both ends of each link. To illustrate its use, let T_A be the time of the clock at node A, and let T_B be the time of the clock at node B. Let D_{AB} be the transmission delay from node A to node B, and let D_{BA} be the transmission delay from node B to node A. Then the time difference measured at node A is $K_A = T_A - (T_B - D_{BA})$ and the time difference measured at node B is $K_B = T_B - (T_A - D_{AB})$. Subtracting K_A from K_B and dividing by 2 gives

$$T_B - T_A = \frac{K_B - K_A}{2} + \frac{D_{BA} - D_{AB}}{2} \qquad (1)$$

When the transmission delays in the two directions are the same, they cancel, giving the time difference between the two nodes independent of transmission delay. Adding K_A to K_B gives

$$D_{AB} + D_{BA} = K_A + K_B. \qquad (2)$$

When D_{AB} is equal to D_{BA}, the transmission delay between nodes is also available by dividing $(K_A + K_B)$ by 2. Only a few bits of information per minute are required on each link to transfer the required timing data. Although timing difference measurements are made quite frequently, the clock time corrections may be made much less frequently because time errors will accumulate very slowly.

The other three data are used with a simple set of rules to allow each node to unambiguously select its time reference from the incoming link that should provide the best reference. Other cross checks are available to determine whether this path is reliable. If it is not reliable, an alternate choice can be made by applying the same set of rules. The basic rules are as follows:

<u>Rule 1.</u> The time reference for the local clock is taken from the link coming from the node which uses the highest ranking clock as its time reference. However, if the local clock outranks the others, the local clock is used as reference. If any two links come from nodes referencing the same highest ranking clock, the criterion is inconclusive. In a normally operating network, all nodes will be referencing the same master time reference so that this criterion will normally be inconclusive and rule 2 must be applied.

<u>Rule 2.</u> When the first test is inconclusive because the links come from nodes all referencing the same highest ranking clock, select the one that comes over the highest merit transmission path, i.e., the one with the best time transfer capability. If two or more come over transmission paths with the same highest merit rating, this test will also be inconclusive and rule 3 must be applied. In most cases this will be a conclusive test.

<u>Rule 3.</u> When the first and second tests are both inconclusive, select from those links with time reference coming from the same highest ranking clock over paths with the same highest merit rating the one that comes from the highest ranking, directly connected node.

Nodes carry the same ranking as the nodal clock that they are using at the moment. Multiple clocks of different rank may be provided at an individual node for reliability. Considerations in ranking the network clocks include the quality of the clock and the merit (time transfer capability) of communications paths to the higher ranking nodes. Those nodes equipped with cesium beam clocks will normally be ranked higher than those equipped with rubidium clocks which in turn will be higher than those equipped with quartz clocks. Of those nodes with cesium beam clocks those with the best time reference path to the highest ranking nodes will normally outrank those with poorer paths, e.g., those with a direct high resolution satellite path would normally outrank those with other types of long transmission paths. A node with more than one type of clock will be identified in rank by the particular clock in use at the moment.

Each transmission link will be assigned a merit (or perhaps more appropriately—demerit) value which depends upon its length and the transmission medium. Each node is informed of the accumulated transmission path merit for the time reference used at the other end of the link (one of the four pieces of information exchanged). Using the characteristics of the link over which the time reference information is received, the merit rating is further degraded before it is used at the local node. Thus, the path merit rating is increasingly degraded as the time reference information is passed through more nodes of the network.

Examination of the rules above shows that they assure that there will be no system closed loops to contribute to system instability. This is true because of the additional degradation of the path merit rating as additional links are traversed. Any return path must have a lower merit rating and therfore cannot be selected as the reference. The rules assure that every node will have a time reference signal so long as any one communications link to the node is still useful. These same rules permit the next ranking node to take over as the reference for the system if the highest ranking node becomes inoperable. They also direct that the highest ranking node in any isolated portion of the network will be selected as its reference.

The nodal clock is used for all time division multiplexing and switching functions at the node. It also clocks the bits out of the "elastic" storage buffers associated with each received link and times the data on every outgoing data link. The receivers for every incoming link derive their time from the received signal. (This is usually done by providing a phase shifted signal from the nodal clock and making it coincide with the timing of the received signal. This takes advantage of the stability of the nodal clock.) This receiver timing is used to demodulate the received signal and clock bits into the "elastic" buffers; thus bits are independently clocked into the buffers by the received timing and out of the buffers by the nodal clock.

SOME ADVANTAGES OF THE TECHNIQUE

1. By referencing one node of the network to a precise time source, such as the Naval Observatory, an accurate time reference becomes available throughout the network.

2. Since the rules for selecting the reference sources prevent the establishment of system closed loops, there is no problem with system stability.

3. It has superior self-monitoring capability. Every node receives time reference information from every directly connected node; any disagreement in these time references at any node indicates a potential problem. This indication can occur while the system is functioning quite satisfactorily. It can be used to initiate maintenance procedures so that the problem can be corrected before any degradation in system performance can be detected.

Each node can have transmission delay information available for every connected link and the status of buffer contents can also be available for the same links. Any incompatibility among them can indicate a potential problem and permit corrective action to begin early. Any sudden change in (1) the time reference information received over any link, (2) measured transmission delay of any link, or (3) the status of buffer contents can indicate a potential problem.

4. Redundant timing information can serve as a powerful trouble-shooting tool.

5. Since the effect of transmission delay on timing is mostly cancelled on every transmission link and everything is retimed at every transmission node, a high degree of nodal environmental isolation is provided; i.e., the environmental effects upon the time delay of any transmission link are removed and not permitted to propogate from node to node.

6. A fixed, accurate, time reference is a familar concept easily grasped by operating and maintenance personnel.

7. The technique places limits on the size of "elastic" storage buffers which are required at each node to absorb variations in transmission path delays and/or nodal timing errors.

8. It requires no resetting of buffers such as that required to compensate for time differences between independent clocks.

9. The availability of more accurate time will encourage innovation of future applications which will be of benefit to the overall effectiveness of the communications system and its users. There will be a growing need for accurate time among several government agencies[8]. Availability always stimulates need which in turn will generate new capabilities and operational improvements which were initially unplanned.

