

**NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)
CLOCK PROGRAM: PRESENT AND FUTURE**

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ABSTRACT

The Global Positioning System (GPS), well into its developmental phase, provides the most salient example today of both Rubidium and Cesium Atomic Frequency Standards being applied in a space environment. Indeed, the whole success of the GPS program rides on the performance and reliability of space-qualified atomic clocks. Program status is provided by this paper and plans for ensuring the long-term continuation of the program are presented as well. Performance of GPS clocks is presented in terms of on-orbit data as portrayed by GPS Master Control Station Kalman Filter processing. The GPS Clock Reliability Program is reviewed in depth and future plans for the overall clock program are published.

Introduction

The Navstar Global Positioning System (GPS) was first conceived by Department of Defense planners as the ultimate answer to the question of how to provide precise, continuous, real-time navigation data to friendly military forces deployed world-wide. With passive equipment, the user, it was planned, would merely "dial-up" the several satellites in his view and know directly, with practically "pin-point" accuracy, where in the world he was, as well as the correct time.

Data gathered since Navstar 1 first became operational in March 1978, later to be joined by Navstar's 2 through 6, provide conclusive and persuasive evidence that the system works extremely well, for all the different potential operational users, under all ordinarily-encountered circumstances of ambient environment.

Clock performance, then has not recently been a GPS issue; the really significant question facing GPS has long been the reliability of the atomic clock. Reliability has, in the past, been given mainly "short-shrift" insofar as GPS clocks have been concerned. Schedule imperatives have demanded that satellites be committed to launch containing clocks using designs not thoroughly proven by ground test. Failures occurred, and it was necessary to implement design, material, and process changes in the same real-time as space vehicles were being prepared for launch. We bent some of the rules of good engineering practice, but enough good luck and extremely good people were with us, so that we got the job done. Now the situation is different and has improved. We have the "breathing room" to reassess and change our tactics. Our firm intention, and the plan, is to develop a good ground-test baseline for space-reliable clocks, and then to allow only a minimum perturbation of our proven design.

Navstar makes use of the state-of-the-art in both the rubidium (Rb) and cesium (Cs) atomic frequency standard technologies. Six years ago, when the Air Force first began to procure atomic clock hardware for GPS, neither type of clock had been space-qualified, to levels specified by military standards. Today, with relatively minor exception, Navstar flies fully space-qualified clock hardware of both varieties, and Rb clocks are performing head-to-head with the Cs standard on Navstar 6. The Rb standard was intended originally to be employed as an interim device, against the time when Cs standards, with their known superior long-term stability, would be ready. Rb's performance has been excellent and with some improvements aimed at decreasing temperature sensitivity, may be the right answer for the operational satellite. The Navstar 6 Cs standard, on the other hand, has also been performing in an excellent fashion and while it has exhibited behavior (to be discussed in detail later) which requires further examination and understanding, it has shown that it fits well into the Navstar navigation system and is, therefore, a completely viable candidate for use in the operational satellite. The above states then, the quandry and trilemma of the GPS program office: Should GPS proceed with Rb clocks, Cs clocks, or a combination of both? The right answer to this question, provided in a timely fashion, could save the government a considerable sum and practically guarantee the long-term existence of GPS.

GPS Navigation System Tutorial

As shown in figure 1, the GPS navigation system consists of three segments: Space, Control, and Users. The Space Segment is the set of orbiting satellites, each one containing redundant atomic clocks which, running one-at-a-time, provide precise timing to that satellite's Navigation Subsystem (Nav). Within the Nav, several functions are performed as follows: two L-band carriers are synthesized from the 10.23 MHz clock output; a pseudo-random

noise code (PRNC) is generated based upon the clock's timing; ephemerides and clock data for the whole GPS constellation are impressed on the PRNC and used to modulate the L-band carriers for transmission to the users and to the Control Segment.

Periodic updates of each satellite's ephemeris and clock data are performed by the Control Segment, which also continuously predicts the major parameters of total GPS system performance using a Kalman filter. The Control Segment consists of monitor stations, located in Guam, Hawaii, Alaska, and Vandenberg AFB, CA., with primary and secondary upload stations located at Vandenberg AFB, CA., and Sunnyvale AFS, CA., respectively, and a Master Control Station (MCS) at Vandenberg. Put in basic terms, the monitor stations receive the satellites' L-band Nav signals and pass them to the MCS for processing. The MCS, using a Kalman filter, takes the raw satellite data, makes the known, systematic corrections, weighs it statistically in the context of previous data, compares it with the best available reference, and then outputs its "best guess" as to the behavior of the several major Space and Control Segment operating parameters for the next 24 hours. The model thus generated is uploaded to each satellite daily or as necessary to keep the satellites, individually and collectively, operating in a useable fashion. The reference is periodically refreshed by passing data from Kalman to the Naval Surface Weapons Center for generation of a new reference.

The several space vehicles transmit the clock and ephemeris information, pertinent to all the satellites, by impressing it upon the two L-band carriers, as described above. Special equipment of the User Segment receive and process this data and develop a navigation solution, in the four dimensions of space and time, for the specific user. To date, users have successfully employed the GPS Navigation System to determine their position accurately on land, at sea, and in the air. Air Force has used it convincingly in exercise bombing runs, as has the Navy for instrumentation of test firing missiles at sea.

Clock Program Status

It has been said that the atomic clock is the heart of the satellite. Perhaps the idea needs to be expressed more strongly. Without reliable clocks on board each space vehicle, of high stability and modellability, the GPS navigation program cannot reasonably proceed.

