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STATUS OF FREQUENCY AND TIME SUPPORT FOR NASA SYSTEMS

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Abstract

The National Aeronautics and Space Administration (NASA) has Frequency and Timing Systems at many Facilities and Centers. This paper covers timing systems with specifications tighter than several microseconds. These ground based systems support scientific experiments and spacecraft tracking for the following programs: NASA Satellite Laser Ranging (NSLR); Network Mission Operations Support (NMOS); Kennedy Space Center (KSC); Very Long Baseline Interferometry (VLBI); Tracking Data Relay Satellite System (TDRSS) Ground Terminal Network, and the Deep Space Network (DSN).

Major equipment assemblies, specifications, performance and requirements, both present and future, will be presented.

INTRODUCTION

This paper describes six NASA ground based timing systems currently in use, the purpose of each timing system, and the program supported. The major equipment; frequency standards, clocks, and time synchronization receivers are included. Related specifications and performance are listed. Some of these specifications and performance characteristics are presented in graphical form.

NASA SATELLITE LASER RANGING NETWORK

The NASA Satellite Laser Ranging Network (NLSR) is a global network of both fixed and mobile laser ranging systems that measures the range to many satellites. These satellites are TOPEX, ERS-1, STELLA, LAEGOS I and II, STRAELLE, AJISAI and ETALON I and II. Another important function of the NSLR provides precise orbit determination of the operational satellites.

The centimeter accuracy of modern satellite ranging systems allow better estimates of the Earth's internal mass distribution, and global geodesy with accuracys of a few centimeters over continental distances.

Satellite laser ranging stations are located globally in over twenty countries and on every continent except Antarctica. The NASA network consists of four fixed stations and four transportable vans. The vans are moved approximately every six months to another field site.

The accuracy of laser ranging is critically dependent on the proper operation of highly stable reference oscillators in each NSLR station. The timing system at each station is driven by a Hewlett Packard "Standard Tube" Cesium Beam Frequency Standard that provides the time base frequency for the Ranging Time Interval Counter. To correlate the ranging measurements performed at different stations, ranging data at each location is synchronized with reference to UTC (USNO) to within less than one microsecond using GPS timing receivers. Performance specifications for frequency are those of a "Standard Tube" Cesium Beam Frequency Standard. This performance for Allan Deviation and Phase Noise is shown in Figures 1 and 2. The typical Laser Ranging System timing block diagram is shown in Figure 3.

The station time position data, time steps and other pertinent timing information are transmitted daily to the AlliedSignal Technical Services Corporation (ATSC) VAX computer system through the NSLR communication network. The data is reviewed and analyzed using an automated time position program that performs a least squares analysis and subsequently produces time position information for the stations. The results of the timing data analysis are reported to the Data Operations Group for inclusion in laser data analysis and the data base. This post processing of the time synchronization data resolves the offset to ≈ 0.5 microseconds.

NETWORK MISSION OPERATIONS SUPPORT

The Network Mission Operations Support (NMOS) provides pre–launch, launch support, and range safety for the Space Shuttle and other NASA spacecraft. The network also provides tracking and collection of data from low orbiting satellites. These timing systems are located at the Merritt Island Launch Area (MILA), Bermuda Island, Wallops Island, and Dakar, Africa.

The frequency standards at these stations are two Hewlett Packard model 5061A "Standard Tube" Cesium Beam Frequency Standards. The NMOS Frequency stability specifications are the same as for the frequency standard. This performance for Allan Deviation and Phase Noise are shown in Figures 1 and 2. The clocks at MILA, Bermuda, and Wallops are TRAK Systems model 8407–3 triple redundant with majority voting capability. The block diagram of these triple redundant clocks are shown in Figure 4. The time offset specification is less than 5 microseconds versus UTC (USNO).

Time synchronization is accomplished by using GPS or LORAN–C; depending on the location. MILA, Bermuda, and Wallops use LORAN–C as the reference source.