10. Some major navigation systems are already being coordinated in accurate time. Overall system coordination among all of these systems and a communications network should be synergistic, providing each with benefits beyond its individual contribution.

11. A by-product of the Time Reference Distribution technique is that accurate time at each node of the network can easily be made available to external users.

12. All normal decision processes and time corrections can be made automatic and do not require human intervention.

13. System operation is not dependent upon the continued operation of any node. Time reference is always available to all surviving nodes that could make use of it.

14. The system is compatible with all external references which are accurately related to universal time. Any of these external time references can be utilized and blended into the system by applying the same rules that are applied to the nodes of the network. Each external time reference can be assigned a rank and a transmission path merit. However, the method of correcting for transmission path delay would normally be different because the duplex communications path would not be available with most of these external time references. External references such as Loran-C could be used on an interim basis during development of the complete Time Reference Distribution system and could phase into participation with the Time Reference Distribution system as the complete system becomes operational.

15. Time Reference Distribution permits the convenient collection of much valuable engineering information, including statistical information about transmission time delay of the individual links and any variation in time reference as received over different paths. This information could be very valuable in the development of future systems of many different types.

16. The Time Reference Distribution technique is capable of effectively utilizing future technological improvements to provide greater precision without the major system redesign that other timing methods might necessitate. It also has the capability of making use of the greater precision thus provided.

17. The Time Reference Distribution technique provides accurate time reference information at the nodes. This information can be used to evaluate the performance of nodal clock oscillators. All information to predict future drift rates and their rate of change can be made available. This information can be used to compensate for the predicted drift of the oscillators and provde

a resulting clock of much higher accuracy than could otherwise be obtained in a similar price range. This ability to greatly enhance the effectiveness of lower cost oscillators could be significant advantage.

18. If the timing for all link receivers at a node is derived by phase shifting a signal from the very stable reference of an accurate nodal clock, the time to reacquire synchronization after a deep fade can be minimized. The technique integrates naturally with the Time Reference Distribution technique and, if desired, can be incorporated into the time difference measurement (first of the four pieces of information exchanged between nodes).

19. Time Reference Distribution appears to have a superior flexibility for handling unforeseen requirements as they arise.

20. Fall back modes of operation are provided and could be extended. Whenever the incoming link that is being used for a node's time reference fails, the node selects the next best link as its time reference. This process can continue until all incoming links have failed and there is no longer need for a time reference. The same procedure provides for failures of other nodes since they are equivalent to link failures as far as incoming signals are concerned. Assume that some failure of the timing system should occur independent of the data transmission system so that the data transmission system would continue to function but lacked time reference information. The affected node could fall back to an independent clock mode of operation (requiring periodic or automatic resetting of buffers at the other end of each link).

DIFFERENCE IN TRANSMISSION TIME DELAYS IN OPPOSITE DIRECTIONS

In the Time Reference Distribution system presented here, timing information is passed in both directions over every transmission link. This information is used to permit the time provided by the two clocks at the ends of the transmission link to be directly compared by cancelling the time delays of the transmission link. The cancellation of propagation delays depends on the assumption that the transmission delay is the same in both directions over the link. A question naturally arises as to whether this is a good assumption—particularly about over-the-horizon tropospheric scatter transmission that depends on bending and scattering of the electromagnetic waves. The multipath character of troposcatter transmission causes substantial frequency selective fading and intersymbol interference on digital links. These characteristics appear to make it somewhat questionable as a time reference distribution medium. Well known nonreciprocal delays in HF ionospheric propagation are attributed to the wave passing through an ionized medium in the presence of the earth's magnetic field. Many researchers agree that there is no comparable mechanism for tropospheric transmission whereby the propagation delays in opposite directions over the same path at the same time and frequency should not be the same[9,10,11].

No record of actual measurements of delays in both directions between the same pair of terminals at the same time for tropospheric scatter have been located. Because there is no known mechanism for making the tropospheric medium non-reciprocal, any differences in transmission delays that might occur in the two directions would be attributable either to the terminal equipment or to different paths being used in the two directions. The difference in paths could be attributed to different antenna positions or to the use of different frequencies. In either case, the difference in propagation delay times between two independent paths in opposite directions should be the same as the difference between two independent paths in the same direction. Measurements have been made of the difference in time delay between two independent tropospheric paths 168 miles long at 900 MHz[12]. The standard deviation of the relative delay was found to be 22 nanoseconds. Phase data observed over a 230 km path[13] indicated that random variations of a 900 MHz signal over several minutes rarely exceed about 10 radians. This corresponds to about 5 nanoseconds at the 900 MHz frequency. The 5 nanosecond observations of[12] are based on phase fluctuations of a single carrier frequency, while the 22 nanosecond deviation from[12] is based on correlation measurements on simultaneously transmitted, pseudo-random-modulated PSK signals. The 22 nanosecond standard deviation seems to be the prefereable reference point, since it was measured more nearly in the form of the desired application. Note from equation (1) that the error in time measurement is only half as great as the difference in transmission times in the two directions.

$$T_B - T_A = \frac{K_B - K_A}{2} + \frac{D_{BA} - D_{AB}}{2} \qquad (1)$$

(repeated for convenience)

The random fluctuation of the differential time delay between two independent paths may be expected to contain frequency components of many cycles per minute. By averaging the measurements over several minutes the resulting average measurement should have a standard deviation which is only a small fraction of the 22 nanoseconds measured in the experiment. The interval between clock corrections for the Time Reference Distribution system may be quite long because stable clocks are used. Therefore, the time measurements may be averaged over long periods, making it possible to almost completely remove the effects of fluctuations in the propagation medium from the time reference measurement. The most significant errors could be associated with equipment rather than the propagation medium. The stability of time delays in the equipment should be given consideration and tolerance in time delays among units of the same type should be minimized.

A CONSERVATIVE PRELIMINARY ESTIMATE OF ACCURACY

As previously mentioned, a troposheric transmission link is probably one of the more difficult types of transmission link for time transfer because of its multipath characteristics. If we use the 22 nanosecond standard deviation mentioned previously as a starting point we may reach some rough estimates of the accuracy that might be obtained from a Time Reference Distribution system.