The GPS Program Office is firmly of the view that there is a bright future for GPS. This very positive perspective has not come easily or without much effort and agony on the part of the government and its several clock vendors alike. Numerous problems, some of them potentially catastrophic to the program, have been worked over the past two years and two are now discussed.

a. Transformers: The power converter board of the Rb clock contains a power transformer and a timing transformer. There have been two iterations of redesign in terms of the materials and processes used to construct the transformers. The basic problem is that, because of constraints introduced by the total clock design, the power transformer runs at about 100°C and is a significant source of heat for the rest of the clock. Materials originally chosen for this device were not intended for compatible operation at elevated temperature and numerous clock failures, on the ground, and on-orbit, resulted. A program to redesign and retrofit clock transformers was instituted at Rockwell, Anaheim and the present transformers have operated without failure in Navstar 3 and subsequent vehicles since then.

b. Lamps: The lamps included in the Rb clocks have been, naturally, a subject of great interest and controversy, industry-wide, in the light of the GPS lamp failures on Navstars 1-4. Because of these several failures, reliability improvement and lamp study programs were set in motion by the program office. Outputs from these programs, to date, include lamps of known, adequate Rb fill which are flying in Navstar 5 and subsequent vehicles. Increased perception into the mechanism of lamp failure is being pursued by the Aerospace Corporation in conjunction with EFRATOM, Inc., the lamp maker. EFRATOM is also hard at work on an improved process for building and filling lamps which shows great promise for follow-on GPS satellites.

At present GPS has six satellites on-orbit, five of which are considered operational for contractual purposes. Navstar 2, whose three Rb standards have all failed in the atomic mode, still produces a navigation signal but this satellite is not regularly uploaded so the information it provides is of relatively little value to present users. Status of the 5 operational satellites is shown in Table A. Of special interest and note are that Navstar 1 has functioned reasonably well on a crystal clock since 25 Jan 1980.

Recent Kalman filter data from this clock is shown in figure 2. Navstar 3 is on a Rb clock which is the longevity leader, now running nominally and continuously for 22 months as of 20 Nov 80. Typical Kalman data is in figure 3. Navstar's 4 and 5 are also working well on Rb clocks with data shown in figures 4 and 5 respectively. Navstar 5 deserves special mention because it contains the first Rb lamps of known, adequate fill. In fairly large measure, the long-term viability of the GPS program may depend upon whether a lamp failure occurs in Navstar 5 in the near future. A lamp failure would send us back to the drawing board.

Navstar 6, with Kalman data in figure 6, contains the first successfully operating space-qualified pre-production model (PPM) Cs standard. Its performance has been excellent overall for its approximately seven months of on-orbit operation. It has shown, however, some anomalous behavior as graphed in

figure 7. The combination of decreasing Cs beam current, intermittent changes in beam current coupled with output frequency shifts, and rising ion pump current has, to say the least, been of interest and concern to the program office. This matter has been discussed, in detail, on several occasions, with the technical staff of the vendor, Frequency and Time Systems Inc., (FTS). Some diagnostics (thermal cycling in vacuum of the PPM qualification (qual) unit at NRL) have been done and added little perception to the problem. Further testing, with the qual unit at FTS, and on-orbit, are planned in the near future.

Navstar 7 is planned for launch in the Spring of 1981, and like Navstars 4-6 contains three Rb clocks and one Cs standard. Present plan is to make use of the Cs standard first but a firm decision has not yet been made. Navstar 8 will be launched in late summer next year with the same complement of clocks.

Navstar GPS Clock Plan

Given as first principle that GPS intends to fly, on each satellite, the best clock hardware available at that time, the clock plan is multifaceted and involves many corporate entities. The intelligent evolution of the overall clock design and testing to ensure the long-term reliability of that design are, prima facie, conflicting efforts but the program office intends to pursue them both, making good engineering trade-offs as clock development proceeds.

As part of the former effort, the GPS program office is funding relatively small design improvements to the Rockwell-built Rb clock. Further, automatic thermal control, which will hold clock baseplate temperature steady to 0.1°C , while its environment changes by $3^{\circ}\text{--}5^{\circ}\text{C}$ diurnally, will be added to at least one Rb clock on Navstar 8. Offline, in addition, the program office is funding a second-source Rb clock using EG&G Inc., in Salem, MA. This clock uses a physics package different from that of the Rockwell clock, as well as numerous state-of-the-art circuit advances not known at the time that GPS first entered the clock business.

In the Cs arena, the Naval Research Laboratory (NRL) is funding the offline improvement of the FTS PPM with an immediate eye to eliminating the several qual deficiencies of that clock; an incremental improvement in the clock's performance should be derived. NRL is also funding two alternate sources of Cs clocks, on a head-to-head basis, using KERNCO in Danvers, MA., and FEI in Long Island, N.Y., respectively. Both of these clocks are being designed with a view to supporting the needs of the GPS operational phase.

Relative to the reliability issue, the GPS program office is sensitive to criticisms arising from the paucity of good long-term stability and reliability data for both the Cs and the Rb clock. It is not that long-term tests haven't been done under the banner of this program office. Both Rockwell, Anaheim.,

and NBS, Boulder., have generated bodies of long-term stability data for the Rb clock over periods as long as 100 days. NRL, in its turn, has run the PPM qual unit for a total of about four months. The results have been positive and encouraging but not really enough of the right kind of data to prove the reliability for the design. The program office is taking action to free-up, as soon as possible, at least one Rb clock, of flight configuration, to operate in long-term thermal vacuum, at NRL. Coincidentally, NRL is buying a separate flight PPM Cs clock for the same kind of very purposeful testing. It is planned to have both a Rb and a Cs clock, into long-term testing by early Spring, 1981. Further planned is the purchase of critical subassemblies, for example Cs beam tube and power supply combinations for the same kind of long-term test.