KENNEDY SPACE CENTER

The NASA Kennedy Space Center (KSC) also provides the pre–launch and launch support for the Space Shuttle and other NASA missions. This launch center has a centralized timing system, which consists of two separate clock systems. One clock is dedicated for support of the launch pads and the second is for support to the KSC industrial users.

Both of these timing systems are quite similar. The launch pad support timing system is a triple redundant clock each driven by a separate frequency source. One frequency source is a Frequency and Time Systems model 4065 Cesium Beam Frequency Standard. The second source is an Austron model 2100 LORAN–C timing receiver steering an external Austron model 2010B Crystal Oscillator Disciplined Frequency Standard. The third source is an Odetics model 325–868 GPS receiver also steering an internal crystal oscillator disciplined frequency standard. The 1 PPS from the three clocks (Odetics model 300–601) are intercompared by monitoring equipment (Odetics model 450). The resultant best clock of the three in the triple redundant set is the centralized complex on-line clock. This timing is then distributed to the KSC launch pads and industrial users.

Eastern Test Range timing (ETR) is available to this timing system through an ETR receiver and time code generator. This Kennedy Space Center Central Timing System is shown in Figure 5.

The time codes available for distribution are the IRIG serial codes D through G and NASA 36 Bit. Reference frequencies available are 5 MHz and data clock frequencies of 1.544 and 2.048 MHz.

The requirements for time synchronization are one microsecond maximum offset versus UTC at the centralized triple redundant clock. There is no requirement for propagation delay correction for timing distribution to the launch pads. The maximum time offset (propagation delay) from the central clock to the launch pads is less than one millisecond.

The performance specifications for the Industrial Users are the same.

VERY LONG BASELINE INTERFEROMETRY

NASA in coordination with the National Oceanic and Atmospheric Administration (NOAA), USNO, and agencies of several foreign countries conduct Very Long Baseline Interferometry (VLBI) experiments to determine time – varying geodetic baseline vectors for a variety of uses in the earth sciences. These Space Geodesy Program measurements result in the measured location of Tectonic Plates and associated plate motion.

Space Geodesy Stations are currently located in: Maryland, Massachusetts, Alaska, Hawaii, Canada (two locations), Chile, Brazil, Tasmania, and Norway.

The local oscillator at each of these sites is a model NR Hydrogen Maser Frequency Standard which was engineered and manufactured by Goddard Space Flight Center and the Johns Hopkins University Applied Physics Laboratory. All of these hydrogen masers are maintained and serviced by AlliedSignal Technical Services based in Columbia, Maryland. The 1 PPS clock output of the NR Hydrogen Maser is used to synchronize the clock in the VLBI Formatter assembly.

The required Allan Deviation performance is 2 to 3×10^{-15} at sampling times of 1000 seconds. The 1000 second sampling time is considered a representative period for geodetic VLBI. The NR Hydrogen Maser meets this requirement. Time offset versus UTC is maintained at less than $\approx$ 13 microseconds versus UTC (USNO) to facilitate VLBI data correlation during post processing. Frequency offset of the Hydrogen Maser is specified and maintained to less than 5×10^{-13} versus UTC.

The Global Positioning System (GPS) is used for time synchronization at the VLBI sites.

TRACKING DATA RELAY SATELLITE GROUND TERMINAL NETWORK

At present, there is one NASA Ground Terminal (NGT) located at White Sands, New Mexico. This ground terminal supports the NASA Tracking Data Relay Satellite System (TDRSS). A Second Tracking Ground Terminal (STGT) is currently under construction and is planned to be operational during the Fall of 1994.

Goddard Space Flight Center (GSFC) supplied the NGT timing system in 1979. This consists of two Hewlett Packard model 5061A–004 High Performance Cesium Beam Frequency Standards. Automatic non–dropout frequency switch equipment is provided. The clock is a TRAK Systems model 8407-1 triple redundant unit with majority vote/fault sense circuitry and distribution of multiple serial and parallel time codes as shown in Figure 4. GPS time synchronization receivers are used to measure time offset versus UTC.

