PRESENT AND FUTURE FREQUENCY AND TIMING CAPABILITIES OF THE DEEP SPACE NETWORK

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PRESENT AND FUTURE FREQUENCY AND TIMING CAPABILITIES OF THE DEEP SPACE NETWORK

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Abstract.- The world-wide Deep Space Network (DSN), with facilities in the United States, Spain, and Australia, uses atomic frequency standards to generate stable frequency and timing signals to meet the telemetry and tracking requirements for space exploration missions. Outer planet navigation requires doppler accuracy of 30 micrometers per second, range accuracy of two meters, angle accuracy of a few nanoradians (using Very Long Baseline Interferometry (VLBI) techniques), and high reliability. These needs impose stability requirements on frequency standards of parts in 10^{14} over several hours and 10^{12} at one second. In addition, a low drift rate is necessary so as to minimize the number of measurements needed to maintain clock synchronization to 100 nanoseconds and frequency syntonization to 3×10^{-13} between the three complexes. The Jet Propulsion Laboratory (JPL), which operates the DSN for the National Aeronautics and Space Administration (NASA), uses ensembles of active hydrogen masers, cesium beam frequency standards, and high resolution clocks to achieve the required performance reliably. Time synchronization between complexes is currently achieved by the use of VLBI techniques, traveling clocks, and Loran-C. Use of the Global Positioning Satellites (GPS) is under active investigation as a less costly and more accurate alternative. This article covers the above requirements, equipment, techniques, and more stringent requirements of the 1990 time frame.

I. Introduction.- The United States NASA DSN is a world-wide ground station spacecraft tracking network. This network is the tracking and communication link with the spacecraft to study the other planets in this solar system. Some of these missions have been Voyager, Viking, Mariner series, Pioneer series, and Helios. The DSN consists of three complexes, each with three to four antennas. The complexes are located in Spain, Australia, and the United States.

The DSN uses frequency and time as the basic measuring elements for navigation of spacecraft and for the performance of VLBI, radio science, and space experiments. The precision needed to perform measurements imposes stringent timing requirements on the Frequency and Timing Subsystem (FTS) of the DSN. The present and future needs and capabilities of the FTS are described in this article, as well as performance data on the system components being installed. A system block diagram is presented (figure 1) to show the overall function of the FTS.

II. Background and History of the DSN Frequency Standards. - The DSN has used atomic oscillators as frequency references and clocks since the early 1960's. In 1961 cesium beam standards were used in a Venus radar experiment; in 1964 rubidium vapor standards, developed under contract to JPL, were in operational use; the first experimental hydrogen masers were used in the DSN in 1968; by 1975 the first hydrogen maser was operational in the DSN; by 1983 each station will operate with