Since the delay difference may be expected to contain some higher frequency components, averaging over several minutes should provide a much lower standard deviation than 22 nanoseconds. The timing error due to differences in transmission delays in the two directions is only half the difference in transmission delays. Assuming that there is no measurement averaging, the standard deviation of the timing error is 11 nanoseconds. It should be better than this in practice where averaging would be used Allowing ±4 standard deviations for the tolerance range makes the potential accuracy ±44 nanoseconds. Allowing an additional ±156 nanoseconds (much more than that allowed for the particularly severe tropospheric scatter medium) for error contributions of the equipment employed gives a total time reference transfer tolerance of ±200 nanoseconds for a tropospheric scatter link. If the time transfer errors of all links are random and independent of all other links, the tolerance for a tandem connection should be the square root of the sum of the squares of the tolerances of the individual links. In a highly connected network, the largest number of tandem time transfers required should be a small percentage of the total number of nodes in the network. Assuming that the number of tandem time reference transfers does not exceed 100 and all tolerances in the path are the same, the overall tolerance for the tandem path will be $\sqrt{100} = 10$ times the tolerance for any individual link. If all links have a 200 nanosecond tolerance, then the time at any node in the network will be within 2 microseconds of the time at any other node.

This should be a conservative estimate. It is quite unlikely that any network would be 100 percent tropospheric scatter links, and line of sight microwave links are much better for time transfer. (Only 18 percent is troposcatter in the DCS in Europe while over 63 percent is line-of-sight microwave[14].) Even for tropo links the propagation time variation of the transmission medium would be largely eliminated by averaging over a significant period of time. The ±156 nanoseconds allowed for error contributions of the equipment on each link is very large for broadband microwave equipment. Two-microsecond accuracy between any two nodes of the network should be a desirable goal that is both readily achievable and useful.

CONCLUSIONS

The Time Reference Distribution system will not only satisfy the timing requirements of a digital time division communications system, but will provide a large number of additional advantages.

The viewpoint should not be too narrow when considering the merits of a timing technique for a digital time division communications system. In addition to keeping the bits in the proper sequence, monitoring and testing the system should be given careful consideration. Other uses for timing within the system should be considered along with timing relationships external to the network. Under this type of evaluation, Time Reference Distribution should rank very high. A large communications network that distributes accurate time for its own use should be a natural vehicle for coordinating the many other users of accurate time.

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TIME REFERENCE DISTRIBUTION FOR A TIME DIVISION COMMUNICATION NETWORK

TOLERANCE CONSIDERATIONS

1. EXACT TIME AT EACH NODE. (unrealistic)
   FIXED DELAYS BETWEEN NODES. (unrealistic)
2. EXACT TIME AT EACH NODE. (unrealistic)
   TOLERANCES ON VARIABLE DELAYS BETWEEN NODES.
3. TOLERANCES ON TIME AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.
4. TOLERANCES ON FREQUENCY AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.
5. TIME OR FREQUENCY NOT DIRECTLY CONTOLLED.
   TOLERANCES ON TIME DIFFERENCES BETWEEN CONNECTED NODES.

TOLERANCE CONSIDERATIONS

1. EXACT TIME AT EACH NODE. (unrealistic)
   FIXED DELAYS BETWEEN NODES. (unrealistic)

2. EXACT TIME AT EACH NODE. (unrealistic)
   TOLERANCES ON VARIABLE DELAYS BETWEEN NODES.

3. TOLERANCES ON TIME AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

4. TOLERANCES ON FREQUENCY AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

5. TIME OR FREQUENCY NOT DIRECTLY CONTROLLED.
   TOLERANCES ON TIME DIFFERENCES BETWEEN CONNECTED NODES.

TOLERANCE CONSIDERATIONS

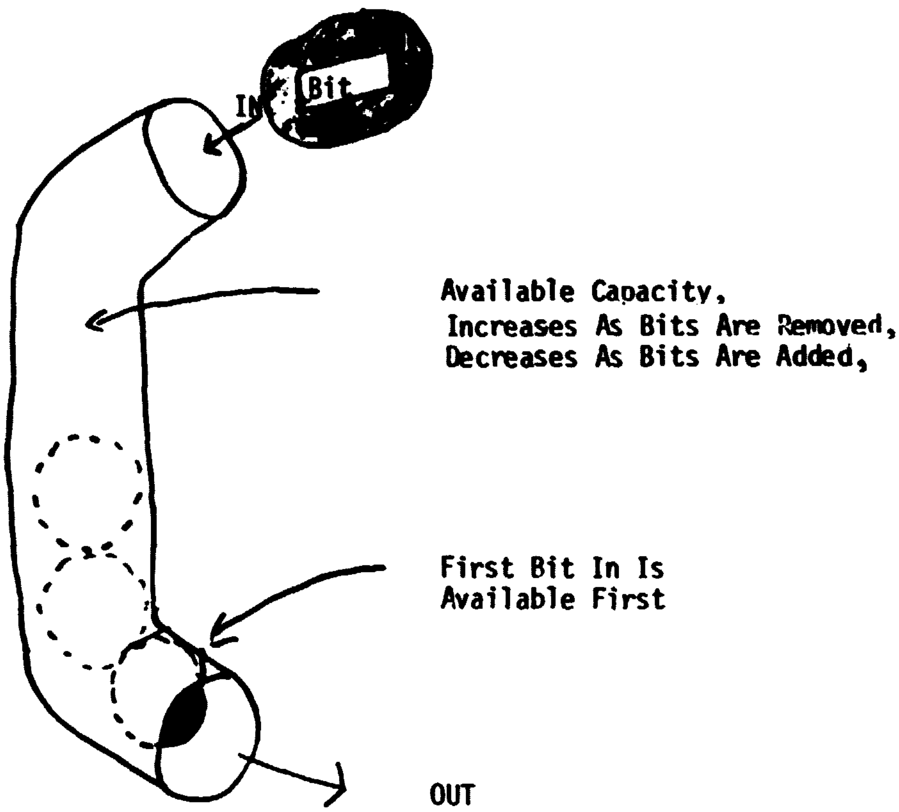
1. EXACT TIME AT EACH NODE. (unrealistic)
   FIXED DELAYS BETWEEN NODES. (unrealistic)

