NEW TIME AND FREQUENCY SERVICES AT THE NATIONAL BUREAU OF STANDARDS

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INTRODUCTION

The National Bureau of Standards (NBS) established two new time and frequency services in 1983. They permit the user to obtain time and frequency traceable to the NBS with greater precision and less effort than previously possible. The new services are for users who require time transfer accuracies in the three nanosecond to one microsecond range or frequency calibration capability in the 1 part in 10^{11} to one part in 10^{14} range. However, many applications not requiring this level of precision may benefit from these services because of the high degree of automation, simplicity of use, and support from the NBS.

Frequency calibration requirements at the part in 10^{11} to part in 10^{12} level and timing requirements at the 1 microsecond level can be satisfied using low frequency radio signals broadcast from stations such as WWVB or Loran-C. The NBS Frequency Measurement Service helps the user set-up a low frequency receiver and data logging system most appropriate for his needs and location. A typical system includes a receiver, microcomputer, floppy disc units and printer-plotter. The user supplies a dial-up phone line and modem so that his data can be compared with data recorded at NBS when necessary, thus providing increased assurance that the measurements are valid. The user also receives a bulletin by mail containing NBS measurements of many signal sources. To assist the user in getting the most from his system, NBS provides specific training using the actual equipment in one of its seminars on frequency measurements.

The NBS Global Time Service provides higher precision time and frequency data and a greater degree of automation. A Global Positioning System (GPS) receiver, located at the user's facility communicates automatically with an NBS computer that stores raw data, determines which data elements are suitable for time transfer calculations and provides an optimally filtered value for the time of the user's clock with respect to the NBS atomic time scales. The user is assigned an "account" on one of the NBS computers through which he may access the results of the NBS analysis. Tests, based upon receivers in Colorado, Germany, France, Washington, DC, Wyoming, and California, demonstrate that the system can perform time comparisons with a precision of three nanoseconds and frequency comparisons with a precision of one part in 10^{14} after four days of operation.

THE MEASUREMENT ASSURANCE APPROACH

The most common way to relate industrial calibration measurements to the national standards is to have the local reference standards calibrated in a way that provides traceability to the national standards. Depending upon the required level of accuracy, these calibrations may be performed by private or governmental laboratories at the local, regional or national level. NBS provides approximately 12,000 calibrations per year for this purpose. NBS Calibration services are described in Special Publication 250 (available from the Office of Physical Measurement Services, National Bureau of Standards, Washington, DC 20234). The cost of each calibration is published in an Appendix to this publication.

The ordinary calibration process has serious deficiencies. First, the standard or instrument to be calibrated must travel to the calibration laboratory, so it is out of service for a period of time. For example, the complete characterization of a cesium beam frequency standard requires that it be at NBS for a period of not less than five weeks. Even more serious is that the confidence in the calibration deteriorates with the passage of time. The fact that the instrument must be shipped to and from the calibration laboratory contributes substantially to this problem. Finally, only selected individual standards or instruments are calibrated and thus little information is available concerning whether or not the total measurement process is under control.

A general goal of the NBS program is to increase the reliability and effectiveness of the national measurement system. The two new time and frequency services are examples of what is frequently called "measurement assurance". In a measurement assurance program, most of the measurements are performed at the user's site rather than at the NBS and feedback and analysis of measured information is an important part of the process. In addition, the NBS establishes a long term interaction with the user and assists in training user personnel. The complete measurement process undergoes repeated scrutiny and is therefore likely to remain under control at all times. Of the six base units of measurement -the kilogram, the second, the Kelvin, the candella, the ampere, and the mole -the second is unique by the relative ease with which it may be compared by radio at remote locations without the transport of physical artifacts†. Because of the unique property of the second, the new services provide the user the accuracy he requires through a simple program of coordinated measurements made at his site and at the NBS. No artifacts need be shipped to NBS,and the user exchanges calibration data with the NBS via telephone.Thus, the user obtains NBS traceable frequency measurements and time synchronization in real time. Traceability is provided at whatever level is required up to the ultimate stability of the NBS atomic time scales and the full accuracy of the NBS primary frequency standard. Since the link to NBS is established on a regular basis, the user's confidence in the performance of his in-house standards is greatly increased. Because of the high degree of automation, inherent in both of the new services, the improvements in precision and accuracy are obtained with negligible operational burden on the user.