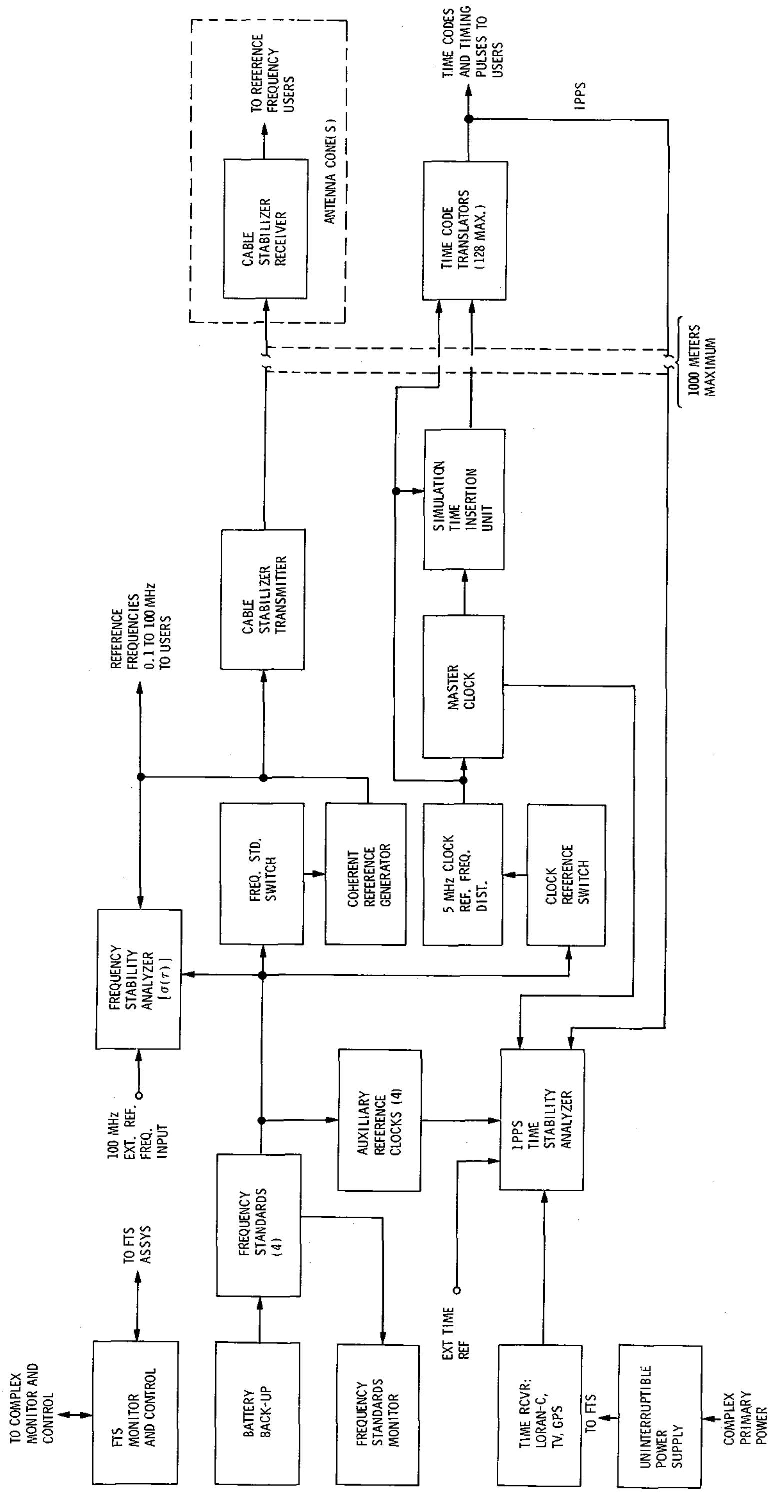

Figure 1. Frequency and Timing Subsystem (FTS) Block Diagram

two hydrogen masers and two cesium beam standards; the DSN of 1990 will incorporate even more advanced standards, possibly trapped ions, superconducting cavities, and hydrogen masers.

This evolutionary growth was a result of the needs of the various missions and the increasing sophistication of the navigation and the experiments as the spacecraft flights moved from the moon to Venus, Mars, and the outer planets.

III. Needs and Capabilities of the DSN (1981-1986).- Performance requirements of the DSN FTS are shown in Tables I and II. These are the most stringent requirements from all missions in this time period. In addition, the FTS must meet other requirements, as follows:

1) Generation and distribution of the reference frequencies needed in a station.

2) Generation and distribution of the various time codes and timing pulses needed in a station.

3) Synchronization of the three complexes within the DSN to 50 microseconds with knowledge of time within 10 microseconds and between the master clock bank at Goldstone and the National Bureau of Standards (NBS) to 50 microseconds with knowledge of time to within 5 microseconds.

4) Syntonization of the three complexes to 3×10^{-13}.

5) Monitor and control of the FTS through each station's master control computer to ensure proper operation and to change configuration as necessary.

6) Operational requirements on reliability, availability, maintainability, training, and sparing.

Figure 1 shows a block diagram of the FTS designed to meet the above requirements.