2. EXACT TIME AT EACH NODE. (unrealistic)
   TOLERANCES ON VARIABLE DELAYS BETWEEN NODES.

3. TOLERANCES ON TIME AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

4. TOLERANCES ON FREQUENCY AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

5. TIME OR FREQUENCY NOT DIRECTLY CONTROLLED.
   TOLERANCES ON TIME DIFFERENCES BETWEEN CONNECTED NODES.



FIFO BUFFER ANALOGY

TOLERANCE CONSIDERATIONS

1. EXACT TIME AT EACH NODE. (unrealistic)
   FIXED DELAYS BETWEEN NODES. (unrealistic)

2. EXACT TIME AT EACH NODE. (unrealistic)
   TOLERANCES ON VARIABLE DELAYS BETWEEN NODES.

3. TOLERANCES ON TIME AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

4. TOLERANCES ON FREQUENCY AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

5. TIME OR FREQUENCY NOT DIRECTLY CONTROLLED.
   TOLERANCES ON TIME DIFFERENCES BETWEEN CONNECTED NODES.

TOLERANCE CONSIDERATIONS

1. EXACT TIME AT EACH NODE. (unrealistic)
   FIXED DELAYS BETWEEN NODES. (unrealistic)

2. EXACT TIME AT EACH NODE. (unrealistic)
   TOLERANCES ON VARIABLE DELAYS BETWEEN NODES.

3. TOLERANCES ON TIME AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

4. TOLERANCES ON FREQUENCY AT EACH NODE.
   TOLERANCES ON DELAYS BETWEEN NODES.

5. TIME OR FREQUENCY NOT DIRECTLY CONTROLLED.
   TOLERANCES ON TIME DIFFERENCES BETWEEN CONNECTED NODES.

TIME REFERENCE DISTRIBUTION

- ALL NODES HAVE ONE OR MORE CLOCKS
- EACH COMMUNICATION PATH IS A TIME REFERENCE PATH
- ALL CLOCKS HAVE RANK ORDER
- TIMING INCLUDED IN FRAME SYNC OR SUPERIMPOSED ON DATA
- FOUR TYPES OF DATA ARE TRANSFERRED OVER EVERY LINK

  (1) TIME DIFFERENCE BETWEEN REMOTE CLOCK AND LOCAL CLOCK AS OBSERVED AT LOCAL CLOCK

  (2) RANK OF MASTER TIME REFERENCE USED FOR LOCAL CLOCK

  (3) MERIT OF TRANSMISSION PATH FROM MASTER REFERENCE

  (4) THE RANK OF THE LOCAL CLOCK.

TIME REFERENCE DISTRIBUTION

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  (2) RANK OF MASTER TIME REFERENCE USED FOR LOCAL CLOCK

  (3) MERIT OF TRANSMISSION PATH FROM MASTER REFERENCE

  (4) THE RANK OF THE LOCAL CLOCK.

SELECTION RULES

Rule 1: SELECT REFERENCE SOURCE FROM HIGHEST RANKING CLOCK

Rule 2: IF MORE THAN ONE PATH FROM SAME HIGHEST RANKING CLOCK, SELECT REFERENCE FROM HIGHEST MERIT PATH

Rule 3: IF MORE THAN ONE PATH OF THE SAME HIGHEST MERIT RATING, SELECT ONE FROM HIGHEST RANKING DIRECTLY CONNECTED NODE.

TIME REFERENCE DISTRIBUTION AS A MEANS OF NETWORK SYNCHRONIZATION HAS MANY ADVANTAGES RELATED TO HAVING ACCURATE TIME AT EACH NODE AND THE METHOD OF PROVIDING IT.

TIMING COMPARISON BETWEEN NODES

T_A = TIME OF CLOCK AT NODE A

T_B = TIME OF CLOCK AT NODE B

D_{AB} = TRANSMISSION DELAY FROM NODE A TO NODE B

D_{AB} = TRANSMISSION DELAY FROM NODE B TO NODE A

TIME DIFFERENCE MEASURED AT NODE A

$K_A = T_A - (T_B - D_{BA})$

TIME DIFFERENCE MEASURED AT NODE B

$K_B = T_B - (T_A - D_{AB})$

TIME DIFFERENCE BETWEEN CLOCKS

(1) $$T_B - T_A = \frac{K_B - K_A}{2} + \frac{D_{BA} - D_{AB}}{2}$$

Very Small

TRANSMISSION DELAY

(2) $D_{AB} + D_{BA} = K_A + K_B$

CONSERVATIVE PRELIMINARY ESTIMATE OF ACCURACY

22ns = STANDARD DEVIATION OF TRANSMISSION BETWEEN TWO INDEPENDENT 168 MILE TROPO LINKS

11ns = STANDARD DEVIATION OF RESULTING TIMING TIMING ERROR IF NOT REDUCED BY AVERAGING

4X11ns = 44ns = ALLOWED TOLERANCE FOR PROPAGATION

156ns = VERY LAX TOLERANCE FOR EQUIPMENT

44ns+156ns = 200ns = TOLERANCE PER LINK

200nsX $\sqrt{10C}$ = 2000ns = 2μs = TOLERANCE FOR 100 TANDEM TIME TRANSFERS

QUESTION AND ANSWER PERIOD

MR. EASTON:

We have five minutes, time for two questions.

DR. KARTASCHOFF:

I have one question about the propagation time delays.

Do you have any data about pattern dependent jitter cable systems? Because that is one problem which bothers the civilian communications when one works quite often over coaxial cable with, say, about a hundred pulse regenerative repeaters. There is not much data available, actually, about long term spectral density on the pattern dependent jitter.

Do you have any data or do you have the same problem that there is not much data available?

DR. STOVER:

I don't have the data, but I know that it is very bad, so I would jump to the conclusion initially that one of the other paths, through a satellite, will be better. Therefore it will be chosen as the reference, and the need for using the cable can be avoided in most cases.

DR. KARTASCHOFF:

Well, thank you very much, but you see, in the civilian systems we will use cable, and we will go Digital, too, in the next 20 years. So, this problem remains. It needs to be investigated.