NBS FREQUENCY MEASUREMENT SERVICE

This new Frequency Measurement Service, using straight forward measurement techniques [1], utilizes precision navigation and timing broadcasts from Loran-C and WWVB to provide frequency traceability to the NBS at approximately a one part in 10^{11} level. Prior to the introduction of this service, there did not exist a total measurement system with the following features: LF receiver and antenna; time interval counter; dual floppy disc data storage system; printer/plotter; instrument controller; and telephone modem data line to the NBS.

Figure 1 shows the Loran-C version of the frequency measurement system. Using the NBS software, this system is capable of monitoring Loran-C transmissions, storing, listing and plotting the frequency calibration data. Figure 2 is a sample plot of phase vs time. The slope calculated by the system program is the frequency offset of the user's clock. The numerical value of the calibration is printed on each plot. The plots are made automatically once each day. Four separate frequency sources can be calibrated simultaneously.

The new NBS Frequency Measurement Service is more than an automated data acquisition system. It begins with consultation between NBS staff and the user to determine the best method of satisfying the user's requirements. If the Frequency Measurement Service is selected, consultation continues to determine the most appropriate radio transmission including an analysis of possible propagation and reception problems. The second step is training of the user's technical staff. A general foundation in time and frequency measurement techniques is provided by the two yearly NBS Seminars: "Frequency Measurements" and "Frequency Stability and Its Measurement". Direct experience with the equipment used in the