Frequency Standards.- Figure 2 shows the Allan variance performance requirements for stability, as well as the performance of typical hydrogen masers as measured over the last three years. In order to achieve this performance, the hydrogen masers must be housed in an isolated, temperature-controlled room with 0.05°C variation in temperature. The measured performance upturn at 10^3 seconds, as shown in figure 2, is believed to be caused partly by aging and partly by environmental effects. The new masers being built for the DSN have design improvements to reduce the aging effects. They will be tested in the Interim Frequency Standard Test Facility (IFSTF) at JPL to determine if the design goal of 2-3 times improvement over the present 1×10^{-14}/day typical aging rate has been obtained. A set of two hydrogen masers (one prime, the other a backup) and two backup cesium beam standards will be used at each complex to achieve the required reliability and allow continuous monitoring of frequency stability. The requirements on the secondary standards are not as stringent as they are on the prime standard. Figure 3 shows the requirement with typical performance of the cesium beam standards. These standards readily meet the requirement.

Reference Frequency Distribution. - The existing frequency synthesis and distribution equipment will be expanded from 155 to 210 output ports to support additional users. Seven 100-MHz reference frequency output ports will be added to improve the stability of the receiver and transmitter.

An active cable compensator will be used to distribute reference frequencies to the antenna area for VLBI measurements, with equipment propagation delay known

Table 1

FREQUENCY STANDARD REQUIREMENTS

1981-1986

Allan Variance

Sampling Time	Primary Standard	Secondary Standard
1 second	1×10^{-12}	1×10^{-11}
10^4 seconds	1×10^{-14}	3×10^{-13}
12 hours	1×10^{-14}	3×10^{-13}
10 days	1×10^{-13}	3×10^{-13}

Power Spectral Density of Phase: BW = 1 Hz ± 10 Hz

Reference Distribution Frequency	Primary Standard	Secondary Standard
5 MHz	Better than -116 dB	Better than -110 dB
10 MHz	Better than -110 dB	Better than -104 dB
50 MHz	Better than -96 dB	Better than -90 dB
100 MHz	Better than -90 dB	Better than -84 dB

Table II

TIMING REQUIREMENTS

1981-1986

Timing Pulses

Rate	1, 10, 100, 1000 PPS
Jitter(1)	10 ns RMS (1σ)
Risetime	15 ns
Settability	100 ns steps

(1) 2 ns RMS (1σ) for selected users

Time Codes

36-bit binary (ms of day, day of year)
30-bit BCD(2) (sec of day, day of year)
46-bit binary(3) (μsec of ms, ms of day, day of year)

(2) Existing users only.
(3) Selected users only.