I think it must not necessarily be traumatic, but it is worse than microwave line of sight.

DR. STOVER:

I agree with that. As far as the Trans-Atlantic cable is concerned, again I come back to my statement about this being synergistic with all these other systems. If you are talking about, say, Trans-Atlantic, for example, and we are going to use Universal Time, you have already a reference in Europe that is much better than you could get across that cable.

So, there is a good reference there, and if you tie it into the network somehow, again you always use your best reference back to the Naval Observatory or whatever we use as our link with Universal Time.

DR. COSTAIN:

I understand in some of the networks they go via satellite one way and land line or microwave the other. You would have to have a third of a second discrimination, I think, in the time differences for the two paths.

DR. STOVER:

Well, I am assuming that we will have a duplex link for all links. You are right.

MR. LIEBERMAN:

You talked strictly about time division multiplex. Wouldn't synchronous systems fit into this by regeneration?

DR. STOVER:

There are large numbers of systems that will be compatible with this. All I am suggesting is that all of the nodes in the network have accurate time, and how we get it there is—I suggested one instance there are other possibilities, of course, but I have tried to point out that using this system has some of its advantages, just from this technique of getting it there, as well as advantages of having it there. Most other systems under consideration wouldn't even have it there.

So, my first advocate is to have it there, and my second advocate is to provide a system similar to this for getting it there.

MR. LIEBERMAN:

One last question.

What is the comparative cost of this versus some of the other systems you talked about?

DR. STOVER:

I believe that the cost of all the systems is somewhere in the same ballpark, because most of the equipment required to establish the synchronization is required for any type of digital network. We always have to lock onto the frame sync, and once you have got that, you have most of what we need, and as far as the accuracy of the clock, as I pointed out, the information we have permits us to use a lower precision clock, and operate on it with the information we have available to get a higher precision than we otherwise would.

So, I believe for the same accuracy it would cost less than some of the other approaches. But among all the approaches, I don't think the cost is a significant factor.

DR. WINKLER:

My comment is not related to your paper, but to Dr. Kartaschoff's question.

At the Observatory, for purely internal reasons, we have made some tests using RG58 cable, coaxial cable. The effects which we found of course are in agreement with your comments, they are very bad. For a 10,000 foot loop above ground we found a diurnal change of about 10 to 20 nanoseconds, time delay.

Now, that is average, using a relatively long time constant in the order of 1 second. The diurnal, of course, is completely thermal.

We used these data only to assure ourselves that the clock time scale which utilizes underground cabling (less than 700') in between the clock vaults is not limited by these delays variations.

But subsequent to that, I happen to have come into possession of some commercial literature on low temperature sensitive cables. It appears that there are some dielectric cables available which minimize these variations. I don't remember where I have the information, but you may contact me on that.

DR. KARTASCHOFF:

Thank you very much, Dr. Winkler.

The cable, that is one problem. I think that the worst problems in digital communications over a long cable line are the repeaters. The repeaters which at every end regenerate the pulse, and send it out again in a nice form to the next repeaters and so on. For these repeaters, their average phase of the transition is dependent on the pulse pattern, that is on the content of the information which goes through the link and of course this is user dependent.

So, you can have any form of pattern, and there can be very large excursions in the instant of time with which the information arrives at the end.

The general suggestion we have now in our discussions internal in our telecommunications system is that we should try to absorb these delay variations by buffer memories, and use good oscillators for keeping the long term average rate constant.

DR. STOVER:

I agree that you want to absorb the variations with buffers. As far as the use of cables, again, I state, that in most cases, any of your major nodes will have other links coming in besides cable links, and they would be given a priority, and I am not suggesting that we use this distribution technique down to every TBX and everything.

I am suggesting that all local groups would be slaved to the thing. Only the ones that would have a number of links coming in from widely separated geographical locations would need to have the time reference distribution.

All the ones that communicate primarily with one point would be slaved to that point.

MR. EASTON:

Thank you very much, Dr. Stover, for the fine paper.

FUTURE DCS OBJECTIVES IN COMMUNICATION NETWORK TIMING AND SYNCHRONIZATION

J. R. Mensch
Defense Communications Agency

ABSTRACT

The Defense Communication System will be moving rapidly toward providing switched digital service to it's users within the next ten years. The principal driving force in the transition to a digital system is the requirement for high performance secure voice service. Additionally, the anticipated data requirements in this time frame can be handled most effectively by a digital network. The characteristics of a switched digital network which impose timing and synchronization requirements on the system design will be presented.

Several alternative approaches to implementing a timing subsystem suitable for a switched digital communications system have been considered. These include pulse stuffing, independent stable clocks, and clock correction techniques. The advantages and disadvantages of each approach will be discussed relative to both the strategic and tactical communication system requirements.

An inter-agency committee worked through mid-1973 to develop recommended parameters for interoperability between the various DoD communications systems, allied systems, and the commercial networks.

BACKGROUND

Synchronization in a communications system can be considered on at least three different levels—terminal-to-terminal, link, and network. Terminal-to-terminal synchronization is widely used today for digital communications between data terminals using modems connected by circuit-switched or dedicated analog channels. The terminal device, or the transmit portion of the modem, provides transmit clock. The receive modem develops timing from the incoming data stream (transmitted as quasi-analog signals through the analog channel), and detects and regenerates the digital data. Frame synchronization is developed by the terminal equipment as required. Thus the terminals, consisting of digital devices and modems, are designed to operate over half-duplex or full-duplex circuits, and develop timing and synchronization between the calling and called terminals independent of the network.

Link synchronization is used in digital multiplexing, such as in the commercial T-type PCM carrier equipment. In the primary channel bank a group of analog channels (24) are digitized and combined into a single digital stream. Timing is supplied by a clock internal to the channel bank. The digital stream is either transmitted to the distant link terminal via cable or radio, or is combined with several other similar streams in a second level time division multiplexer (TDM). Since each channel bank has an independently derived time base, the TDM must asynchronously combine the various inputs to obtain a single higher rate output. The pulse-stuffing technique is used, whereby pulses are added to each input as needed, to bring all inputs to a single common higher rate. These added, or "stuff", bits are deleted at the receive terminal using information carried on a control channel associated with the second level multiplexer. In this case, as in the terminal-to-terminal case, timing and synchronization is provided between transmit and receive channel banks. The network has no synchronization requirements. The individual channels need not be synchronized with one another because the digitized multiplexed channels are returned to their analog form (which does not require timing) at each switch. A circuit may be digitized a second time at the output of a switch, but it will be to a new time base established by another PCM channel bank.