The Future of GPS

To paraphrase Peter F. Drucker, "Where is the GPS Clock Program going, and where should it go?" We who are concerned about the future of GPS Clocks see the Hydrogen Maser looming brightly on the horizon. NRL is funding some excellent exploration in this area and the program office is watching that effort with tremendous interest. As the future slowly unfolds with new data and experience daily, the same issues come to mind in different forms, again and again. Do we really need the unquestionably superior long-term stability of the maser or even the Cs beam standard, in the satellite, to make the system perform to the desired minimum level of navigation accuracy over time? Maybe we are unnecessarily diluting our effort and especially our resources by pursuing the several atomic clock technologies. Rubidium, we've seen, has better short-term noise and stability than Cs but drifts far more. Given the differences between Rb and Cs, can one or the other be considered "better" for our application? Available data, to date, suggest that whereas Cs scarcely drifts, its higher noise level, in the short-term, renders it neither more modellable nor more predictable than Rb. For our purposes, Rb may well be just as good as Cs with no space-borne need for Hydrogen Masers. Time and additional data, perhaps, will tell us with certainty.

Table A - GPS Clock Status

	Rb #1	Rb #2	Rb #3	Cs #4
Navstar 1	(10) L	(7) T	(2) (11/X)	
Navstar 2	(4) T	(10) L (3/X)	(11) L	
Navstar 3	22	(3) ?	U	
Navstar 4	10	(13) L	U	P
Navstar 5	U	9	U	U
Navstar 6	U	U	U	7

LEGEND:

- n = n months of nominal atomic mode operation
- (n) = n months of nominal operation before failure
- (n/X) = n months of crystal-mode operation
- U = Clock untried on orbit
- L = Lamp failure
- T = Transformer failure
- P = Power supply failure
- ? = Unexplained anomaly

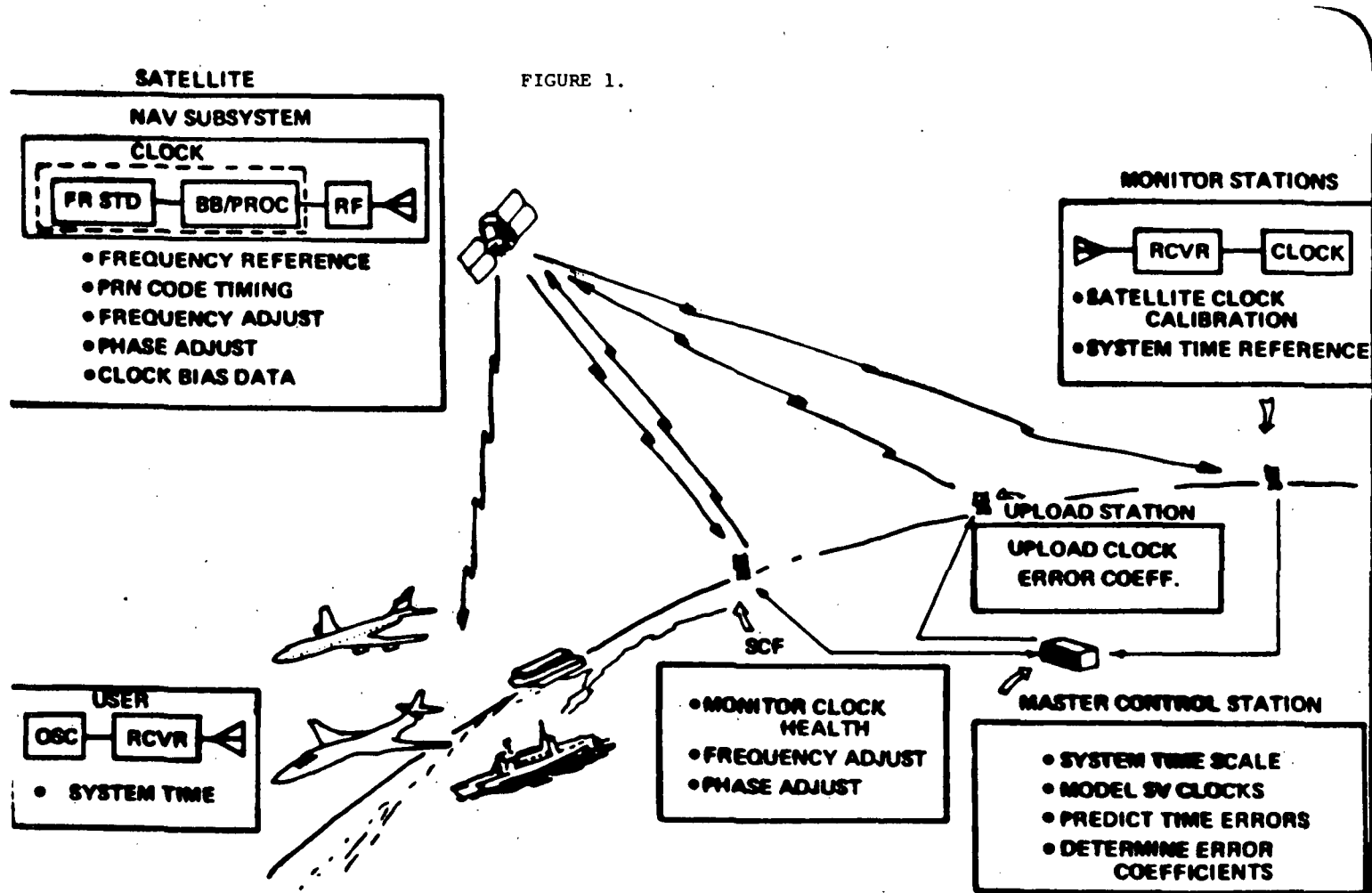
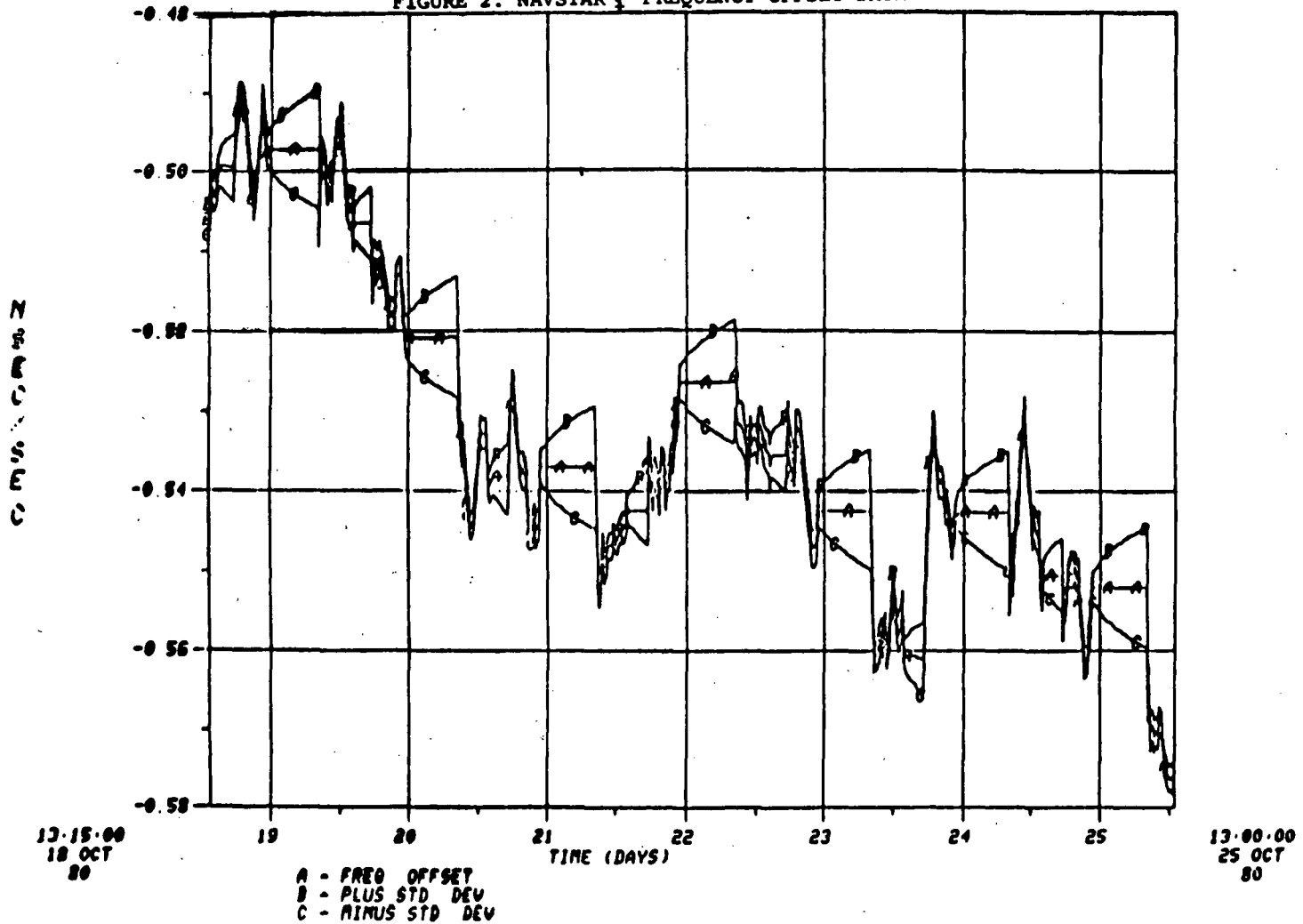


