810-005

DSN Telecommunications Link
Design Handbook

304, Rev. A
Frequency and Timing

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Change Log

Rev	Issue Date	Paragraphs Affected	Change Summary
–	3/1/2004	All	New Module
A	9/30/2010	All	Replaced DSMS with DSN. Eliminated the Rev. E designation for the document series. Deleted references to the decommissioned 26 m station, DSS 16. Updated performance information to match current capabilities.

Note to Readers

The 810-005 document series has been structured so that each document module can be independently revised without affecting others in the series. Hence, the Revision E previously designated at the 810-005 level has become unnecessary. This module is one of the many in the 810-005 series; each may be published or changed, starting as an initial issue that has no revision letter. When a module is updated, a change letter is appended to the module number in the header and a summary of the changes is entered in the module's change log.

Contents

Illustrations

Tables

1 Introduction

1.1 Purpose

This module provides information to assist Deep Space Network (DSN) customers in understanding the limits placed on navigation, quality of science observations, and telecommunications performance by the Frequency and Timing Subsystem (FTS) equipment installed in the DSN.

1.2 Scope

The discussion in this module is limited to the accuracies and stabilities of frequency and time within the DSN including the effects of implementations that are unique to each site. The module deals primarily with general system information of the operational DSN FTS capability. Performance information that pertains only to specific users, such as performance for the radio science community, may be found in the modules for these topics. A brief discussion of proposed enhancements is included at the end of the module.

2 General Information

Figure 1 provides an overview of Frequency and Timing in the DSN. The three Deep Space Communications Complexes (DSCCs) have at least four atomic frequency standards (AFSs) while other sites, with the exception of MIL 71, have one or two. MIL 71 receives its frequency and time references from the Ground Spaceflight Tracking and Data Network (GSTDN) station operated by the Goddard Space Flight Center (GSFC) and co-located at the site.

At each major location, a single atomic frequency standard serves as the source for all coherent, precision frequencies and provides the reference for the station master clock. The other AFSs serve as backups should the selected reference fail or indicate instability. Each station synchronizes its clock to the National Institute of Standards and Technology (NIST) realization of Coordinated Universal Time (UTC), referred to as UTC (NIST), via the Global Positioning System (GPS). Time offset data measured at the DSCCs are forwarded to the DSN Time Analyst at JPL who is responsible for determining that FTS at the three complexes is performing correctly. The frequency and time performance for the test facilities is the responsibility of their respective operations organizations.

2.1 Functions

The FTS provides the following major functions:

1) Generate and distribute very stable reference frequencies, time codes, and timing pulses to other equipment
2) Provide measurements of clock synchronization (time) and syntonization (frequency) traceable to UTC (NIST)
3) Generate phase calibration tones for very-long baseline interferometry (VLBI) via phase calibration generators

2.2 Components

Principal components of the FTS include frequency standards, clocks, frequency and time distribution equipment, and phase calibration generators.

2.2.1 Atomic Frequency Standards

Two types of atomic frequency standards are deployed at the DSCCs. They are the hydrogen maser and the cesium-beam standard. The performance of these standards is a function of multiple factors including model, configuration, and the environment. Figure 2 shows the range of performance routinely available in the DSN in terms of Allan Deviation, σ, over the averaging time, τ. The lower bound of the range in the figure captures the optimum performance that should be expected in the implemented configuration. The upper bound can be considered as the worst case. This figure also shows the performance of the cryogenic sapphire oscillator (CSO), a non-atomic oscillator that is discussed below.