The TDRSS Ground Support Program is currently adding the Second Tracking Terminal (STGT) approximately 16 kilometers from the existing NASA Ground Terminal (NGT). The STGT is currently scheduled to be operational during late 1994. The STGT frequency standards will be two Hewlett Packard model 5061B Cesium Beam Frequency Standards with high performance Cesium tubes. One Disciplined Crystal Oscillator Frequency Standard will be connected to each of the Cesium Beam Frequency Standards to reduce the close to the carrier phase noise. The clock will be a dual redundant unit.

In 1995, the NGT is planned to be upgraded including a new timing system. This replacement system is to include a new dual redundant clock. The frequency standards are planned to be Hewlett Packard model 5071 High Performance Cesium Beam Frequency Standards each driving a disciplined crystal oscillator to improve the phase noise performance. The frequency stability performance (Allan Deviation) is to be the same as the frequency standard.

NGT and STGT clock time offset requirements and performance versus UTC are one microsecond maximum. This is determined by measuring the station clock versus UTC using GPS receivers.

DEEP SPACE NETWORK

The Jet Propulsion Laboratory (JPL) controls the Deep Space Network (DSN) for NASA. This includes management, engineering and operation. The three complexes are located at Goldstone, California; Robledo, Spain; and Canberra, Australia. The DSN has provided support for all the Deep Space probes to the other planets, (*e.g.*: Magellan mapping of Venus and Galileo en route to Jupiter). Recently the DSN has been assigned the additional responsibility for the earth orbiting station at each of the three complexes.

The Frequency and Timing Subsystem (FTS) at each complex provides support for all missions. Some of the specialized operations are VLBI, Radio Science, Planet Mapping and photographs for all deep space missions.

The Signal Processing Center (SPC) at each complex has two Hydrogen Masers and two Cesium Beam Frequency Standards. One of the Hydrogen Masers is the prime, or on line standard, with the other acting as an operating spare. The clock is a TRAK model 8407–2 triple redundant unit with majority voting circuitry. The basic block diagram of this clock has been shown in Figure 4. The timing distribution to the local and remote users is via coaxial cables within the SPC and fiber optic cables between the SPC and each antenna. Each user is issued a Time Code Translator (TCT) which is really a Synchronized Time Code Generator that is driven by 5 MHz and synchronized by the master clock distribution equipment. Adjustable circuitry in each TCT reduces the propagation delay at the users interface to less than 50 nanoseconds offset versus the complex master clock. The block diagram of this complex frequency and timing system is shown in Figure 6.

Some reference frequency and timing users are located at the antennas which are remotely located from the SPC by 300 meters to 20 kilometers. For most of these antennas, it is necessary to meet the required Allan Deviation and Phase Noise specifications of the Hydrogen Maser. The requirements and actual measured performance is shown in Figures 7 and 8. The timing offset between Goldstone, the National Institute of Standards and Technology (NIST), and the two complexes in Spain and Australia is 3 microseconds (3 sigma) maximum. Knowledge of this offset, or measurement error, must be less than 50 nanoseconds. Frequency offset (syntonization) must be less than 6×10^{-13} (3 sigma) between complexes. Knowledge of this offset must be less than 3×10^{-13}. In order to guarantee this performance, the measurement must be considerably better.

To guarantee the time synchronization requirement, GPS receivers are utilized. This is accomplished by using the Common View technique and the current BIPM schedule. Data is collected twice weekly from the site receivers, reduced and published. It is estimated that the worst case frequency and timing measurement error is approximately 1×10^{-14} and 30 nanoseconds between Goldstone and Australia. Two Way Time Transfer is not in use by the DSN today because there is no Ku band commercial satellite link between the United States and Australia.

The Deep Space Network (DSN) has plans in progress to both expand and improve the Frequency and Timing Subsystem (FTS). This includes the addition of three 34 Meter Beam Wave Guide (BWG) antennas at Goldstone and one in Canberra. In addition there will be one 11 meter antenna installed at each of the three international complex sites to support the Orbiting Very Long Baseline Interferometry (OVLBI) program.