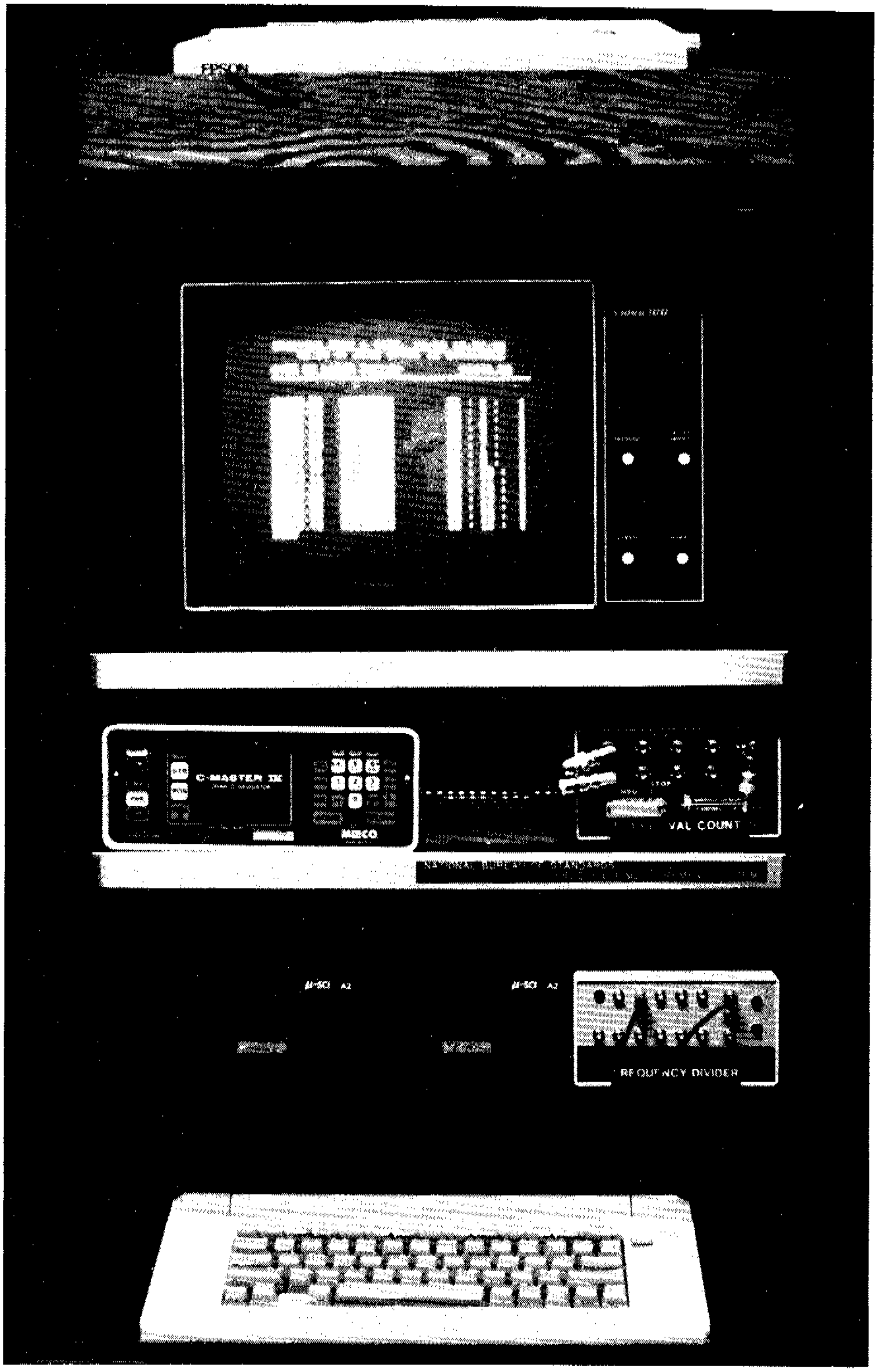

Figure 1. Photograph of frequency measurement system[††].

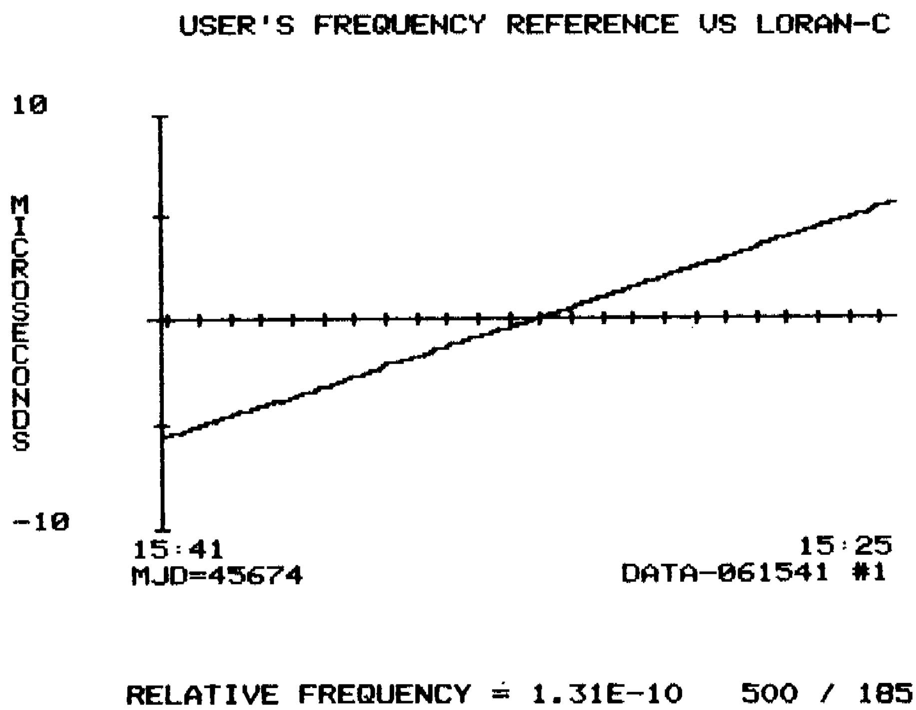

Figure 2. Sample plot of calibration data from the frequency measurement system.

frequency dissemination service will be provided using equipment now operating at the NBS facility in Boulder, Colorado. Step three is the acquisition of the necessary measurement equipment. If desired, NBS can provide the complete integrated measurement system, insuring that all the parts are compatible and operate with the NBS software. Finally, the NBS will consult with the user during the installation of the antenna, the initial set-up of the equipment and verification of proper operation. Interaction between the NBS and the user will continue throughout the program and the user will receive NBS data via the monthly "Time and Frequency Bulletin." Also, through direct computer-to-computer data exchanges, the NBS will monitor the user's data without interfering with the operation of the user's measurement system. Thus the NBS will be able to help diagnose any anomalies. Finally, the NBS will provide additional training for newer staff members and will upgrade the calibration service with future releases of improved software and calibration equipment.