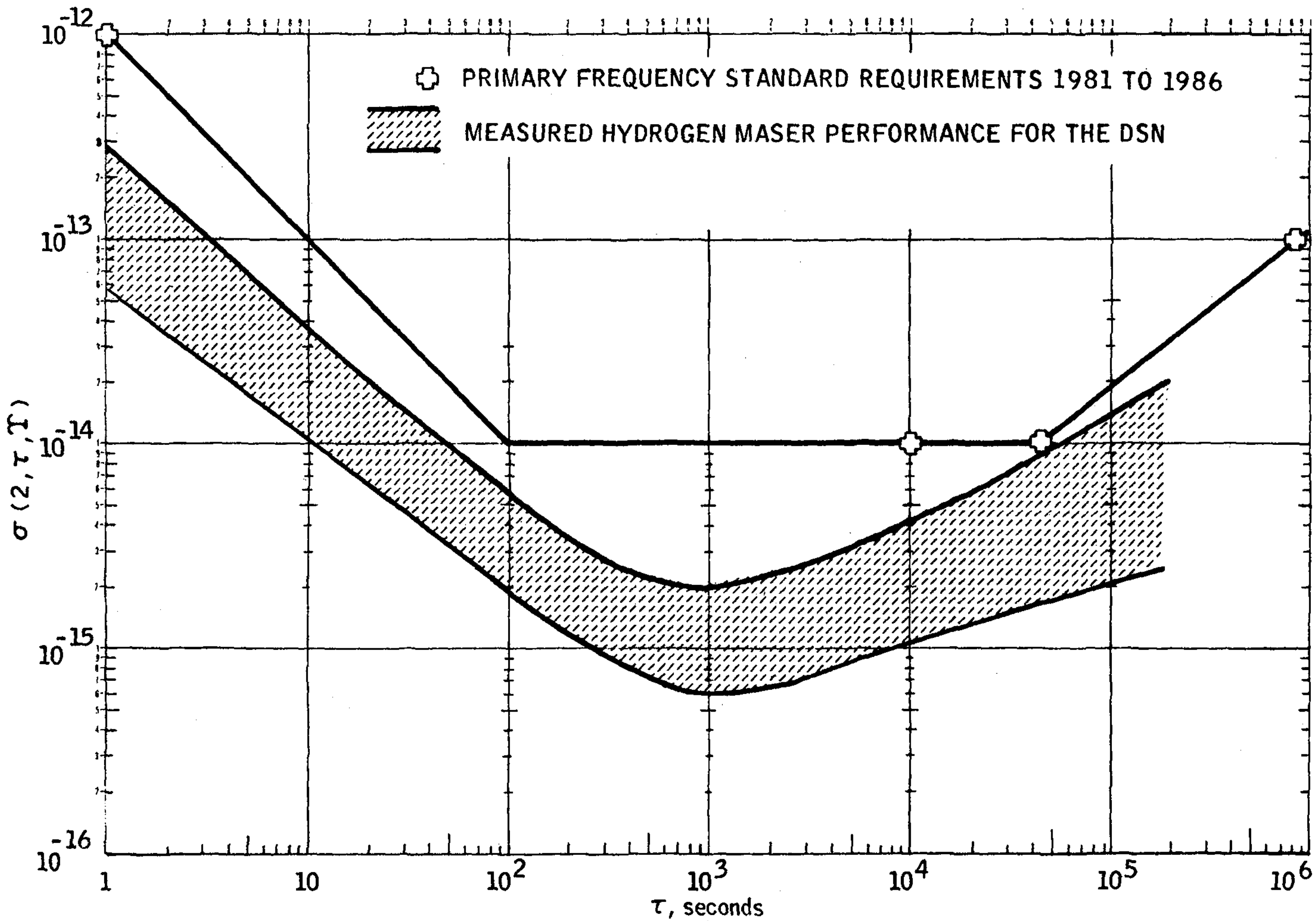

Figure 2. Allan Variance Requirements Compared to Actual Performance

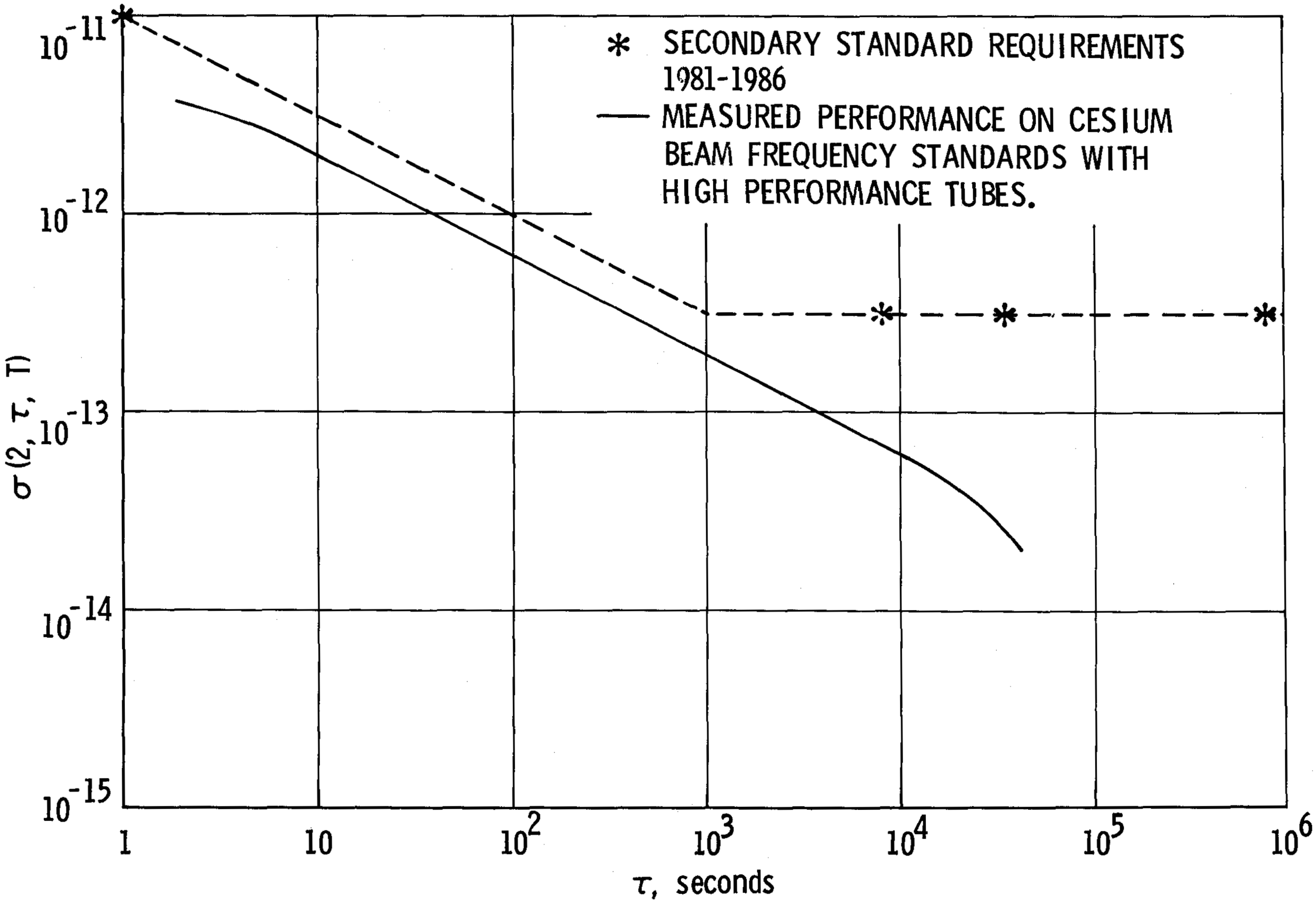

Figure 3. Secondary Standard Stability Requirements Compared to Actual Performance

to less than 1 nanosecond and phase stability of less then 1.1 picoseconds (for root-mean-square (RMS) sampling times less than 10 seconds).

Time and Timing Distribution.- The exising digital clock will be replaced with a master clock with majority voting of all time codes and timing pulses generated by the three time code generators to meet the performance requirements of Table II and provide high reliability.

A modified IRIG-G(1) time code will be supplied to each serial-to-parallel time code translator which internally generates a time code from an external 5-MHz reference. This time code is synchronized to the incoming modified IRIG-G time code. The required output time codes and pulse trains are generated synchronously with the IRIG-G code to give day of year in milliseconds. The propagation delay to each of the 128 translators at each site can be adjusted to within 100 nanoseconds of epoch at distances up to 1000 meters from the master clock. This distance is sufficient to reach each of the co-located antennas at all three complexes.

Each complex requires simulation time (a time offset up to one year from UTC, Universal Time, Coordinated) for training and diagnostic purposes. This will be provided by addressing the appropriate set of translators to read simulation time while the balance of the complex will remain on real time (UTC) for multiple mission capability.

Time Synchronization.- A bank of seven cesium beam frequency standards is maintained at the Goldstone complex for both time synchronization and frequency syntonization. A cesium beam traveling clock is transported from Goldstone to the United States NBS for the time synchronization at 60-day intervals. Time synchronization between the three global complexes is performed by traveling cesium beam clocks from the United States Naval Observatory (USNO) and by VLBI, with daily checks performed using Loran-C in Spain and the "TV Mutual Look"(2) in Australia with the Division of National Mapping. The accuracy of these techniques for time synchronization is more than adequate to meet the DSN requirements.