Frequency and timing distribution is required for each of these new antennas at these remote locations which are mostly 16 to 25 kilometers from the frequency standards and master clock in the complex signal processing center. Two of the 34 meter BWG antennas at Goldstone and one at Canberra will be provided with 100 MHz reference frequency distribution that does not degrade the Hydrogen Maser Allan Deviation and phase noise performance. The timing offset will be less than 50 nanoseconds with respect to the complex master clock. This distribution will be via single mode fiber optic cables buried five feet underground in order to greatly attenuate the diurnal temperature deviations and the resultant 100 MHz phase shift fluctuations[1].

For the DSN, JPL is currently developing new frequency standards for use in the future. These are the Linear Trapped Mercury Ion Frequency Standard (TIS) and the Superconducting Cavity Maser Oscillator (SCMO) currently being developed under the NASA Advanced Systems Program at JPL. The performance of the two Trapped Ion research and development units is approaching the short and medium term performance of the existing Hydrogen Masers and the long term performance (Tau greater than 10,000 seconds) is better than the Hydrogen Maser[2]. FTS engineering is currently discussing building four of these for implementation in the DSN over the next five years. The SCMO short term Allan Deviation and Phase Noise performance have been measured and are much better than anything available today[3]. A combined frequency standard combination of TIS and SCMO would produce short term and long term Allan Deviation and Phase Noise performance better than the Hydrogen Maser[4]. The TIS will reduce the clock drift with respect to UTC, thereby reducing the number of frequency adjustments per year from 2–3 to less than one. The Cassini mission to Saturn ground support FTS performance requirements today are barely met using Hydrogen Masers. We expect these to become tighter in the future and expect to need the combined TIS and SCMO frequency sources.

SUMMARY

Four of the above timing systems use Cesium Beam Frequency Standards and two use Hydrogen Maser Frequency Standards. Both meet the requirements for the particular project. Three of the six systems use triple redundant clocks, all with majority voting capability. GPS and LORAN–C are the two time synchronization methods. LORAN–C is utilized at three locations, which are within ground wave range of a local LORAN–C station. The GPS common view method is required for one global long baseline system with a 50 nanosecond timing and 3×10^{-13} frequency knowledge specification. The balance use GPS satellite time thus meeting the performance requirements.

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REFERENCES

[1] Malcolm Calhoun and Paul Kuhnle, *"Ultrastable Reference Frequency Distribution Utilizing a Fiber Optic Link"*, Proceedings 24th Annual Precise Time and Time Interval Applications and Planning Meeting, December 1992.

[2] R. L. Tjoelker, J. D. Prestage, G. J. Dick, L. Maleki, *"Long Term Stability* Hg^+ *Trapped Ion Frequency Standards"*, 1993 IEEE International Frequency Control Symposium.

[3] G. John Dick and Rabi T. Wang, *"Ultra-Stable Performance of the Superconducting Cavity Maser"*, IEEE Transactions on Instrumentation and Measurement. Vol. 40. No. 2. April 1991.

[4] J. D. Prestage, R. L. Tjoelker, R. T. Wang, G. J. Dick, L. Maleki, *"* Hg^+ *Trapped Ion Standard Performance with the Superconducting Cavity Maser as L. O."*, 1992 Frequency Control Symposium.

