ACTIVITIES AND PLANS OF THE TIME AND FREQUENCY DIVISION OF THE NATIONAL BUREAU OF STANDARDS

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ABSTRACT

In keeping with the other standards activities of the National Bureau of Standards, the Time and Frequency Division realizes and maintains the standards associated with its name, coordinates these standards nationally and internationally, provides access to the standards through a set of dissemination services, and develops new standards, measurement methods and dissemination methods in anticipation of future national requirements. This paper describes the current work of the division with emphasis on those activities which most directly concern the attendees of this conference. Projections for relevant future programs are also discussed.

1. INTRODUCTION

The purpose of this paper is to present a concise outline of the activities and plans of the Time and Frequency Division. In each area several references are cited so that interested readers might locate more detailed information on a particular subject. The first section describes present and future primary frequency standards, and this is followed by a section describing the NBS time scales and their coordination with other major laboratories. The last two sections describe broadcast services and measurement services including some potential new services.

The division meets its responsibilities through cooperation with many other institutions in the U.S. and abroad and the spirit of this cooperation has been very good. Space does not permit recognition of each interaction, but it is appropriate to acknowledge this cooperation at the outset.

2. PRIMARY FREQUENCY STANDARDS

The Division program on primary frequency standards involves operation of the present standard, the development of a new standard based on optical pumping of cesium, long-range research on standards based on radiative cooling of trapped ions and a study of improved methods for relating the higher frequency of a future ion standard to microwave frequencies.

2.1 The Present U.S. Primary Standard of Frequency

The present U.S. primary standard for frequency is NBS-6, a cesium-beam standard with an accuracy of 8 parts in 10^{14} [1][2]. NBS-6, which was completed in 1975, features a reversible beam and a 3.7-meter Ramsey cavity providing a resonance linewidth of 25 Hz. This standard is not operated continuously, but is used to periodically calibrate the rate of the NBS time scale, TA(NBS).

2.2 An Optically-Pumped Primary Standard of Frequency

A new cesium-beam standard, NBS-7, based on optical state selection and detection is now under construction in the Division [3][4][5]. The design goal is an accuracy of 1 part in 10^{14}. This standard will operate on a more nearly continuous basis, but the philosophy of periodically calibrating TA(NBS) will be retained in order to maintain a very high level of reliability in the time scale. At the design accuracy, calibration of the time scale will have to occur more frequently. This requirement dictates the use of a significant level of automation in the evaluation of systemmatic errors.

2.3 Research on Stored Ions

As a step toward a future standard based on stored ions, the Division has demonstrated a prototype frequency standard using a ground-state hyperfine transition in $^9Be^+$ [6]. Despite the low clock frequency of 303 MHz, the accuracy was at about the same level as NBS-6. Current studies are focusing on mercury ions. Experiment and theory both indicate promising possiblities for both microwave and optical frequency standards [7][8]. It appears that Hg^+ ions can be cooled continuously through interaction with cooled Be^+ ions providing for accuracy beyond the level of 1 part in 10^{14} [9]. Recent studies of the S→D optical transition in mercury suggest the potential for an optical frequency standard of unprecendented accuracy. This will require the development of improved methods for optical frequency measurement.

2.4 Studies on Methods for Frequency Synthesis/Division

The potentially high accuracy and stability of optical frequency standards has prompted consideration of the development of simpler methods for accurately relating optical frequencies to microwave frequencies. Frequency synthesis techniques used to measure the speed of light and redefine the meter could prove to be useful [10]. A new frequency divider concept also appears worthy of study [11]. Plans for work in this area are now under consideration.

2.5 Additional Plans

Following recent successes at laboratories in the U.S. and Europe in cooling and confining neutral atoms, the Division is planning to initiate a small basic research project in this area. Initial work will be directed at manipulation of the velocities of cesium atoms.

3. THE NBS TIME SCALES AND THEIR COORDINATION WITH OTHER LABORATORIES

3.1 Time Scale Operation

NBS atomic time is generated from an ensemble of approximately twelve commercial and one laboratory cesium beam frequency standard and two laboratory hydrogen masers [12][13]. The time of all the clocks is measured every two hours, and the time scale, UTC(NBS), is computed using a weighted-average algorithm. UTC(NBS) is steered with a long time constant (about 1 year) to within 1 μs of UTC maintained in Paris by the Bureau International de l'Heure (BIH) and the Bureau International des Poids et Mesures (BIPM).

At the end of each month, the TA(NBS) time scale is computed using a Kalman algorithm [14]. This computation is optimum in the statistical sense for clocks having both white frequency noise and random-walk frequency noise, a good model for the clocks in the NBS ensemble. The second of TA(NBS) is steered toward NBS's best estimate of the SI second based on yearly calibrations of the ensemble by NBS-6.