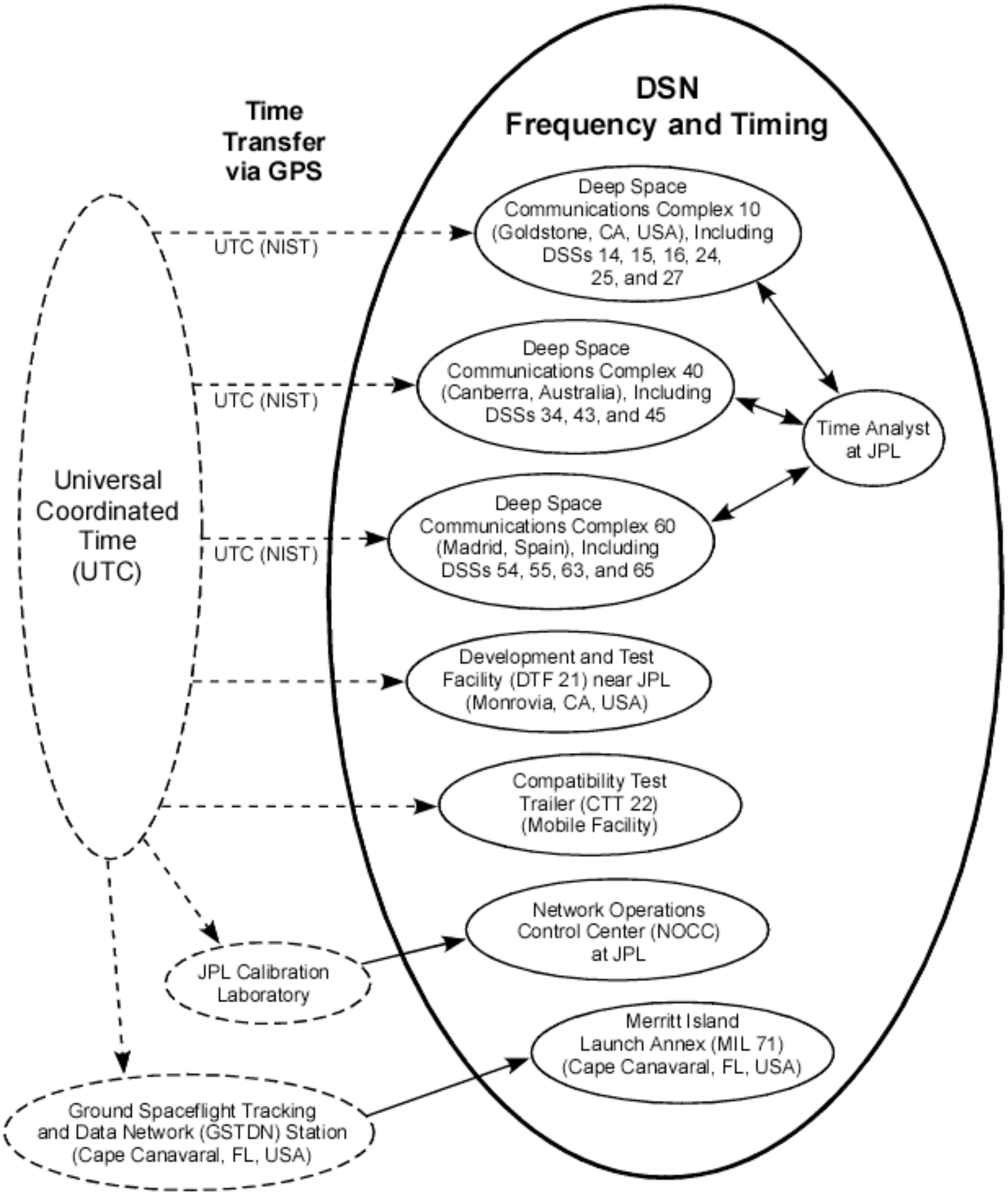

Figure 1. DSN Frequency and Timing.