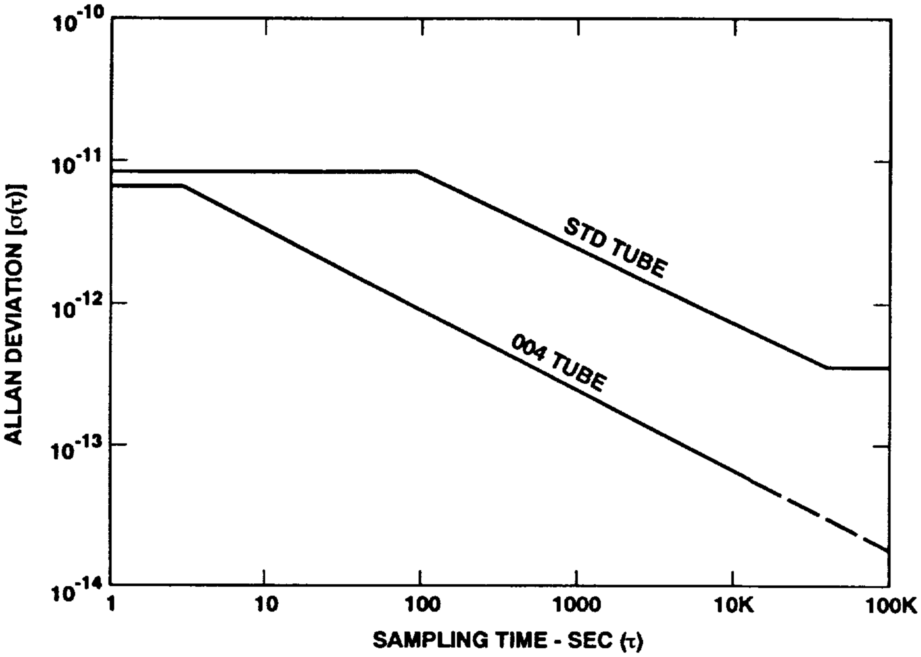

Figure 1. Allan Deviation HP 5061 Cesium Beam Frequency Standard

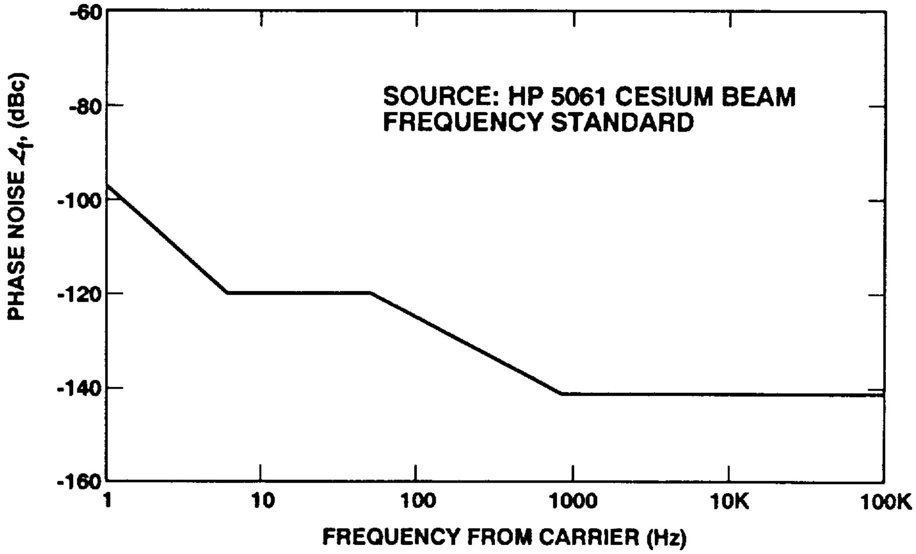

Figure 2. Single Sideband Phase Noise