Network timing and synchronization must be considered when digital multiplexed channels are to be switched. This follows from the requirement for many different digital channels originating at various points in the network to be simultaneously passing through the switch with varying connectivity. If the switch uses time division switching, all these channels must be operating on the same time base as the switch. Even if a space division switch is used, where common timing is not required in the switch, common timing will nevertheless be required at the multiplexing point. That is, if the channel carrying digital signals from device "A" is to be multiplexed with the channel servicing device "B", these channels must be synchronous.

Precise network synchronization is fundamental to maintaining bit integrity in a digital switched system. Even when high error rates are experienced on the transmission media, or when the multiplex equipment loses framing and generates an error burst, if the time base is accurately established between the two nodes the system can maintain synchronization through the link interruption. This justifies a precise synchronization specification.

NETWORK SYNCHRONIZATION CONSIDERATIONS

There are two principal approaches to achieving network synchronism—(1) operate all terminals independently and use the pulse stuffing technique to align the channels at the switches and multiplex, and (2) develop a form of synchronous network such that all equipment is operating at a constant frequency or time base.

Although the channel pulse-stuffing technique is technically sound, and offers the possible advantage of avoiding network synchronization problems, the tremendous proliferation of stuff-destuff devices and attendant cost, reliability and maintenance problems, etc., act to negate this advantage. These devices would be required at every digital channel terminal, at every channel termination on a digital switch, and at every channel input to a multiplexer. No digital network now in the planning stages is known to be based on individual channel pluse-stuffing. Thus only the alternative of a synchronous network is considered further in this paper.

The definition of "synchronous network" can become highly complex and unenlightening. From a practical viewpoint, the principal parameter is the period of time over which synchronism is maintained. For example, a pair of interconnected Teletype machines are synchronous for the period of one character. Similarly, an independent clock technique is described later which provides network synchronism for periods on the order of one day. The objective for the Defense Communications System (DCS) is network synchronism for an unbounded period of time, which requires the same average frequency at all nodes of the network over some specified period of time or equivalently, the maintenance of a time coherence with some fixed, specified tolerance between all nodes of the network.

In addition to the network timing system which provides the time and/or frequency base throughout the system, "elastic" buffers are required at the termination of each transmission link at a network node. The purpose of this buffer is twofold: (1) to provide a reservoir of bits to adjust for instantaneous differences in the transmitting and receiving rates at the two ends of the link, and (2) to adjust for variations in the absolute time delay through the link. The size of the buffer will depend on the magnitude of these two factors, and on the digital rate of the link. Thus clock tolerance and buffer size, adjusted by path delay variations, can be traded to obtain the most effective system design.

A number of network synchronization techniques are capable of satisfying the basic communications requirement for keeping bits in the proper sequence at time division multiplexers and/or switches. These include such concepts as: (1) timing derived from external sources such as the Loran-C navigation system, (2) an independent clock system in which precise clocks are placed at each node, (3) discrete control correction (a form of frequency averaging) in which a weighted average of the contents of the storage buffers at each node are used to correct the frequency of the nodal clock at discrete intervals of time to prevent buffer overflow, and (4) time reference distribution in which time reference information is distributed over every transmission link of the network to assure that all nodal clocks of the network have the same time.

One presently planned communication system (TRI-TAC) will use the independent clock system with a tolerance on frequency rather than time. The principal advantage of this technique is that the timing of each node is self sufficient and independent of the rest of the network, which is a highly desirable property for a tactical, mobile system. Atomic standards will be employed at each node to provide a frequency accuracy on the order of one part in 10^{11}. This accuracy permits the use of reasonable size buffers to equalize the frequency difference between nodes for periods up to 24 hours. The buffers are reset, with attended link interruption, when required. The impact of link interruption for buffer reset is considered undesirable, and it is not acceptable for a strategic world-wide communication system.

A different technique, which avoids the buffer reset requirement, obtains the time reference for the nodal clocks from a source external to the communications system. Several sources could be used such as Loran or navigation/timing satellites. The use of Loran-C to provide the reference imposes the least technical risk of all the different techniques. It can be made compatible with other systems if satisfactory standards and buffers are provided. Its accurate time can be used for the resynchronization of switches, multiplex, and cryptographic equipment. It is an existing technique for which considerable experience has been accumulated. It could be implemented with a high degree of confidence. However, the survivability of a communication system based on an external reference system must be considered, since the required use of an external reference system for the DCS would make that timing system a "desired" target. Also Loran-C presently does not provide world-wide availability, thereby limiting its application.

The discrete control correction system uses the weighted average of the contents of all of the buffers at each node to make frequency corrections to that nodal clock at discrete instants of time. The timing at the nodes is independent except at these discrete correction times. Studies have shown that this technique provides a stable network and frequency base, and that its frequency can be locked to that of an external network by selecting the proper weighting factors. Its major advantages are simplicity of implementation and the lack of any requirement for resetting of the data storage buffers.

The time reference distribution system might be considered to be an upgrading of the TRI-TAC independent clock technique, wherein the clock time at each node is corrected instead of resetting the buffers. In this concept the communications path is used for the distribution of a time reference. This reference is based on the master clock in the system; e.g., the Naval Observatory. All nodes have their time traceable back to this master. If the master is lost, provision is made to pass this function to another "qualified" node in the system. When considered from an overall system point of view, including system monitoring, maintenance, trouble shooting, and the application of future technology, it has many advantages. Since a time reference is available from every incoming link at a node, each node will always have a time reference if it is connected to the network. Thus the technique is highly survivable. Its major disadvantage is that it is somewhat more complex than other alternatives and has not been proven in practice. However, its concepts are closely enough related to systems which have been or are being implemented so that it can be approached on an evolutionary basis with a high degree of confidence. Refer to "A Time Reference Distribution Concept for a Time Division Communication Network" for a more detailed discussion of this technique.