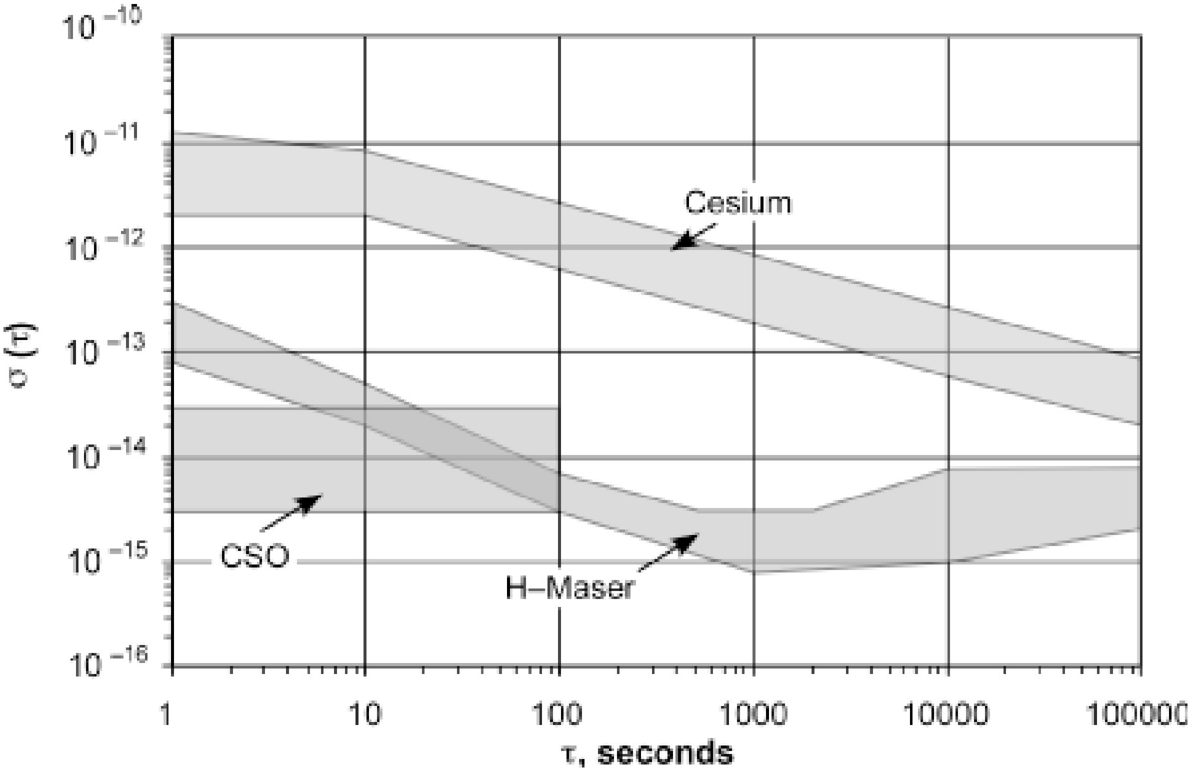

Figure 2. Allan Deviation of Frequency Standards.

Hydrogen masers have been employed as the main DSN frequency standard for some years. They provide spectral purity commensurate with a very good quartz crystal oscillator and frequency stability that is optimal for measurement periods between 1000 and 10,000 seconds. Spectral purity is especially important because the frequency standard must be multiplied to DSN transmit and receiver local oscillator frequencies and the multiplication degrades the spectral purity (expressed as a signal-to-noise ratio) by 6 dB per octave or 20 dB per decade. Noise injected by a local oscillator has the same effect on receiver performance as noise from any other source and can significantly degrade radio science investigations. Stability for measurement times through 10,000 seconds is important for navigation, where frequencies are compared delayed by the round-trip light time to the spacecraft. Another driver for stability at medium-to-long measurement times is radio science and VLBI investigations that normally are performed over a period of 8 to 12 hours. Table 1 summarizes the performance of the DSN frequency standards in the implemented configuration.

Table 1. DSN Frequency Standard Performance.

Parameter	Value
Frequency Offset Relative to UTC	
Worst Case	$<9 \times 10^{-13}$
Typical	$<3 \times 10^{-13}$
Resolution reconstructed by analysis (3 σ)	$<1 \times 10^{-13}$
Fractional Frequency Drift	
Specified	1×10^{-13} /10 days
Typical	$<3 \times 10^{-14}$ /10 days
Harmonic distortion (sine waves)	<5%
Stability (Allan Deviation)	See Figure 2
Phase Noise at 100 MHz	In 1 Hz Bandwidth, 1 Hz from carrier. For other frequencies, add 20 log (f/100) to these values, where f is the desired frequency in MHz
Hydrogen Maser	–97 to –104 dBc/Hz
Cesium Standard	–65 to –85 dBc/Hz
DSS 27 at 5 MHz	– 121 dBc
DSS 27 at 100 MHz	– 95 dBc
Availability	> 0.9999

2.2.2 Frequency Standards at the DSCCs

The present complement of standards at each DSCC comprises two hydrogen masers and two cesium standards. The standards are located in an environmentally controlled area of the Signal Processing Center (SPC).

2.2.3 Other Frequency Standards

In addition to the complex frequency standards, additional frequency standards are used by the DSN as described below.