in a 1 Hz Bandwidth at 5 MHz

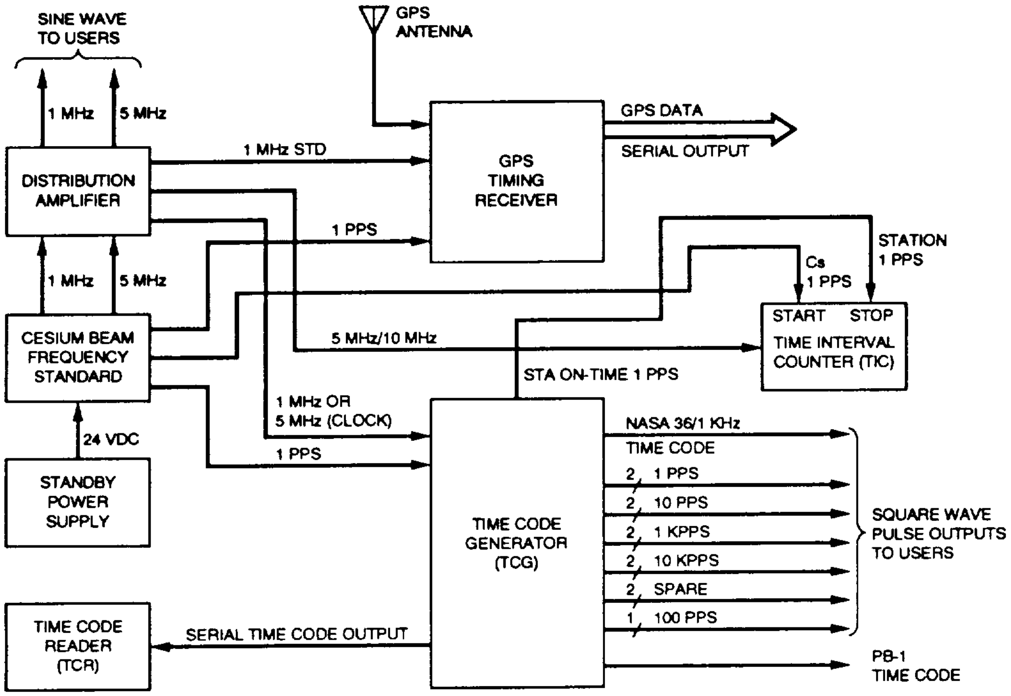

Figure 3. NSLR Timing Equipment

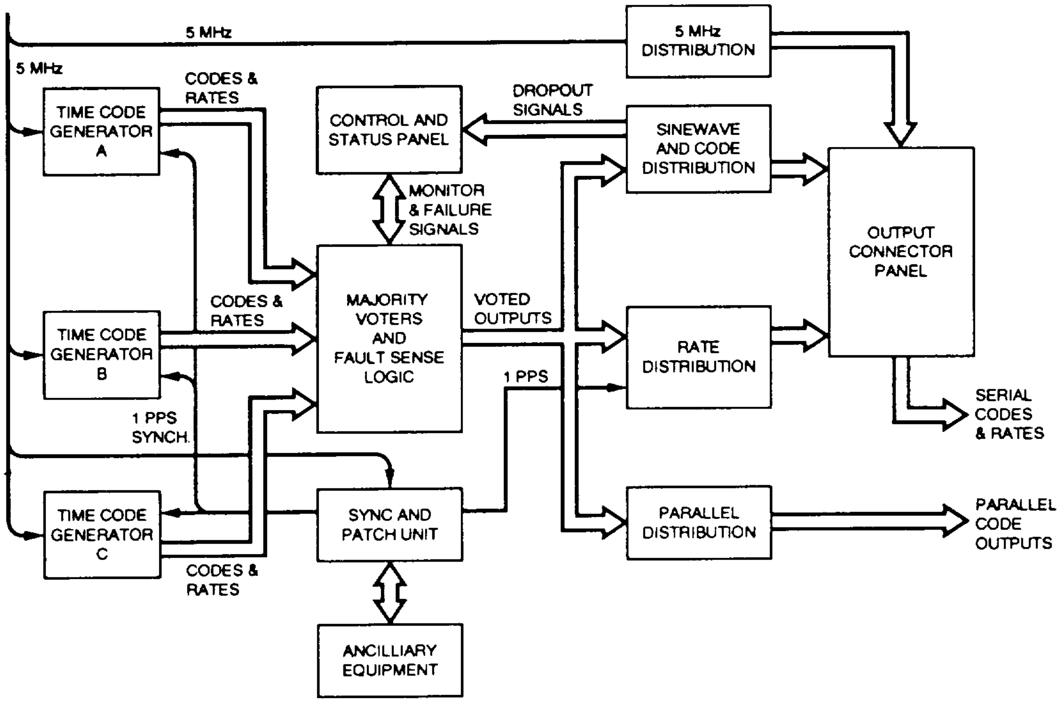

Figure 4. TRAK 8407 Triple Redundant Clock