DOD INTEROPERABILITY COMMITTEE RECOMMENDATIONS

Interoperability among the DCS, tactical systems, foreign allies, and domestic and foreign commercial systems is deemed an essential requirement in the design of future systems. Common, or interoperable timing and synchronization between these systems is a basic parameter in achieving this requirement. To address this, and the many other parameters involved in interoperability, a joint committee was formed operating under the co-chairmanship of DCA, TRI-TAC, and NSA. Also participating were the representatives of the military services and the OJCS. The report of this committee, "Final Report of Committee on Interoperability of DoD Telecommunications", dated 20 September 1973, contains recommendations for common or compatible values, methods, and procedures for the system parameters considered to have an impact on the ability to provide end-to-end encryption of DoD telecommunications systems. Specific recommendations are made for network timing and synchronization.

Several forcing factors drive the selection of the time/frequency nodal tolerances for the DoD communications systems. These include the considerations for tactical applications, performance suitable for the long-haul DCS, and the need to maintain bit-count integrity for satisfactory overall digital system performance. Tactical applications involve optimizing parameters for simplicity, survivability, flexibility, ease of movement, and reconstitution of network operations. In the light of these requirements, an independent clock system with frequency tolerances was specified as best meeting these tactical requirements. However, buffers must be reset on occasion, causing traffic interruptions. Since interruptions to the DCS carry a much greater impact, such a system in unacceptable for the DCS unless other approaches cannot be proven or are substantially more costly.

Recognizing the near-term need for digital systems, the committee recommended that equipment under current development continue to utilize the independent clock approach designed to meet the specification tolerances of TRI-TAC (Table 1). This frequency tolerance (one part in 10^{11} per day), combined with properly sized buffers, will limit buffer reset to at most once per day when frequency standards

Table 1

TRI-TAC Timing Specifications

Frequency Tolerances		
Primary STD	Secondary STD	Backup
1×10^{-11} /day	1×10^{-11}/day	1×10^{-9} /day
1×10^{-11}/6 mos.	1×10^{-10} /6 mos.	
Setting Accuracy		**Repeatibility**
Primary STD	Secondary STD	Secondary STD
1×10^{-11}	1×10^{-11}	3×10^{-11}

at adjacent nodes are far from their nominal values in opposite directions. Such current development must not preclude the future inclusion of some form of network clock correction technique to provide the future capability for long-term network synchronization, fail-safe operation in the equipment failure mode (that is, utilization of the independent clock system in a fall-back mode), and avoidance of the need to reset buffers.

As an objective for the ultimate DoD, a time tolerance of ±2 microseconds between any two major nodes was recommended. Minor nodes, such as PABX's, could be slaved to major nodes and must provide independent timing to their subscribers whenever such minor nodes become isolated from the network.

The TRI-TAC timing requirements will be met through the use of atomic frequency standards. Tactical atomic frequency standards are proven and their costs, including the required buffers, are a small fraction of the nodal costs. Their performance is two orders of magnitude better than currently planned commercial standards. Therefore, no difficulty with commercial interfaces is expected in this respect. As techniques are proven and implemented to attain the ±2 microsecond time tolerance objective for the ultimate system, both frequency standard and the time standard can coexist in the network without difficulty or constraint.

CONCLUSIONS

The adoption of the recommended frequency standard for the implementation of near-term DoD systems will result in garbling a relatively small amount of traffic when buffers are reset. While this standard is in use, care should be taken in network operation to minimize this effect. Such care includes: resetting whenever traffic is interrupted for other purposes such as crypto key change on the link; preplanned resetting at low traffic periods; and off-loading of switched traffic prior to resetting.

The recommended objective for future DoD systems requires time coherence to a specified tolerance throughout the network. Although time coordination among the many nodes of a large communications network has not been accomplished, the basic concepts involved have been exercised in the coordination of such Navigation networks as Omega and Loran-C, and through the DSCS time transfer program. Thus, it is believed that a long-term coherence between nodes of a network is a feasible and useful objective for communications purposes, and will provide a precise source of time to other users as well.

QUESTION AND ANSWER PERIOD

DR. REDER:

Did I understand you right that you said the TRITAC committee recommended the use of the atomic standards with the provisions that they are not supposed to be reset to the standard in frequency more often than once a month—once in six months?

MR. MENSCH:

As I understand it, if rubidium standards were used, they would have to be reset in frequency occasionally. If they were used—there is a contractor option. The contractor chose to go cesium, there is no reset requirement in that type of clock, as I understand it.

DR. REDER:

This is my question. Is there no requirement? I think there is. If you do not allow for resetting the crystal, for instance, in the 5061, you may be in trouble, if the requirement is 1 part in 10 to the 11th.

MR. MENSCH:

Will that cesium clock stay within absolute center accuracy, to within 1 part in 10 to the 11th?

DR. REDER:

I have my doubts.

DR. WINKLER:

I think there is a misunderstanding here.

So far as I understand your requirements, Mr. Mensch, the emphasis is on external reference. In other words, this, what you are referring to, would have to be incorporated in the maintenance instructions for that cesium standard. It is true that the cesium standard if left all by itself for one-half year would not necessarily stay within 1 part in 10 to the 11th, but that can be taken care of following the instruction manuals in reference to the cesium standard itself.

That is, in my opinion, fundamentally different from the situation with the rubidium standard where you will have to make even larger adjustments, with respect to an external reference.

MR. MENSCH:

This is my understanding also, Dr. Winkler, that in the case of rubidium, something, like the traveling clock, or some external means would have to be brought in to that terminal in order to bring that within the tolerance window that would be allowed.

DR. REDER:

Apparently I took too literally what you said. If you permit maintenance, which means you watch the meter, and if the error meter shows a deviation more than a certain amount, that you are permitted to reset it, fine.

I thought maybe there was somebody standing with a fly swatter and you know, knock you on the hand or something if you touch it.

(Laughter.)

DR. KARTASCHOFF:

May I perhaps add to this discussion by saying that the current view is in my country now, my own and some of my colleagues, about the use of rubidium versus cesium? We intend to use rubidium on the relatively low level, low rank exchange—not the lowest, but low rank exchanges, and we will slave them to cesium standards in the country.