Frequency Syntonization.- The present method of frequency syntonization uses VLBI time synchronization at weekly intervals. The resolution of these measurements is 30 to 40 nanoseconds so that the syntonization is readily achieved at the 1×10^{-13} level. In the near future the DSN plans to use time synchronization receivers at the three complexes and at NBS that utilize the Global Positioning Satellites. Preliminary tests conducted by NBS for the DSN indicate that 10- to 100-nanosecond time synchronization is achievable, allowing both time synchronization and frequency syntonization requirements to be met more accurately, economically, and reliably than by the use of VLBI.

IV. Needs and Capabilities of the DSN (1986-1990) Frequency Standards.- Further missions to the outer planets are planned which will require better navigation and measurement capability in the DSN. Experiments on gravity waves and relativity are

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(1) IRIG-G definition: the format for serial time code to the nearest 10 milliseconds defined by the Interrange Instrumentation Group now renamed as the Range Commanders Council.

(2) This method is used to determine the time difference of two clocks by simultaneously measuring the time of arrival of television vertical synchronization pulses at each clock and correcting the received data for propagation delays from the source to each user.

also planned. Based on these plans, the mission requirements on the frequency standards in the DSN for an Allan variance of 3×10^{-16} from 100 seconds to 30 days with a goal of 1×10^{-17} from 100 seconds to 25,000 seconds. Figure 4 shows the typical performance of today's active hydrogen masers tested at the JPL IFSTF and the required future frequency stability performance. It is evident that frequency standards will be required that are not available today. JPL is developing equipment and supporting work in several areas to meet these requirements. Cryogenic active hydrogen masers may meet this requirement in the short-term stability region (e.g., to 10,000 seconds) and possibly at longer averaging times on the order of days. Feasibility of this approach has not been demonstrated and other methods may be necessary to satisfy the requirements. Superconducting cavities may be necessary to achieve the short-term performance goal. Continuous hydrogen maser cavity tuning to the hydrogen line frequency may reduce the long-term drift. Trapped ion frequency standards may satisfy the requirement for long averaging times. A combination of several of the above types which are phase locked together, making an ensemble, may be necessary. All the above are being actively pursued at JPL or elsewhere under JPL support.

Time Synchronization.- The 1986-1990 time synchronization requirement is that the three complex clocks be less than 10 nanoseconds apart in real time. Two basic problems exist with meeting this requirement; first is the aging of hydrogen masers, second is the lack of suitable equipment for time transfer between intercontinental sites.

Assuming that the aging rate and direction at all three sites are not the same, the clocks would require synchronization every several days. Atomic frequency standard long-term frequency stability and aging must be improved to meet this requirement.

The GPS receiver mentioned above may be capable of satisfying this requirement based upon preliminary data. Another possibility is the use of the NASA Space Shuttle with an on-board hydrogen maser housed in a proper environment. Using two-way ranging separately between each complex and the Space Shuttle may be an interesting solution to time synchronization. This concept has been proposed jointly by Marshall Space Flight Center and Smithsonian Institute Astrophysical Observatory but has yet to be approved as an experiment.

Phase Coherence.- A further requirement is for phase coherence and timing continuity when frequency standards are switched from the prime unit to a backup unit. Since no two frequency standards are frequency or phase coherent, equipment is being designed to correct the phase of each backup frequency standard to provide a continuous zero degree relative phase angle between standards at the frequency standard selector switch.

All frequency and time distribution systems within the DSN will also have to be improved by several orders of magnitude to support these future requirements to the users who are critically dependent on this performance.

Summary.- The present FTS in the DSN is being upgraded for the 1981-1986 time frame to include two hydrogen maser frequency standards to meet the frequency stability requirements of 1×10^{-14}, syntonization requirements of 3×10^{-13} within the DSN, and clock synchronization to within 100 nanoseconds. Redundant clocks and programmable time code translators, as well as multiple frequency distribution equipment are part of this system.

Work has begun on meeting the more stringent requirements of 3×10^{-16} frequency stability and less than 10-nanosecond time synchronization by 1990, as well as improved distribution and self monitoring.