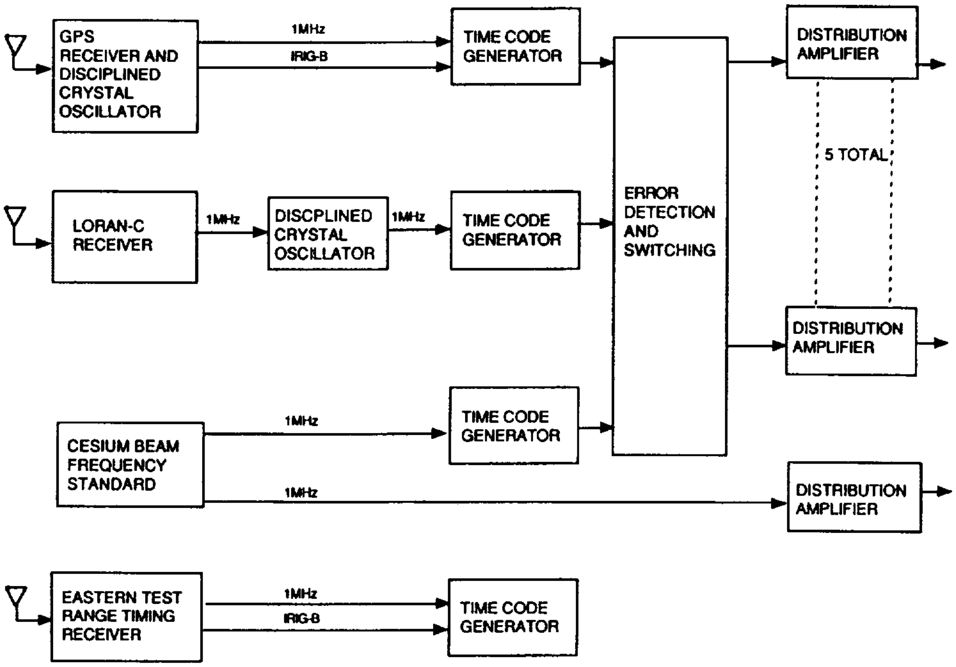

Figure 5. Kennedy Space Center Central Timing System

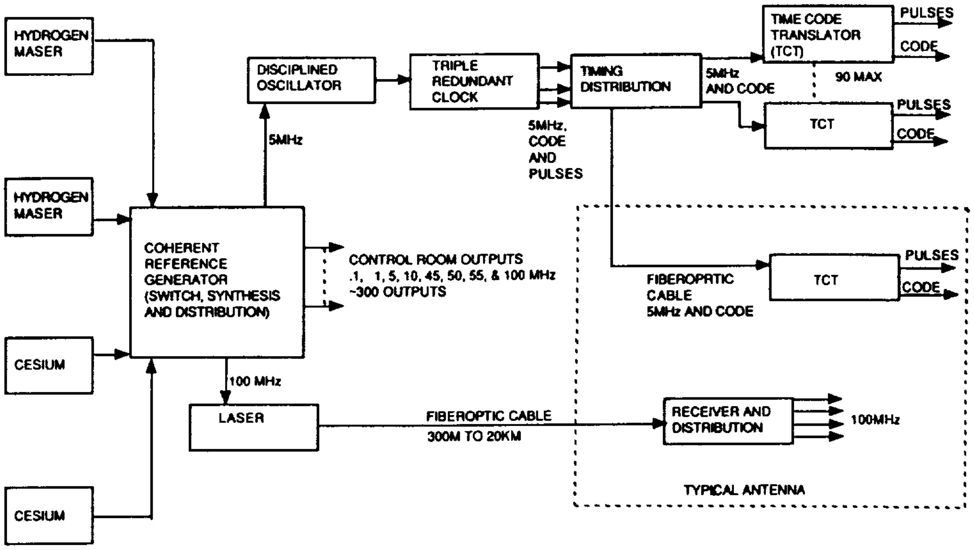

Figure 6. Deep Space Network Complex Frequency and Timing