2.2.3.1 FSTL and DSS 25 Cryogenic Sapphire Oscillator

Cryogenic oscillators provide the best ultra-high short-term stability and low phase noise available today for measurement times less than 200 seconds. The cryogenic sapphire oscillator achieves long-term operation using commercial cryogenic cooling systems. A CSO with the performance shown in Figure 2 has been installed at DSS 25 to provide an improved reference for radio science investigations and the JPL FSTL for low phase noise characterization. The CSO is currently only available for use at DSS-25 through special arrangements.

2.2.3.2 Frequency References for Test Facilities

Reference frequencies at the Development and Test Facility, DTF 21, and the Compatibility Test Trailer, CTT 22, are provided by a local standard consisting of a quartz crystal oscillator synchronized to a GPS receiver. For testing at JPL that requires higher performance, a signal from a hydrogen maser, similar to those used at the complexes, can be made available from the JPL Frequency Standards and Test Laboratory (FSTL) via a fiber optic link. The calibration of this hydrogen maser can be traced to UTC via GPS.

Precision frequencies at MIL 71 are derived from the co-located GSTDN station frequency standard that is based on a commercial cesium-beam standard and a GPS receiver backup and has an accuracy of 5 parts in 10^{12}. The Network Operations Control Center (NOCC) does not require reference frequencies but receive time code through the JPL Calibration Laboratory.

2.2.4 Reference Frequency Distribution

Reference frequencies are distributed by a system of high-quality switched, frequency synthesizers, distribution amplifiers, and cables that are designed to minimize degradation to the frequency standard performance. Reference frequency distribution at the DSCCs and other facilities are implemented as discussed below.

2.2.4.1 Signal Processing Centers

The outputs from the selected standard are routed from the frequency standards to the *Frequency Reference Selection* (FRS) Assembly. The FRS provides a switching capability, a frequency flywheel, and standard coherent reference outputs at 100, 10, and 5 MHz. These reference signals are routed from the frequency standards room to an assembly within the SPC control room referred to as the *Frequency Reference Distribution* (FRD) Assembly. The FRD provides 5, 10, and 100 MHz distribution to all control room equipment.

2.2.4.2 34-m High Efficiency Antennas and 70-m Antennas

The frequency references for the receiver downconverters at the 34-m High Efficiency (HEF) and 70-m antennas are provided by a fiber optic transmission system, the *Fiber Optics Distribution Assembly* (FODA), designed to preserve the stability equivalent to that of a hydrogen maser at the distribution point within the antennas. The FODA installation at these stations uses special low temperature coefficient fiber optic cabling to transport the reference frequency from the SPC to the tilting structure of the antennas. This is important because the cables on the antennas are exposed to the desert environment and can experience significant changes in temperature both from the environment and when antenna motion exposes them or shields them from the sun.

2.2.4.3 34-m Beam Waveguide Antennas

The frequency references for the receiver downconverters and Ka-band equipment at the 34-m beam waveguide (BWG) antennas are provided by FODAs at all antennas except DSS 27. Standard temperature coefficient fiber is used with these FODAs, however it is buried 1.2 m below the surface where there are no significant diurnal changes for antennas located near the SPCs. The diurnal phase change for DSS 26, located 15.5 km from the SPC, has been measured as 1-degree at 100 MHz over a 12-hour period and ~8 ns peak to peak over an annual cycle. All equipment requiring frequency references at the BWG antennas is located within the antenna pedestals so antenna motion has no effect on frequency stability.

A second antenna in the three-antenna BWG cluster at the Goldstone DSCC, DSS 25, is equipped with both a FODA and a stabilized FODA (the SFODA) that uses a return signal to actively compensate for the diurnal and longer duration phase changes. As a result, the phase change at DSS 25 is less than 0.1 degrees at 100 MHz over a 12-hour period when the reference signal is delivered with the SFODA.

The frequency references for the receiver downconverters at DSS 27 are derived from a timing system time code translator. The phase noise will be ~10 dB poorer than that achieved with a FODA. The diurnal phase change at DSS 27 is expected to be twice that expected at DSS 26 (or approximately 5 degrees at 100 MHz) for two reasons. First, its pedestal room is above ground and experiences greater temperature fluctuations. Second, it is located approximately 30 km from the SPC and the fiber passes through several splice vaults that are not temperature controlled. Figure 3 provides the estimated Allan Deviation for DSS 27.

2.2.5 Time Standards

All DSN facilities use a single time source, traceable to UTC, for all equipment and operations within the facility. The accuracy and availability of this time source depend on the requirements of the facility at which it is installed.