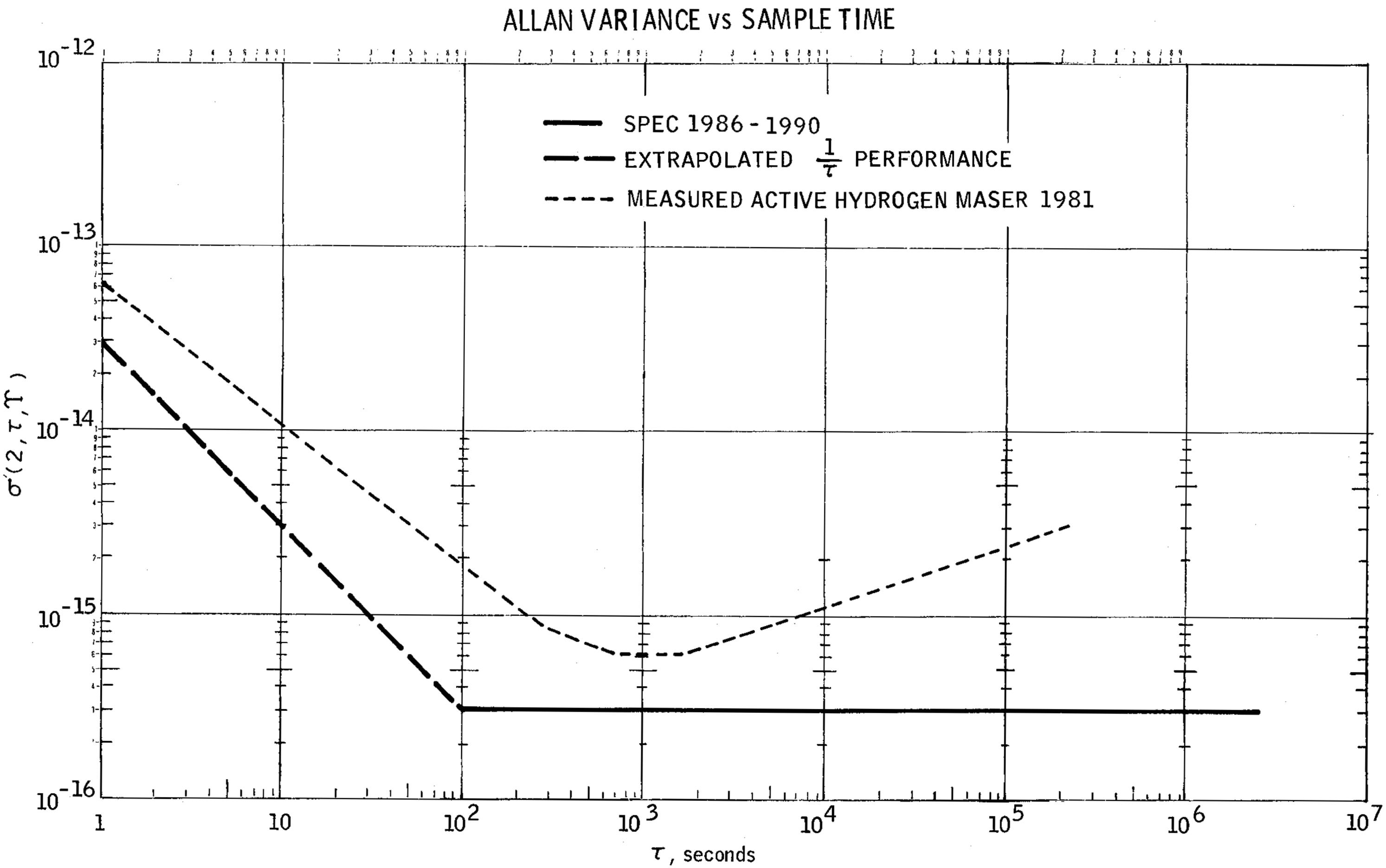

Figure 4. Allan Variance Requirements, 1986 To 1990