3.2 Coordination with BIH/BIPM and Other World Timing Centers

The Time and Frequency Division has developed a Common-View Method for realizing time transfer through the GPS Satellites at a level of about 10 ns [15][16][17]. This method is used by NBS and many other major timing centers for international coordination. The BIPM notes that clock comparisons and dissemination of atomic time have been notably improved by the implementation of this technique [18].

3.3 Other Applications of GPS Time Transfer

The high level of coordination of major timing centers using GPS provides an excellent basis for analysis of the performance of the GPS space clocks. With GPS linking the excellent performance of the time scales at these centers, NBS has been able to devise analytical methods for separating some of the error terms (e.g., ephemeris errors and delay errors) thus providing independent input on performance to the DOD operators of the system [19]. In other areas, time transfer using GPS has become an important part of the Deep Space Network operated by NASA [20] and study of the very high stability of the Millisecond Pulsar has benefitted from the GPS transfer to the Arecibo Observatory in Puerto Rico of a 'best clock' [21].

3.4 Plans

While the GPS Common-View Method has proven to be of significant value, two-way time transfer through communication satellites promises even better performance [22]. The BIPM recommends study of this method because of its potential performance and because it feels that the international community should not be dependent on a single technique for timing links [16]. NBS, in cooperation with the National Research Council in Canada, the U.S. Naval Observatory and several laboratories in Europe, is working on the development of an experimental two-way satellite network. Ground tests of the NBS earth stations indicate very promising performance [23] and plans now call for link tests within the next year.

4. BROADCAST SERVICES

NBS offers continuous time and frequency signals via HF and LF radio broadcasts and a time code disseminated from the GOES satellites [24][25][26].

4.1 HF Radio Broadcasts

HF Broadcasts from WWV (Fort Collins, Colorado) and WWVH (Kauai, Hawaii) can be received on conventional shortwave receivers at 2.5, 5, 10 and 15 MHz for both stations and 20 MHz for WWV only. Accuracies of 1 to 10 ms in time and 1 x 10^{-6} in frequency are typically achieved. These stations provide standard frequencies, standard time intervals, time-of-day announcements, a binary-coded-decimal (BCD) time code, astronomical time corrections, and certain public service announcements (weather and radio propagation alerts). The WWV and WWVH signals are also avaiable by telephone (303-499-7111 and 808-335-4363). The time signal by telephone is reduced in accuracy to about 30 ms due to unpredictable delays in cross-country routing of telephone calls.

4.2 LF and Satellite Broadcasts

WWVB (Fort Collins, Colorado) offers accuracies of 0.5 ms in time and 10^{-11} in frequency, but requires a special 60 KHz low frequency receiver. WWVB's time code signal is a BCD type needing special decoding equipment. The GOES weather satellites broadcast an NBS time code accurate to 100 μs to a major portion of the western hemisphere. These geostationary satellites are located at nominally 75° west and 135° west longitude. The broadcast frequencies are 468.8250 MHz (135° W) and 468.8375 MHz (75° W).

4.3 Plans

With funding from the electrical power industry and in cooperation with the National Research Council in Canada, NBS is investigating the possibility of broadcasting highly accurate time signals from commercial communication satellites in the KU frequency band. It appears that an accuracy of 0.1 μs is feasible. The front end components for receivers of such signals would most likely be the same components now available for reception of direct satellite television broadcasts.

5. MEASUREMENT SERVICES

The Time and Frequency Division provides a variety of other measurement services (described below) including calibration services, a monthly bulletin, an annual seminar on measurement methods and two services based on common-view reception of 1) GPS signals and 2) LF (e.g., Loran-C) radio signals. Most of these services are performed for a fee. More detailed information on the services is avaiable from the Calibration Service Users Guide [27].

5.1 Calibration Services

Oscillators can be readily calibrated in the frequency range from 1 to 100 MHz. Reference calibration accuracy is nominally that of the NBS primary frequency standard (8 x 10^{-14}), but the accuracy level transferrable to the oscillator depends upon the stability and noise properties of the oscillator.

Atomic standards can be characterized by direct comparison with the NBS time scale. The standard test involves 30 days of data acquisition. The square root of the Allan variance, $\sigma_y(\tau)$, is measured to ±2 x $10^{-12}\tau^{-\frac{1}{2}}$ for averaging times, τ, of about 7200 to 10^6 seconds and is presented as a function of τ. For oscillator frequencies of 5, 10 and 100 MHz, the stability in terms of $\sigma_y(\tau)$ can be determined by repeated measurements at 3-second intervals. $\sigma_y(\tau)$is measured to ±2 x $10^{-12}\tau^{-\frac{1}{2}}$ for averaging times of 3 to approximately 10^4 seconds. At the same frequencies phase noise, $S_\varphi(f)$, can be determined for Fourier frequency offsets of 0.1 Hz to 50 KHz. For an offset of 1 Hz, $S_\varphi(f)$ can be measured to -115 dB (relative to 1 rad^2/Hz).