FIGURE 1.

GPS CLOCK FUNCTIONS

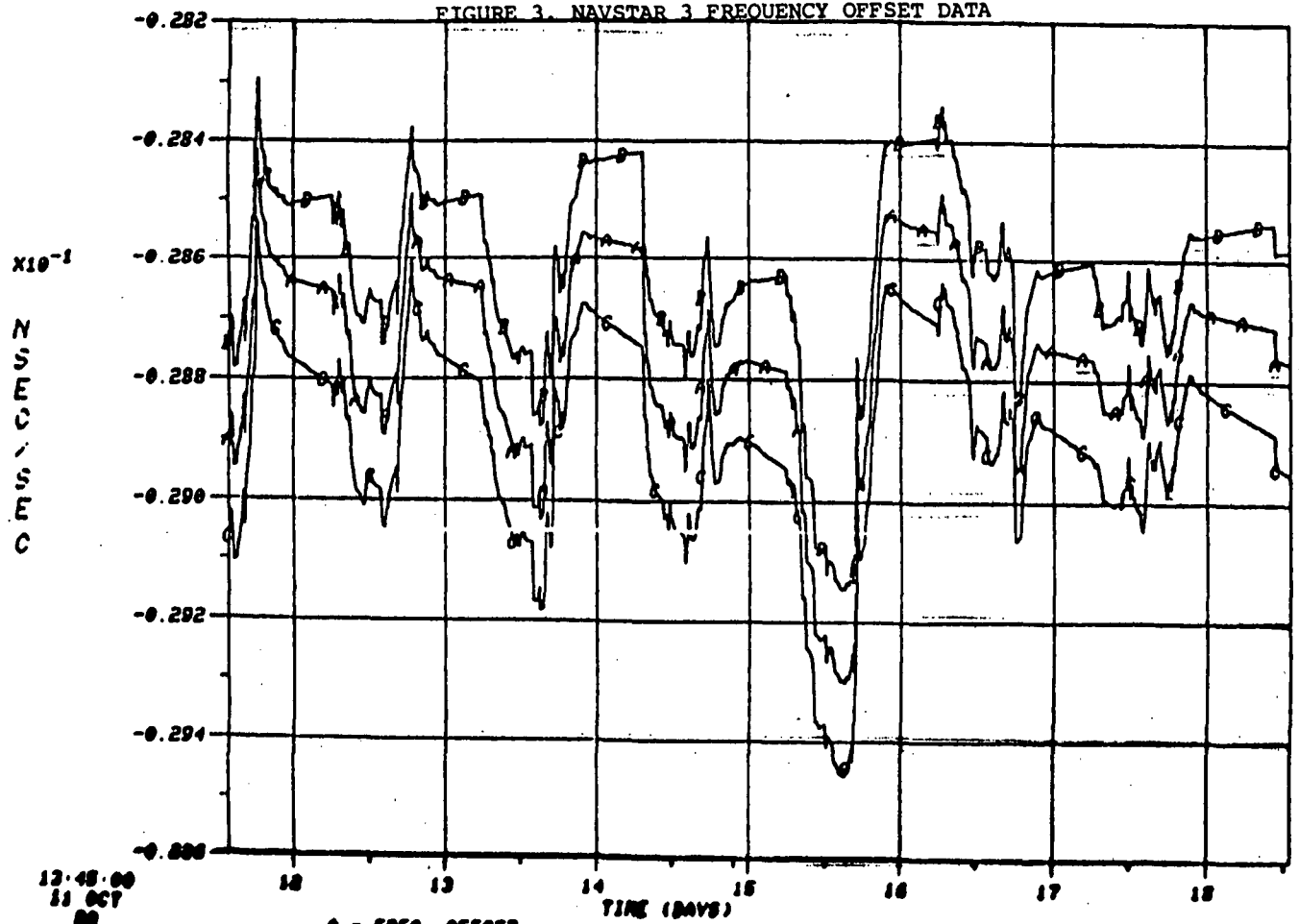
CURRENT KALMAN SV CLOCK ESTIMATE RESIDUAL AND
 STANDARD DEVIATION FOR SV NO. 4
 18:22:38 25 OCT 80/299