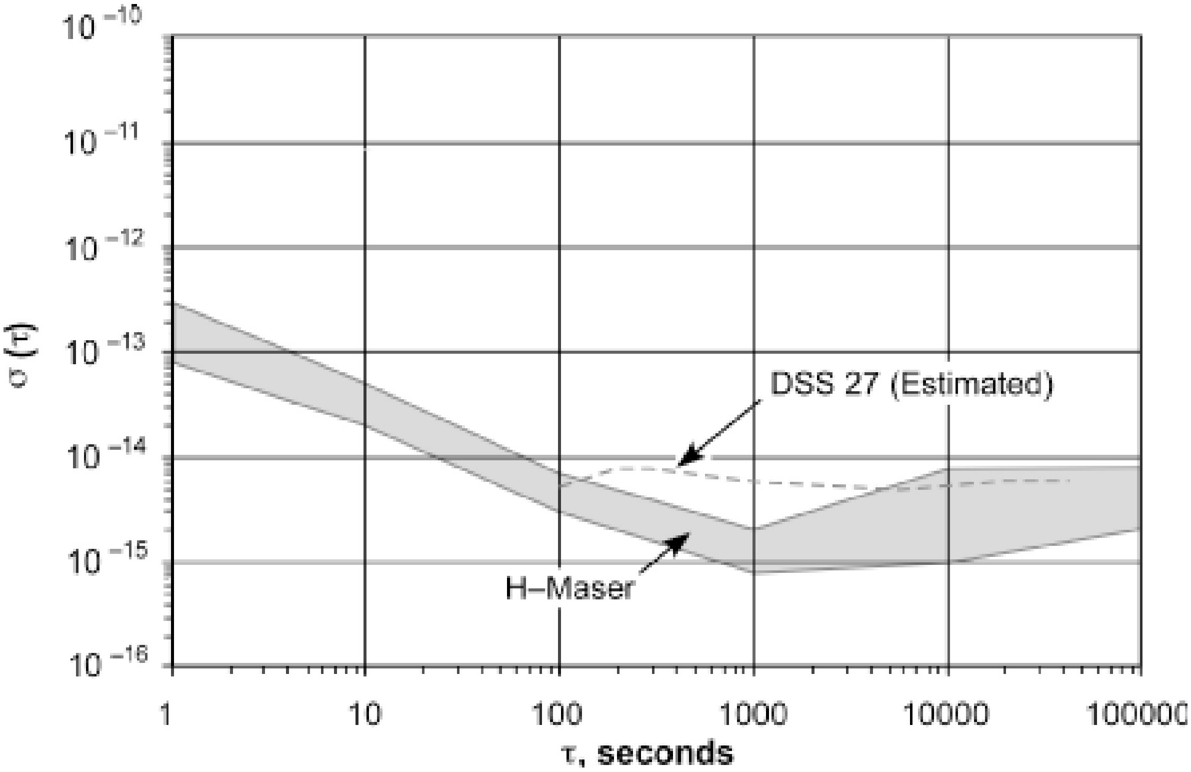

Figure 3. Allan Deviation of Reference Frequencies at DSS 27 Antenna.

2.2.5.1 *DSCC Time Standard*

Each DSCC contains a master clock whose rate is determined by the selected station frequency standard. Should a switch of standards occur, the clocks briefly operate from an internal crystal oscillator, and then slew to the phase of the new standard as soon as switchover is complete. This technique ensures that the maximum clock error after a frequency standard failure does not exceed a clock cycle (10 ns with a 100 MHz reference). Characteristics of the DSCC time standard are provided in Table 2.

Time offset from UTC (NIST) is kept < < 3 μs from UTC with a knowledge <20 ns. Synchronization between the DSCCs and UTC is accomplished using all-in view GPS time transfer between NIST in Boulder, Colorado and the DSCCs.

Table 2. DSCC Time Standard Characteristics.

Parameter	Value
Time Reference	UTC (NIST)
Setability	10 ns
Offsets from UTC	
Requirement	< 3 μs
Resolution from UTC, reconstructed by analysis (3 σ)	< 1 μs
Offsets between DSCCs	
Requirement	< 6 μs
Resolution between DSCCs, reconstructed by analysis (3 σ)	< 100 ns
Availability	> 0.9999

2.2.5.2 DTF 21, CTT 22, and NOCC Time Standards

Timing signals and date at DTF 21 and CTT 22 are derived from a master clock identical to that operating in each DSCC. At DTF 21 the clock rate is derived from a Cesium frequency standard. The master clock may be calibrated to GPS receivers that reference GPS Time and traceable to UTC with an accuracy of ≤100 ns.