5.2 The Global Time Service

This service is based upon the GPS Common-View Technique used for international coordination of time scales (see sections 3.2 and 3.3) [19]. Data from an NBS-designed receiver, located at the user's facility, are automatically sent to an NBS computer which stores the raw data, determines which data are suitable for time transfer calculations, and provides an optimally filtered value for the time and frequency of the user's clock with respect to the NBS time scale. The user receives results through a monthly report and is also given an account on an NBS computer through which access to preliminary calculations can be obtained daily. Precision for the system is estimated at 10 ns for time and 1×10^{-14} (1σ) for frequency.

5.3 The Frequency Measurement Service

Frequency calibration requirements at the level of 1 part in 10^{11} to 1 part in 10^{12} can be satisfied using low frequency radio signals from broadcast stations such as WWVB or Loran-C [28]. This service involves the location at the user's site of a low frequency receiver and data logger system which monitors the user's oscillators. Automated interrogation of the user's system by NBS provides assurance that the oscillator frequencies are accurate.

5.4 Other Services

The Division publishes a monthly bulletin listing the current performance of a number of sources of accurate time and frequency signals as well as notice of changes in systems and accuracies which may affect a user. The Division also conducts an annual seminar intended for engineers, scientists and lab technicians involved in the application of time and frequency measurements.

5.6 Plans

The Division has just initiated a long-term program aimed at the development of methods for phase noise measurement into the millimeter portion of the radio spectrum. The goal of this program is to provide a consistent approach to accurate phase noise measurements in support of emerging requirements for hardware with tight specifications for this quantity. Plans do not call for a calibration service for phase noise, but, in the future, special tests will most likely be performed to provide assurance that agreement on measurements performed at different laboratories is adequate.

6. SUMMARY

The performances of a number of the services offered by the Time and Frequency Division are summarized in Figures 1 through 3 [29]. The first indicates uncertainty in frequency as a function of frequency and the latter two express uncertainty in frequency and time as a function of averaging time. While the Portable Clock Transfer shown in Figure 3 still represents the performance of that method, such transfer has for all practical purposes been replaced by the

GPS Common-View Method. The item labeled as Loran-C refers to the NBS Frequency Measurement Service (see section 5.3) which essentially involves common-view observation of Loran-C transmissions.

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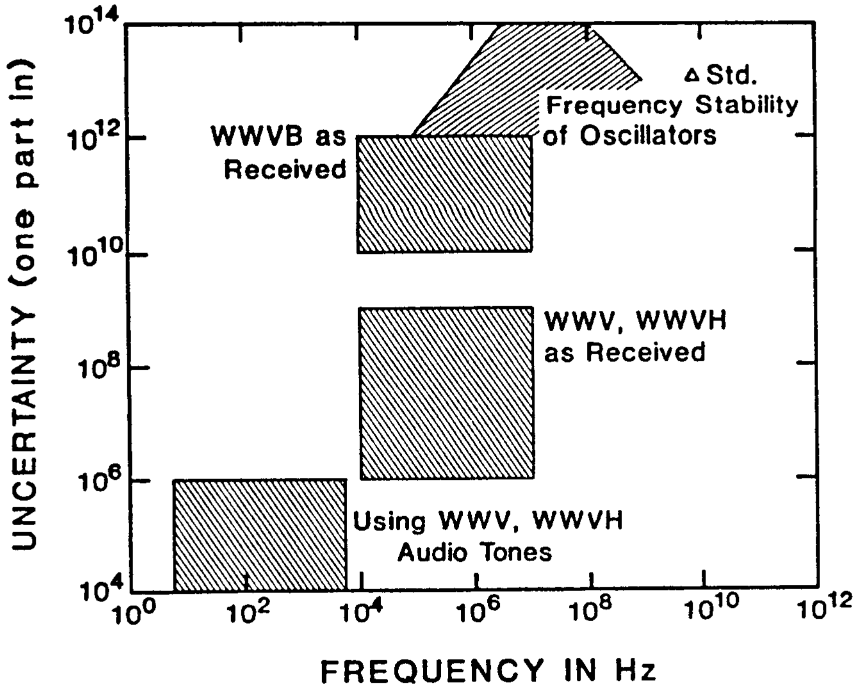

Fig. 1. NBS dissemination services for frequency.