FIGURE 2. NAVSTAR 1 FREQUENCY OFFSET DATA



CURRENT KALMAN SV CLOCK ESTIMATE RESIDUAL AND
 STANDARD DEVIATION FOR SV NO. 6
 16:56:36 18 OCT 80/292

FIGURE 3. NAVSTAR 3 FREQUENCY OFFSET DATA



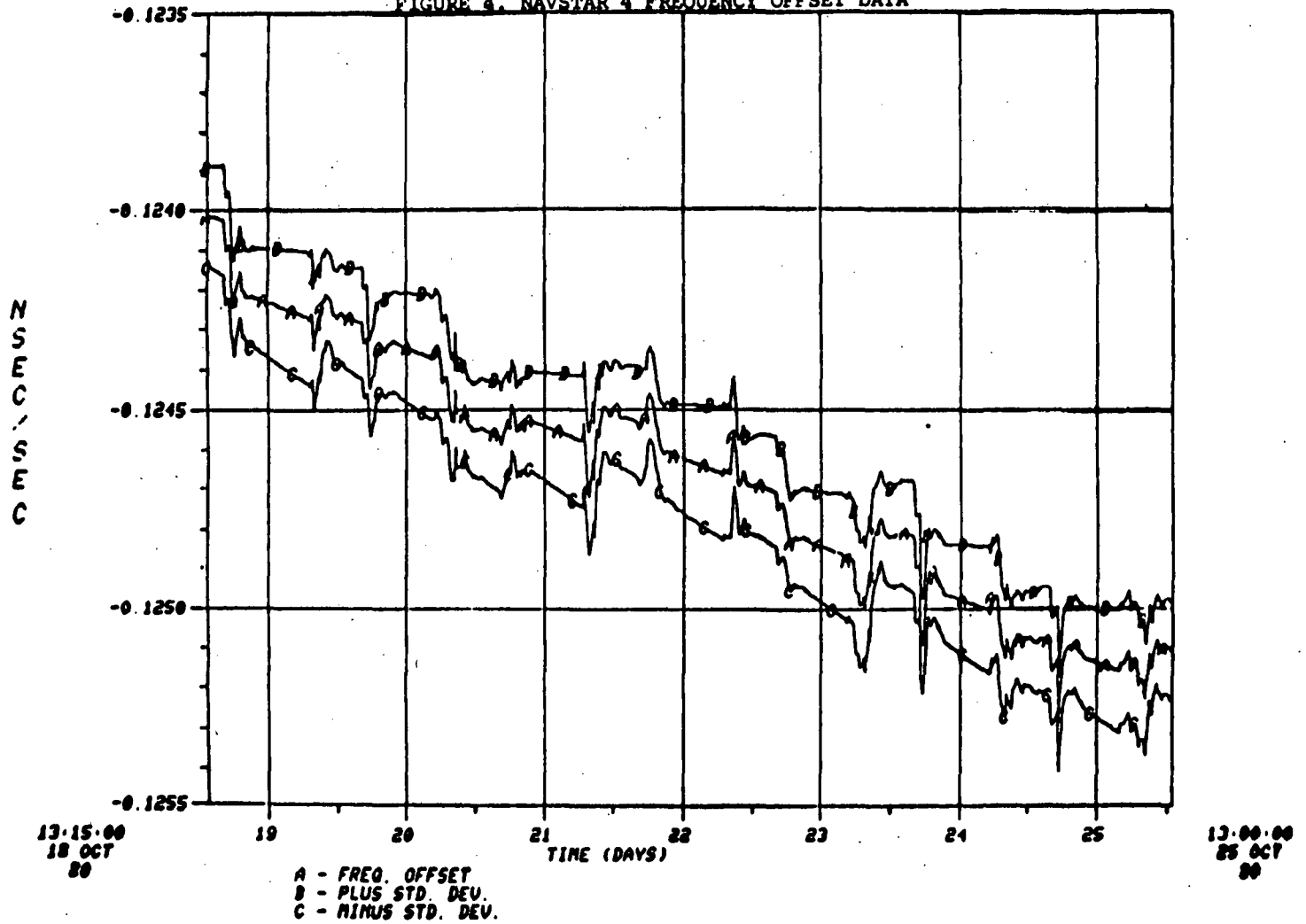
12:48:00
 11 OCT
 80

13:00:00
 18 OCT
 80

712

CURRENT KALMAN SU CLOCK ESTIMATE RESIDUAL AND
STANDARD DEVIATION FOR SU NO. 8
21:42:44 25 OCT 80/299

FIGURE 4. NAVSTAR 4 FREQUENCY OFFSET DATA

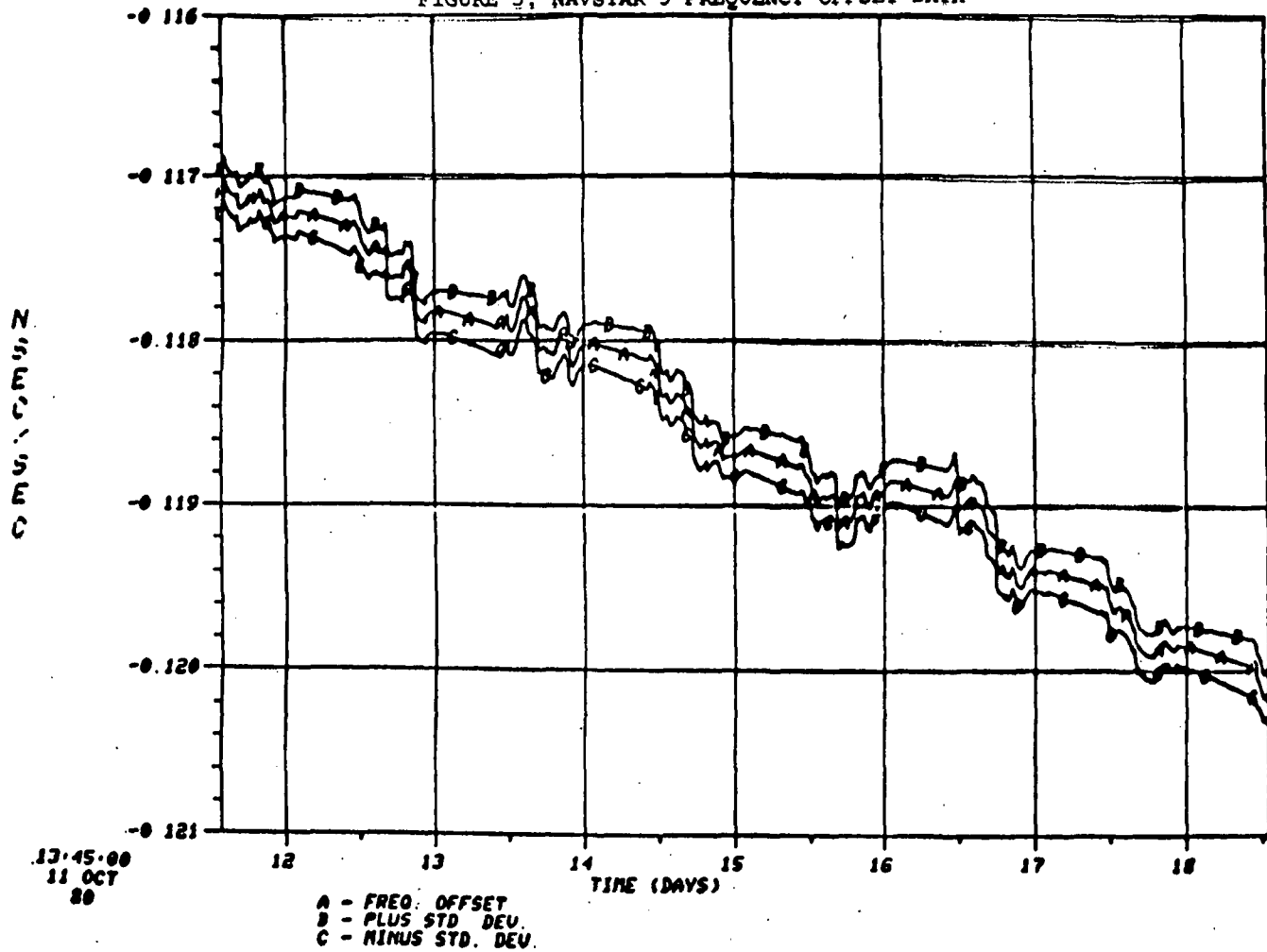


713

CURRENT KALMAN SU CLOCK ESTIMATE RESIDUAL AND
STANDARD DEVIATION FOR SU NO 5

18.38.29 18 OCT 80/292

FIGURE 5, NAVSTAR 5 FREQUENCY OFFSET DATA



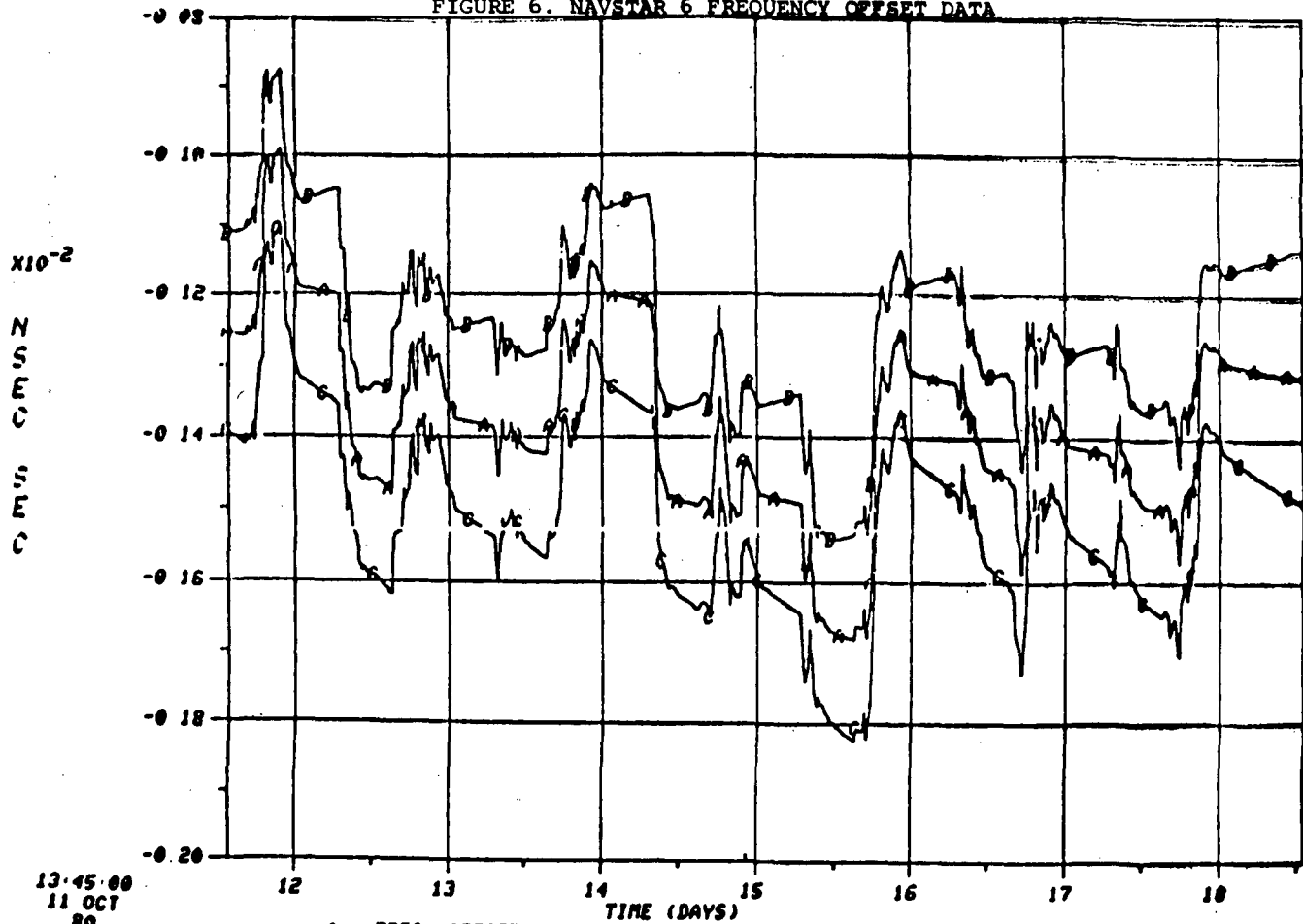
17.45.00
11 OCT
80

18.00.00
18 OCT
80

714

CURRENT KALMAN SU CLOCK ESTIMATE RESIDUAL AND
STANDARD DEVIATION FOR SU NO 9
20:41:46 15 OCT 80/292

FIGURE 6. NAVSTAR 6 FREQUENCY OFFSET DATA



13:45:00
11 OCT
80

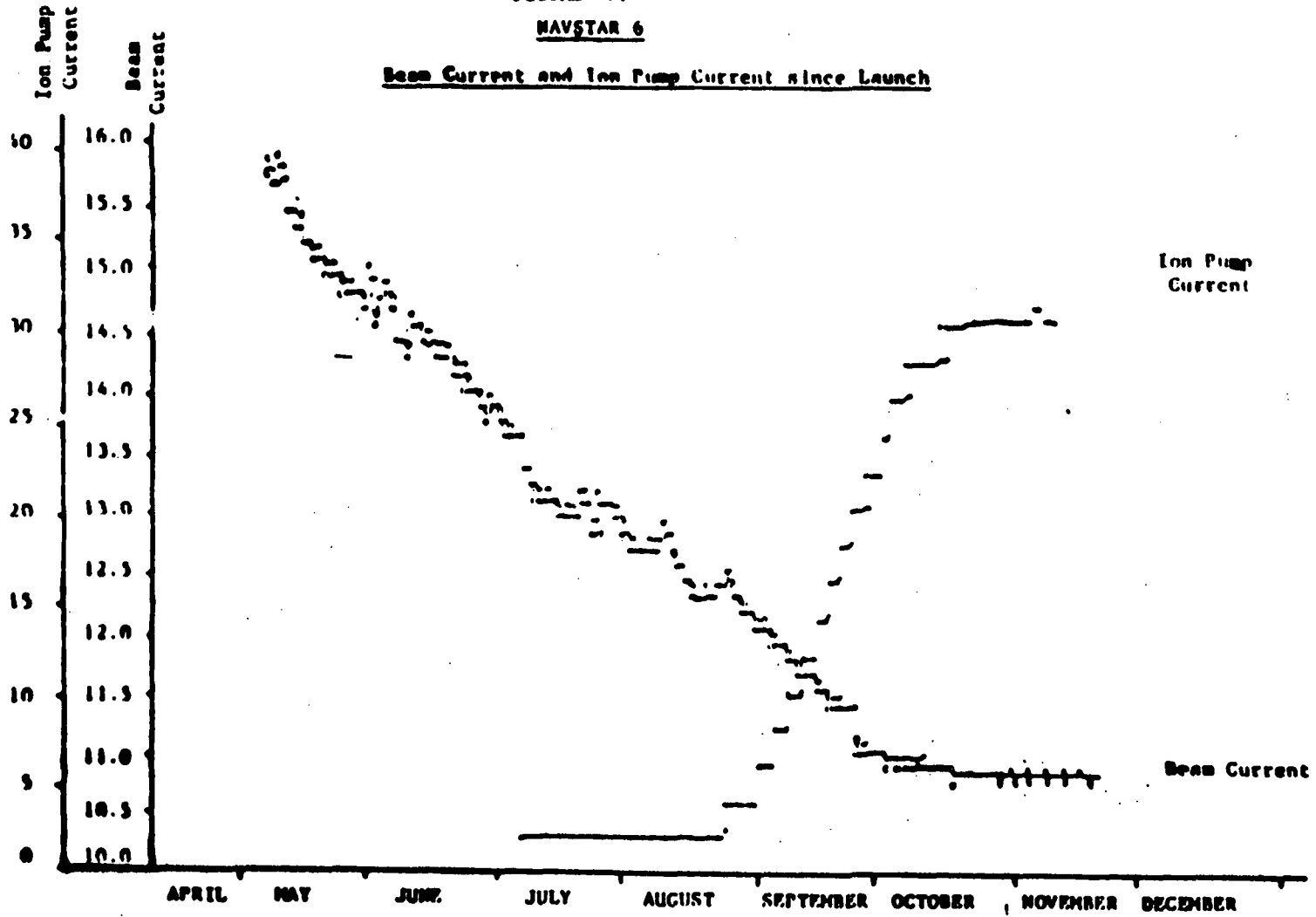
A - FREQ. OFFSET
B - PLUS STD. DEV.
C - MINUS STD. DEV.

13:00:00
18 OCT
80

FIGURE 7.

NAVSTAR 6

Beam Current and Ion Pump Current since Launch



Ion Pump
Current

Beam Current

QUESTIONS AND ANSWERS

CAPTAIN TENNANT:

I believe the question was asked yesterday, relative to the potential for encryption of the CA codes emanating from the satellite. The fact of the matter is the CA code, like the P code, is probably going to be encrypted, by way of making the accuracy of those signals collectively available. If you don't have the decryption gear, your accuracy is going to be fairly limited to like 300 to 1,000 meters. Don't know how bad that would hurt you, compared to what you are getting now.