Time and date at the NOCC are obtained via the Network Time Protocol (NTP) that is derived from UTC. The time is referenced to GPS Time and is traceable to UTC with an accuracy of ≤100 ns. NTP enables all computers at NOCC to be synchronized within 0.1 s of UTC.

2.2.5.3 MIL 71 Time Standard

Precision timing signals at MIL 71 are derived from the Goddard Space Flight Center time standard that is synchronized to UTC within ±10 μs by a GPS receiver. The station also has a WWV receiver to provide backup time synchronization. The time uncertainty when using either of these backup receivers is <20 ms.

2.2.6 Time Distribution

Timing signals are distributed up to 30 km from each master clock by time code translators (TCTs) installed in individual items of equipment. The timing system can remove distribution path length delays with a resolution of 10 ns so the offset knowledge of synchronization from the master clock to a specific user is < 10 ns. The typical jitter stability at the output of the TCTs is < 30 ps (RMS).

Time and date used by the monitor and control computers for logging of station events are provided by NTP and derived from a TCT installed in one of the computers. The accuracy of this time is within 0.1 s of UTC however station logging of monitor and control events is normally to the nearest second.

2.2.7 Phase Calibration Generators

The stability of the receivers used to detect signals from extra-galactic radio sources at the various DSN antenna sites is critical, but often difficult to control because of the extreme and exposed environment of the antenna and its electronics. Performance of VLBI measurements can be improved by comparing phase variations in received signals to a stable calibration tone locally generated in the detection bandwidth.

The Phase Calibration Generator (PCG) system provides these high stability calibration comb tones. A comb spectrum with a fixed 1.0 MHz line spacing can be injected into the feedcone or microwave waveguide ahead of the S-band and X-band low noise amplifiers (LNAs) in the DSN 34-m HEF and 70-m antennas when required. A similar spectrum can be injected into the waveguide ahead of the L-band LNAs in the 70-m antennas.

PCG receiver and comb generator stability tests were performed at the JPL Frequency Standards Test Laboratory both in a stabilized temperature environment and with temperature cycling. The averaged Allan Deviation from the 15 units tested is shown in Figure 4. Based on knowledge of temperature sensitivity of the PCG and the environmental requirements for the locations where they are installed, a curve showing the estimated installed performance of the PCG at a typical DSN site has been calculated and is also shown in Figure 4.