NBS GLOBAL TIME SERVICE

With this new service the user can synchronize his reference clock with respect to UTC(NBS) with state-of-the-art precision and accuracy. The service utilizes the clear access signal broadcast from the Global Positioning System (GPS) satellites. The time transfer measurements are made using a common-view technique, thereby eliminating the noise contribution from the clock errors of the GPS system and greatly reducing the effect of ephemeris errors [2]. When the NBS calculated corrections are applied to the user's clock, that clock becomes a high performance reference with the following characteristics. Between one and four days, mod $\sigma_y(\tau) \cong 10^{-13}\tau^{-3/2}$ [3]. For longer times, up to approximately one-month, $\sigma_y(\tau) \cong 10^{-14}$. Figure 3 shows the results of an anaylsis of data taken between Boulder and Paris confirming this performance level. As a result of these very high precision time transfers, the user not only has access to a very stable frequency reference but also gains direct access to the U. S. primary frequency standard, NBS-6. Access to NBS-6 makes it possible to set an absolute limit of one part in 10^{13} on the frequency excursions of the user's clock. Another way to express the quality of this service is to say that, for time periods longer than approximately four days, the user can take advantage of the full capability of the NBS atomic time scale. The performance is almost the same as if the user were located in the next room and connected by a coaxial cable.

The NBS Global Time Service is more than just a GPS time transfer receiver. A receiver alone provides only short term measurements of the time of the user's clock relative to the time of a space vehicle clock or GPS time. The NBS service provides, in addition: determination of the user's position (necessary for time transfer measurements); scheduling of common view measurements between the user and the NBS; automatic collection by the NBS of the data from the users receiver; computation by the NBS of the UTC(NBS)-user clock time differences; and optimum filtering of the data to provide a daily best estimate of the time of the users clock with respect to UTC(NBS). The NBS provides each user with a monthly report giving the computed daily time differences, the computed daily frequency differences and the Allan variance of the user's clock. Figure 4 is a plot of time difference data taken from one of the Global Time Service reports. The user is assigned an "account" on one of the NBS computers through which he may directly access the results of the NBS analysis.

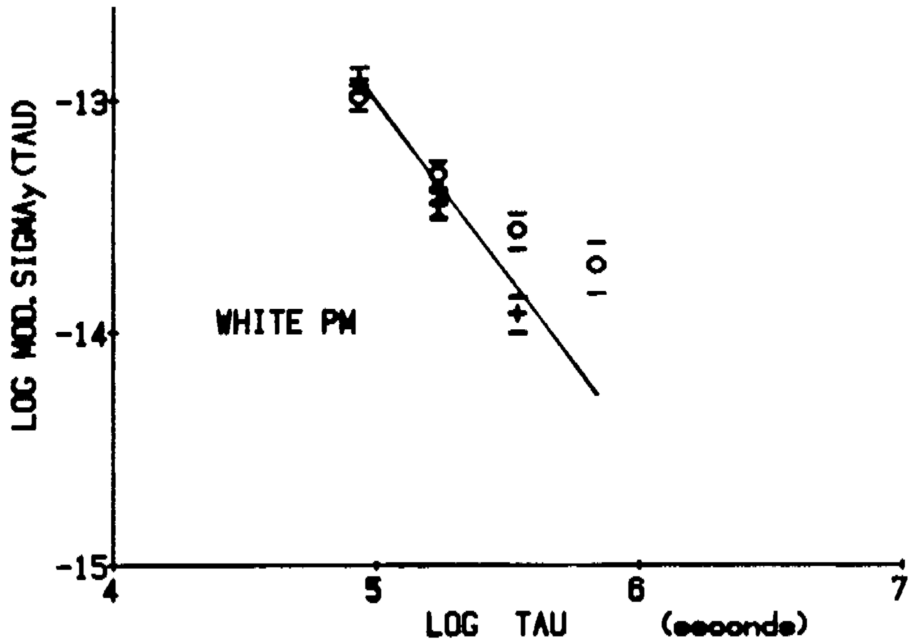

Figure 3. Modified Allan variance analysis of the NBS Global Time Service. The plus signs refer to measurement system noise and the circles refer to the noise of the reference clocks.