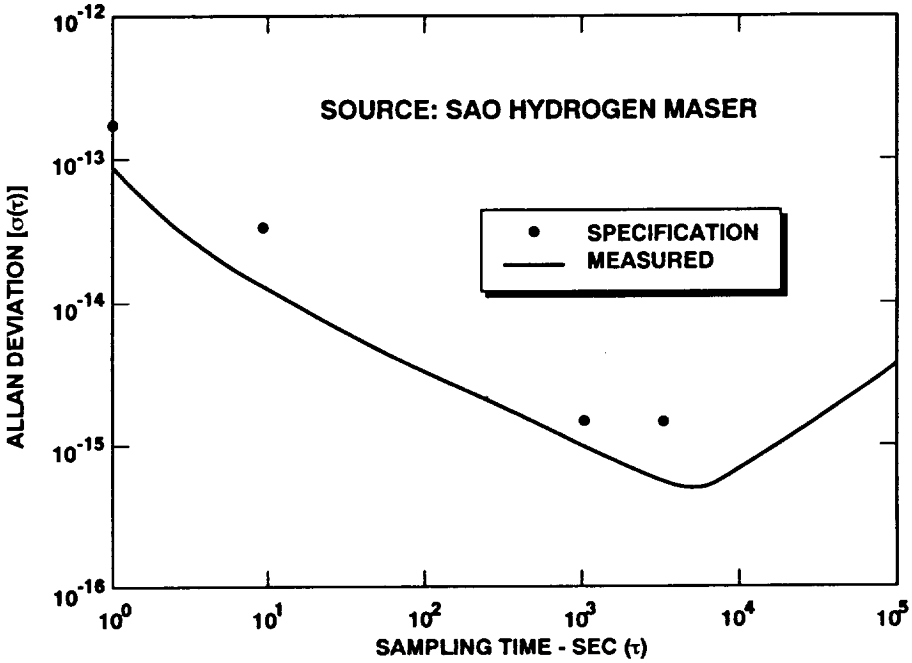

Figure 7. Allan Deviation at the Antenna

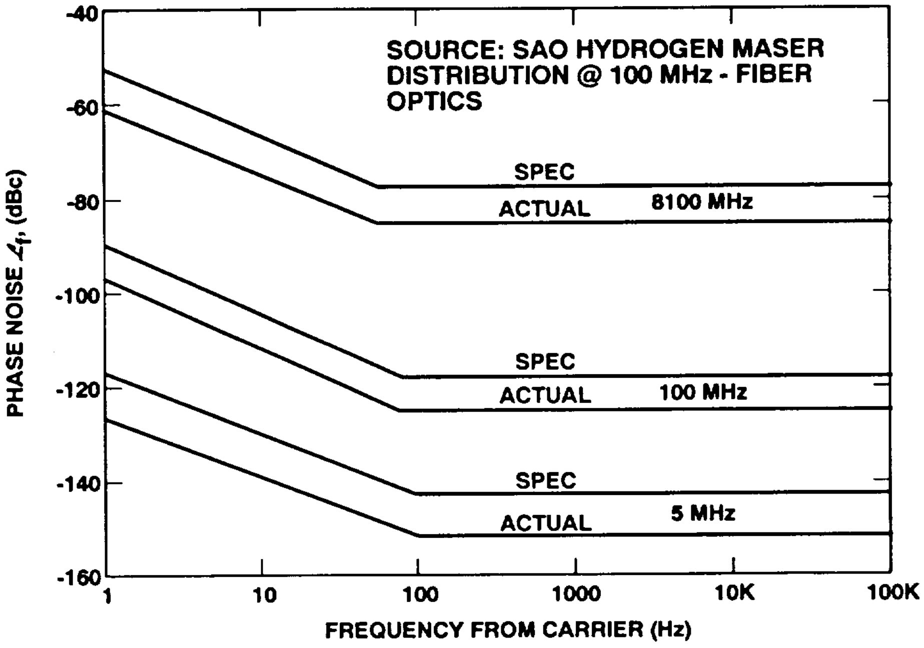

Figure 8. Single Sideband Phase Noise at the Antenna