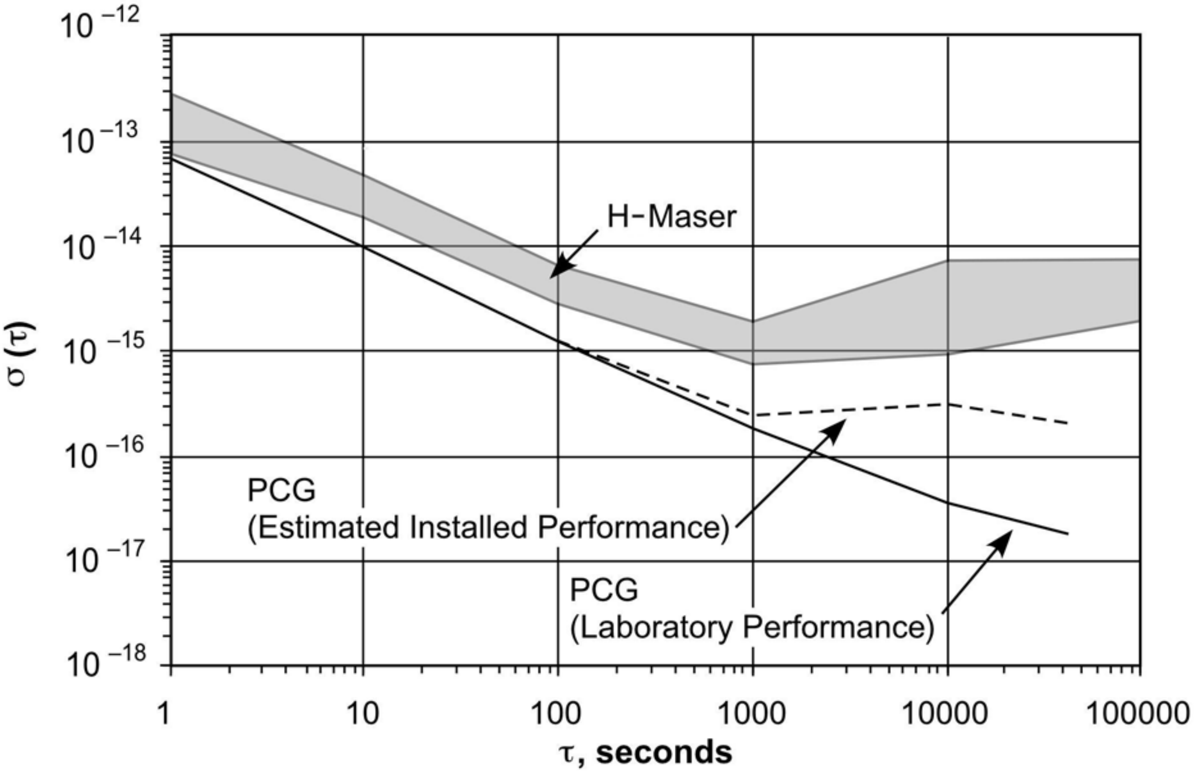

Figure 4. S-band and X-band Phase Calibration Generator Stability.

2.3 *Frequency and Time Synchronization*

DSN frequency and time synchronization is referenced to UTC using all-in-view GPS time transfer. This technique allows the direct comparison of two clocks at widely separated locations by canceling out the effect of GPS clock performance and most media effects; see Figure 5. The DSN GPS receiver takes the time difference between the DSN master clock and the time obtained from one or more GPS satellites (including propagation delay) and creates a data file. NIST maintains a similar database between UTC and all GPS satellites. The NIST database is queried periodically and the DSN Time Analyst uses the data and a weighted averaging technique to derive time offsets. Frequency offsets are derived using a moving average barycentric filter. The resultant information is used to adjust the DSN frequency standards to keep them within the frequency and time specification.

2.4 *Adjustment of DSN Time to UT1*

The Earth’s rate of rotation is not uniform. It is affected by gravitational effects of the sun, moon, and planets, tidal effects, and several other mechanisms. The time scale based on the earth’s rotation, corrected for polar motion, is called UT1 and is maintained by the International Earth Rotation Service (IERS), http://www.iers.org/. UT1 enables proper aiming of telescopes and radio-telescopes (including DSN antennas) at celestial objects.

The mean solar day as determined from the UT1 time scale is approximately 2 ms longer than 86,400 SI seconds established by atomic clocks. By international agreement, the UT1 and UTC time scales are kept synchronized within ±0.9 seconds by step-time adjustments of exactly one second (leap seconds). Notification to perform this adjustment is received from the IERS between 30 and 60 days before the adjustment is required. Leap seconds are added or subtracted, usually at the end of December or June, at the end of the day and set, as described below. DSN users must be aware of the potential for interference between time adjustments and sequences of time-critical events. Table 3 provides the sequences of time codes that occur during leap second adjustments.

Table 3. DSN Leap Second Adjustments.

Day	**Second**	**Time**
Leap Second Add		
n	*t*	23:59:59
n + 1	*t* + 1	23:59:60
n + 1	*t* + 2	00:00:00
n + 1	*t* + 3	00:00:01
Leap Second Subtract		
n	*t*	23:59:58
n + 1	*t* + 1	00:00:00
n + 1	*t* + 2	00:00:01