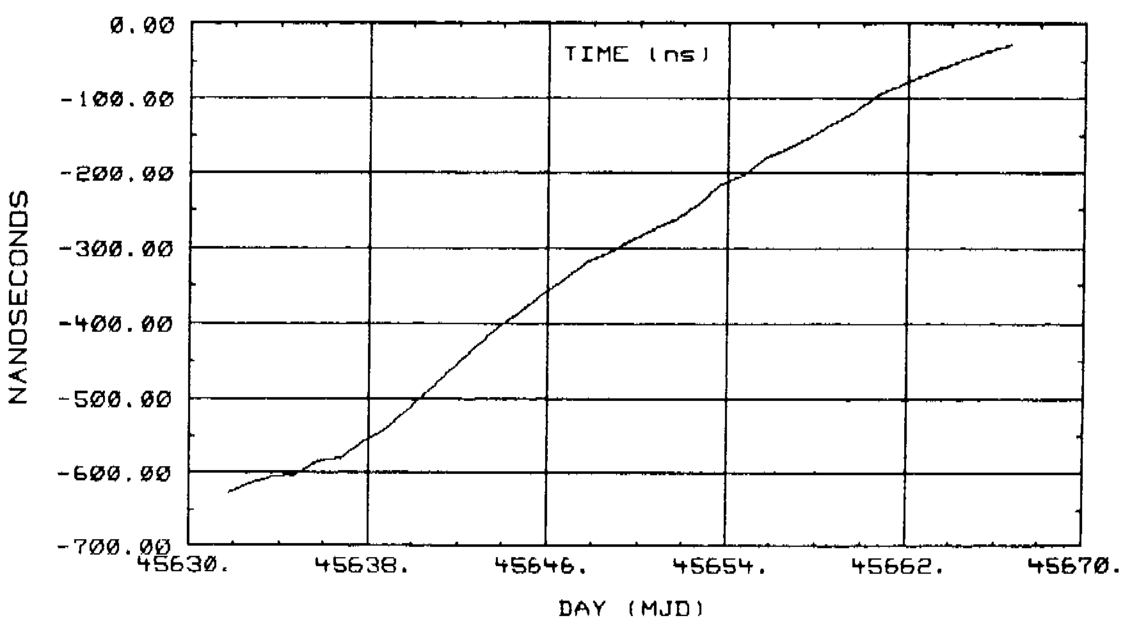

Figure 4. Sample plot of time transfer data provided monthly to users of the Global Time Service.

The service utilizes a GPS receiver developed at the NBS and now in commercial production [4]. Figure 5 is a photo of the NBS prototype. The receiver has 0.1 ns precision and nonvolatile memory for data storage. A simple, small omni-directional antenna makes it possible to lock on to any satellite whose elevation angle is greater than 5 degrees. The receiver, interfaced to a printer, allows local display of the raw GPS measurements and a telephone modem provides communications with NBS. The user is responsible for providing a dial-up telephone line so that the NBS may directly access the data from the receiver. This telephone link is an essential element of the data communications that gives the user access to UTC(NBS).