I expect right much. The availability of the decrypting apparatus is going to be a function of your ability to satisfy the program office and especially the National Security Agency that you need to be able to decrypt the signal and that you can protect the decryption gear if you have it. Other questions, comments?

PROFESSOR CARROLL ALLEY, University of Maryland

I would like to compliment Captain Tennant on his very enlightening and forthright talk about the clock development program. I remember when the RFP went out a number of years ago. It was several feet high, and the amount devoted to clocks was about one page. So that the statement that the whole success of the GPS rides on the performance and reliability of space clocks has at long last been adequately recognized. Thank you.

DR. REINHARDT:

The GPS program is a classic example of the problems that were brought up in the first meeting. You say that reliability and performance were primary concerns, but in fact, what has happened is that non-critical elements, such as size, have been the real drivers. What I see is a lot of research going into areas, unknown areas like new passive masers, shrinking down masers in size, and even cesiums, when that is not necessary if you just make the satellite 50 percent bigger. This is precisely the kind of thing we are talking about -- of designers arbitrarily saying that your box must fit in this little cube and a lot of money and a lot of effort and a lot of loss of reliability is being wasted because of that. Can you comment on that? Is there anything intrinsically that keeps the satellite from being a little bigger or even 50 percent bigger?

Or is it just that the satellite now is too far down the line for anybody to make changes?