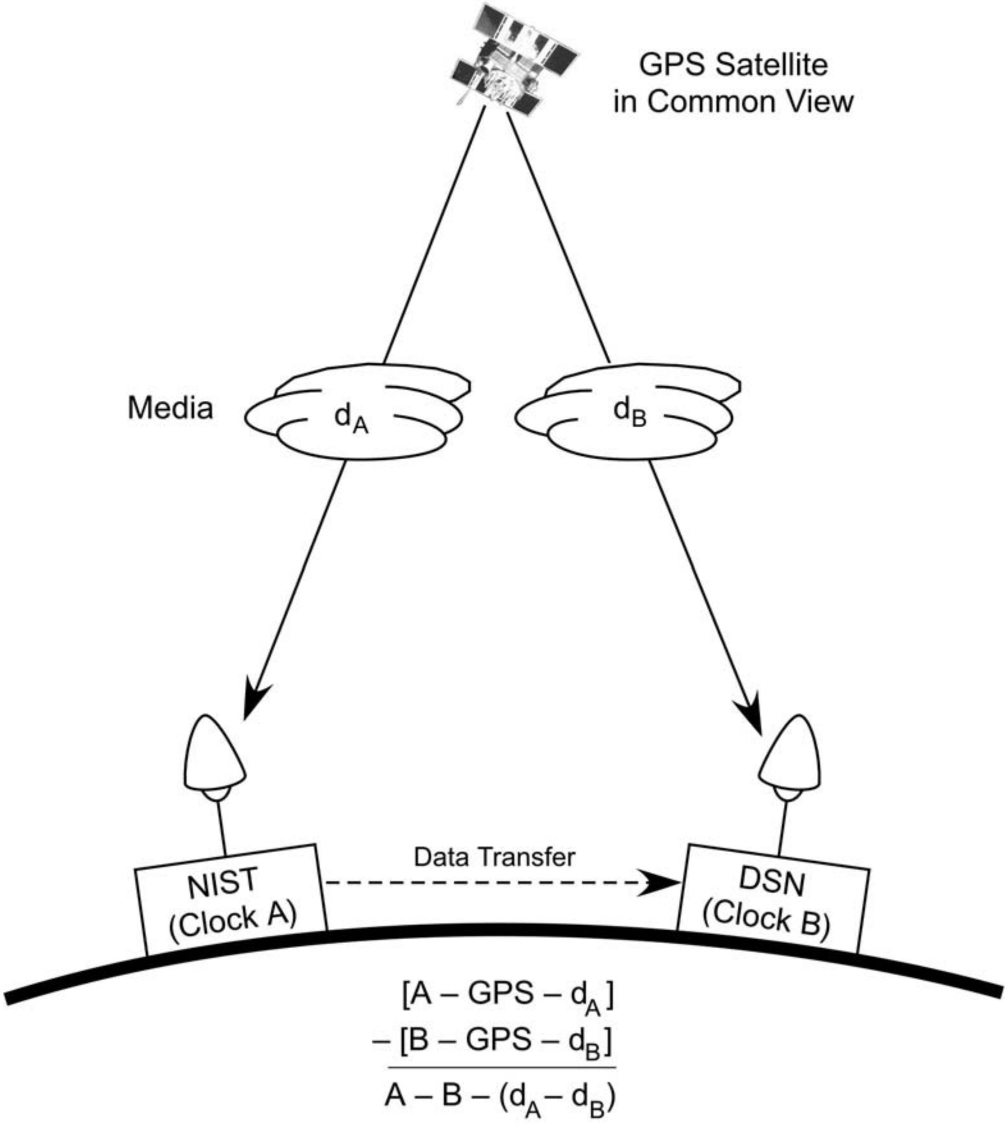

Figure 5. Common View GPS Time Transfer.

3 Proposed Capabilities

The following paragraphs discuss capabilities that have not yet been fully implemented by the DSN but have adequate maturity to be considered for spacecraft mission and equipment design. Telecommunications engineers are advised that any capabilities discussed in this section cannot be committed to except by negotiation with the Interplanetary Network Directorate (IND) Plans and Commitments Program Office.

3.1 Ka-band Phase Calibration Generator

A Ka-band phase calibration generator has been developed for use on several of the 34-m BWG antennas. This new design generates stable comb tones spanning the frequency range from 3 GHz to 40 GHz. The proposed performance capabilities are summarized in Table 4.

Table 4. Ka-band Phase Calibration Generator.

Parameter	Proposed Capability
Stability (Allan Deviation)	
1 s	5×10^{-14}
10 s	8×10^{-15}
100 s	1.0×10^{-15}
1000 s	1.2×10^{-16}
$10{,}000\ \mathrm{s} < \tau < 100{,}000\ \mathrm{s}$	$<5 \times 10^{-17}$
Amplitude Flatness	±1.7 dB, 32 — 33 GHz
Comb Spacing	1 MHz, 2 MHz, or 4 MHz selectable