You just have to look at the results in the U. S. Naval Observatory—they kept a part in 10 to the 12th over six months.

MR. MENSCH:

This would be in more of a synchronized network. Now, in the TRITAC thing I am referring to, let's assume that they implement the equipment that is used at a node with a rubidium standard. These would be sprinkled throughout a network. There would be no synchronization or adjustments between them. There would just be buffers between them, and those buffers are large enough to soak up that frequency difference over some period of time, like 24 hours.

If that buffer fills in that period of time, you then push the button, throw some bits away, and start over. They will also automatically push that button if the link fails between them, if you have a fade. There is another aspect of this, that this link will be incrypted, and periodically we have to come in and change the variable in that crypto equipment, at which time again we drop sync.

So, it is not just due to frequency errors. Will we have an opportunity to, lets say, not just to buffer fill or empty, will we have a situation where we have a loss of sync and get to reset the buffer.

But the point is that each of these nodes in the network is free-running, but they are synchronous for a finite period of time.

Now, we in the long haul business, let's say, of the Defense Communications System, do not want to design a system that requires us to drop sync on purpose, so we are staying on top of that now, let us correct those clocks by some means, either through external timing system, or by distributing time through our network, and as long as we keep those clocks corrected everybody is happy. If we do lose that system, we will then fall back in a fail safe mode to running independently over a short period of time, as short as 24 hours.

Now, the interesting aspect, if we look at the impact of the satellite systems in such a communications network, since satellites will be—are becoming, if we ever get some satellites up that work, a very important mode of communications. The potential variation in that path, depending on the stability of the orbit itself, but we could end up with hundreds of thousands of bit buffers to soak up the absolute path delay variations of a satellite link, if we are working on the order of, let's say, a megabit or two, of our communications link. And we do have some orbital perturbations in that bird.

We are talking about fairly sizeable buffers, and are accepting the fact that in a synchronous network this must be. Now that will be a special box in the satellite link, as opposed to the land situation.

DR. WINKLER:

May I make another comment here, not a question but a comment.

It is in regard to the frequent reference to a master reference standard—presumably they use the U.S. Naval Observatory's master clock.

In view, however, of any of these systems really being totally worldwide, the question of possible interface with NATO or other allies inevitably arises. And here, I would like to inform you that, for those who do not follow the time scale bulletins regularly, that we have demonstrated the capability during the last seven months or so, to stay within one-tenth of a microsecond of the international time reference.

It is our belief that even with very small variations in IAT, the international reference time, that we can sufficiently well in advance predict these changes to stay safely within one microsecond. Actually, we have done ten times better.

So, giving you a number of two microseconds, to which you want to keep all these clocks, I think that you have already a system available in which you have access to any of the national references in the international system, and for which corrections to 0.1 microseconds are known.

MR. MENSCH:

You are saying you are demonstrating the feasibility of being able to achieve this.

DR. WINKLER:

Yes, These numbers are published in advance, in fact. We extrapolate the difference between the master clock and the international BIH time, and if you look at the BIH bulletin Series D, which we distribute upon request, if you look through these you will find that we only have random fluctuations around zero, minus one-tenth, plus one-tenth around zero. It can be done. I am quite confident that we will continue to do so in the future.

MR. MENSCH:

Dr. Winkler, you made one point that I had a note that I didn't mention, and it comes up this way, that we will also have a requirement to interface our digital network with commercial people.

We are encouraging, and plead with anybody that is here, that the commercial systems also consider operating off the same master clock, for international time, to ease the problem of when we hook our channels to them, if they are running on a separate time base, we are going to have to have an awfully big buffer, or reset, and this becomes a problem, because the majority of the Defense Communications Systems is leased channels to the common carriers. We do not own the majority of our circuits.

We are hoping these common carriers, such as the Bell Digital Data system, DATRAC, NCI, et cetera, will go toward not only having master slaves, but that their master clc ~k becomes time coherent with that of our master reference.

DR. WINKLER:

Yes. There is yet another problem which has to be addressed, or not forgotten, and that is the establishment of a well-defined hierarchy in the interest of survivability.

MR. MENSCH:

This is a point that I think was made in Stover's paper. These rules provide exactly this, that there is built into that type of a system, or a master slave system, a procedure that if you lose your master clock, you have a graceful passing down of the master responsibility.

DR. WINKLER:

And that is exactly why we want to use precision clocks, and that is where the difference between a synchronized system and a coordinated system is most striking.

A synchronized system does not operate with any inertia. However, a coordinated system, once you have all your clocks in operation for a couple of weeks, you can actually completely cut your communications, as we have done in other systems already, and you will still stay within a microsecond for a considerable period of time.

MR. EASTON:

We have time for one more question?

MR. CHI:

In view of your stated requirement of a part in the 11th per day, and plus or minus two microseconds, and especially if you use a hierarchy does it not mean also that almost any kind of standard with reasonable stability, such as a crystal, should also be considered. It is just a matter of tradeoff, with the frequency of correction as well as the costs.

MR. MENSCH:

And the size of the buffers that are to be used. It is a tradeoff.

So, the tactical people are going to this atomic clock version such that they can have their little node, or their communications node, and put them and move them several times a day, and not have the network synchronization problem. They just turn it on and they are all set.

This is the tactical doctrine.

In the DCS, where we do not have the mobility requirement, we can see a sprinkling of precise clocks, be they atomic or disciplined, or however we achieve it. But that it is coordinated, as Dr. Winkler says, that they may very well be. The majority of our nodes may be disciplined quartz oscillators, for example, from the cost effective standpoint. Certainly with seven hundred nodes scattered around the world we do not want to have triple redundancy cesium beam standards every place, just from a maintenance standpoint.

But certainly at our major switching nodes it would be a good idea, since these would be the next step in the evolution of hierarchy.

So, the big cost gain is yet to be done. We have not done this, although this then is going to be part of the choosing of what concept is used to arrive at this time coordination, and this is our next step of study to select and recommend the appropriate concept for a future system.

MR. EASTON:

Thank you very much, Mr. Mensch.

APPENDIX

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5th PTTI PLANNING MEETING

Goddard Space Flight Center

December 4-6, 1973

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