CAPTAIN TENNANT:

I am not really qualified to fully answer that question. I know that in terms of the cost; the availability of the hardware to put the satellite we are talking about into orbit; given where we were six years ago; and given the priority associated with putting the satellites up, getting the program moving; we had to go with what we had at the time.

DR. REINHARDT:

A specific example of what I mean is that NASA had just spent \$2,000,000 developing a red shift probe maser to be a flyable maser which would have taken a very small step to turn into a very reliable long-term maser, and it was only 70 pounds. You know it was obviously flyable because it flew on a Redstone.

CAPTAIN TENNANT:

Only 70 pounds? All my clocks weigh less than that.

DR. REINHARDT:

Is there any intrinsic reason that they have to weigh 70 pounds? This is something that is known. People know how to launch heavier satellites and control them. What you are asking the frequency standard people is to go into completely unknown areas and then yet meet scheduled reliability in very short time.

CAPTAIN TENNANT:

The question is too big for me. I am a clock man, not a space vehicle man.

MR. HUGO FRUHAUF, Efratom

To answer the question of satellite weight and resulting clock weight; it was primarily a function of the launch vehicle that was available at the time. The whole program and cost was keyed to a cheap launch vehicle which was the Atlas. So, therefore, the space satellite size and the 11,000 mile nautical orbit was primarily a function of that problem.

At the present time, future launches are planned with the shuttle, and your question and comment at that point should be re-considered.