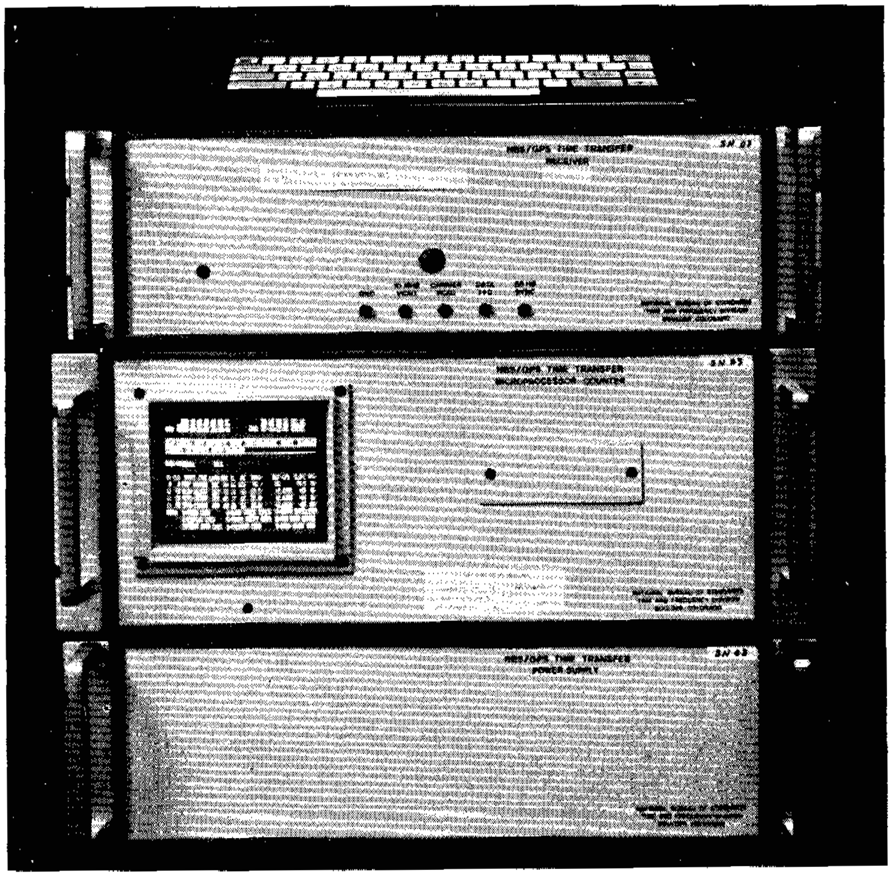

Figure 5. Photograph of prototype receiver for the NBS Global Time Service.

SUMMARY

The two new measurement services offered in 1983 extend the range and capability of the other frequency and time services offered by NBS: telephone time of day; high frequency broadcasts (WWV and WWVH); low frequency broadcast (WWVB), the GOES satellite time code; and laboratory calibrations. These services previously provided routine time synchronization capability in the one second to 25 microsecond range. The new services offer enhanced automation and a greater confidence in the results of the measurements. In addition, NBS provides consultation to assist the user in selecting the best solution to his problems, initial training and follow-up consultation whenever measurement problems are detected. The new time and frequency services provide traceability to NBS and a direct link to one of the world's best time scales. They greatly reduce the need for the user to become an expert on the intracacies of navigation systems such as Loran-C and GPS. The systems reliability will be high because all the components are "off-the-shelf" commercial equipment and because NBS maintains the systems to minimize hardware failures.

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† The seventh base unit, the mole, is now defined in terms of the second.

†† Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for that purpose.

[1] *Time and Frequency Users Manual*, George Kamas and Sandra L. Howe Eds., National Bureau of Standards Special Publication 559. Available from the Superintendent of Documents, U. S. Govt. Printing Office, Washington, DC 20402. Stock #003-003-02137-1. Price $6.00.

[2] Dick D. Davis, Marc Weiss, Alvin Clements and David W. Allan, "Construction and Performance Characteristics of a Prototype NBS/GPS Receiver", Proc. 35th Annual Frequency Control Symposium, May 1981.

[3] David W. Allan and James A. Barnes, "A Modified Allan Variance with Increased Oscillator Characterization Ability", Proc. 35th Annual Frequency Control Symposium, May 1981.

[4] David W. Allan, "National and International Time and Frequency Comparisons," Proc. 37th Annual Frequency Control Symposium, June 1983.

QUESTIONS AND ANSWERS

MR. WARD:

Samuel Ward, Jet Propulsion Laboratory. It's not a question, it's a statement. On the data that you presented against the GPS for the GSC-12. We discovered there was an error that was not on the GSC-12 clock. It was on a cesium standard 1636 that was a part of our master clock ensemble and it was in a rather poorly controlled temperature environment. So that would explain some of the noise that you saw.

DR. STEIN:

It certainly would.

MR. CARLSON:

J. R. Carlson, SCS, Canada. I would be interested in the performance of a system like yours with a distributed ensemble of clock, perhaps tied to a central control, and then feeding data to your lab. It's just a proposal, but have you done any work with a distributed system or user system? I am thinking of considering a baseline interferometer type application.

DR. STEIN:

Of course there already is a major distributed ensemble in the international atomic time; and one of the things that I think that I would like to avoid is an overlap in that kind of operation; but we have considered the question of an ensemble time, say, for an individual user who has his own distributed set of clocks. For example, we have some separated clocks at our radio stations which we like to use at least for redundancy purposes.

The answer to your question is, the one-day performance of the G.P.S. System over thousands of kilometer baselines; using this common mode technique, with a high quality receiver could be as good as approximately eight nanoseconds RMS.

It's not quite as good as, say, a very high quality cesium standard, but it's better than a standard performance device in general, or at least comparable. So that for time periods somewhat longer than a day, one can begin to construct a very high quality time reference this way and, of course, that's what is done internationally.

I think G.P.S. is already beginning to replace Loran-C to some extent in international time scales.

MR. WARD:

Again, a comment to the last gentleman. I have with me a comparative analysis of GPS versus VLB1 for intercoupling an ensemble of standards that includes cesiums and hydrogen masers. So if you come to see me I can give you a sample.