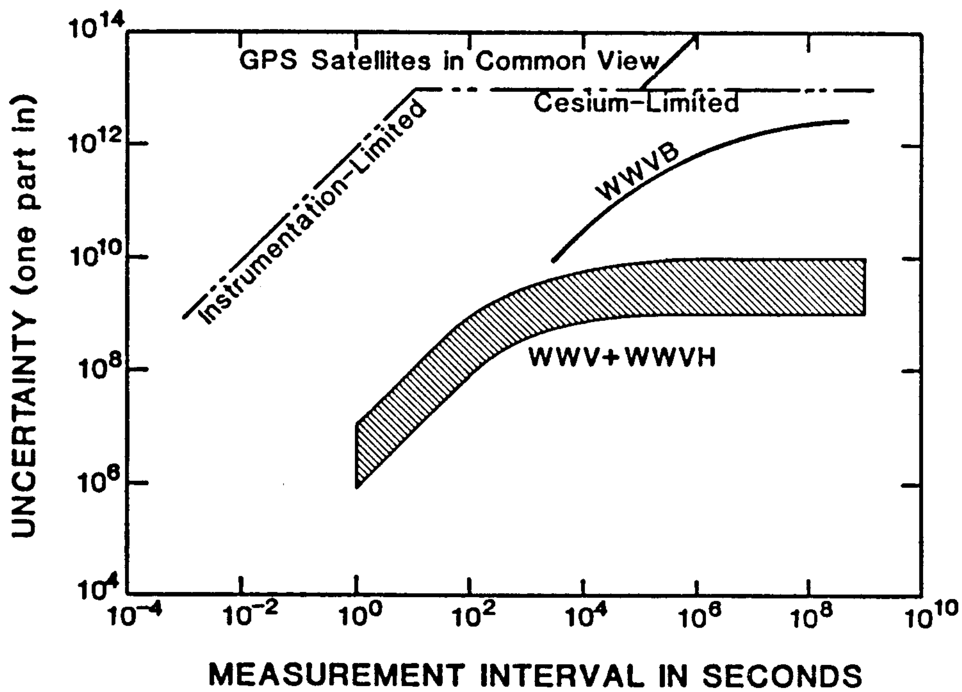

Fig. 2. NBS dissemination services for frequency, showing dependence of uncertainty on measurement interval. The broken line represents limitations common to all methods of dissemination.

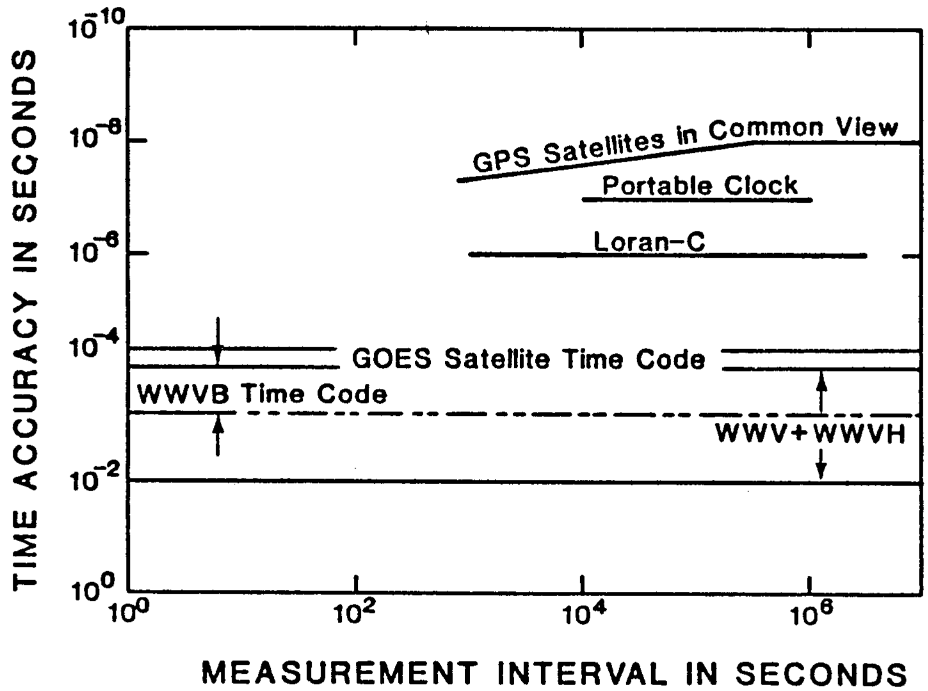

Fig. 3. NBS dissemination services for time.