Deep Space Network

304
Frequency and Timing

Document Owner:

Signature Provided 10/27/2014

Robert L. Tjoelker Date
Frequency & Timing System Engineer

Approved by:

Signature Provided 10/21/2014

Timothy Pham Date
Communications Systems Chief Engineer

Prepared by:

Signature Provided 10/27/2014

John E. Lauf Date
Frequency & Timing Subsystem Engineer

Released by:

Signature Provided 12/15/2014

Christine Chang Date
DSN Document Release Authority

DSN No. **810-005, 304, Rev. B**
Issue Date: December 15, 2014
JPL D-19379

Jet Propulsion Laboratory
California Institute of Technology

Users must ensure that they are using the current version in DSN Telecommunications Link Design Handbook website:
http://deepspace.jpl.nasa.gov/dsndocs/810-005/

Review Acknowledgment

By signing below, the signatories acknowledge that they have reviewed this document and provided comments, if any, to the signatories on the Cover Page.

Signature Provided	10/24/2014
Jeff Berner DSN Project Chief Engineer	Date

Change Log

Rev	Issue Date	Prepared By	Paragraphs Affected	Change Summary
–	3/1/2004	B. Benjauthrit	All	New Module
A	9/30/2010	Robert Tjoelker	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.
B	12/15/2014	John Lauf	Sections1, 2, 3 Figures 1, 2, 3 Tables 1, 2	Corrected configuration information at DTF-21, MIL-71 and CTT-22. Removed references to DSS-27. Replaced references to FODA with PFD and S-FODA with S-PFD. Replaced references to NIST with USNO.

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 potential 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 frequency reference for the three Deep Space Communications Complexes (DSCCs) at Goldstone (GDSCC), Canberra (CDSCC) and Madrid (MDSCC) respectively, is derived from one of at least four, redundant atomic frequency standards (AFSs). The Development and Test Facility (DTF-21) has one AFS while the other two sites, the Merritt Island Launch Annex (MIL-71) and the Compatibility Test Trailer (CTT-22) use disciplined GPS receivers as a frequency reference source.

At each DSCC, a single (prime) atomic frequency standard serves as the source for all coherent, precision, station frequencies and provides the reference for the station Master Clock. The other AFSs serve as backups to the prime standard, should it fail, indicate instability or require maintenance. Each station synchronizes its clock to the United States Naval Observatory (USNO) realization of Coordinated Universal Time (UTC), referred to as UTC (USNO), via the Global Positioning System (GPS). Time offset data measured at the DSCCs are forwarded to the DSN Time Analyst who is responsible for verifying that station frequency and time offsets, relative to UTC (USNO), are within specified limits. The frequency and time performance for the test facilities is the responsibility of their respective operations organizations.

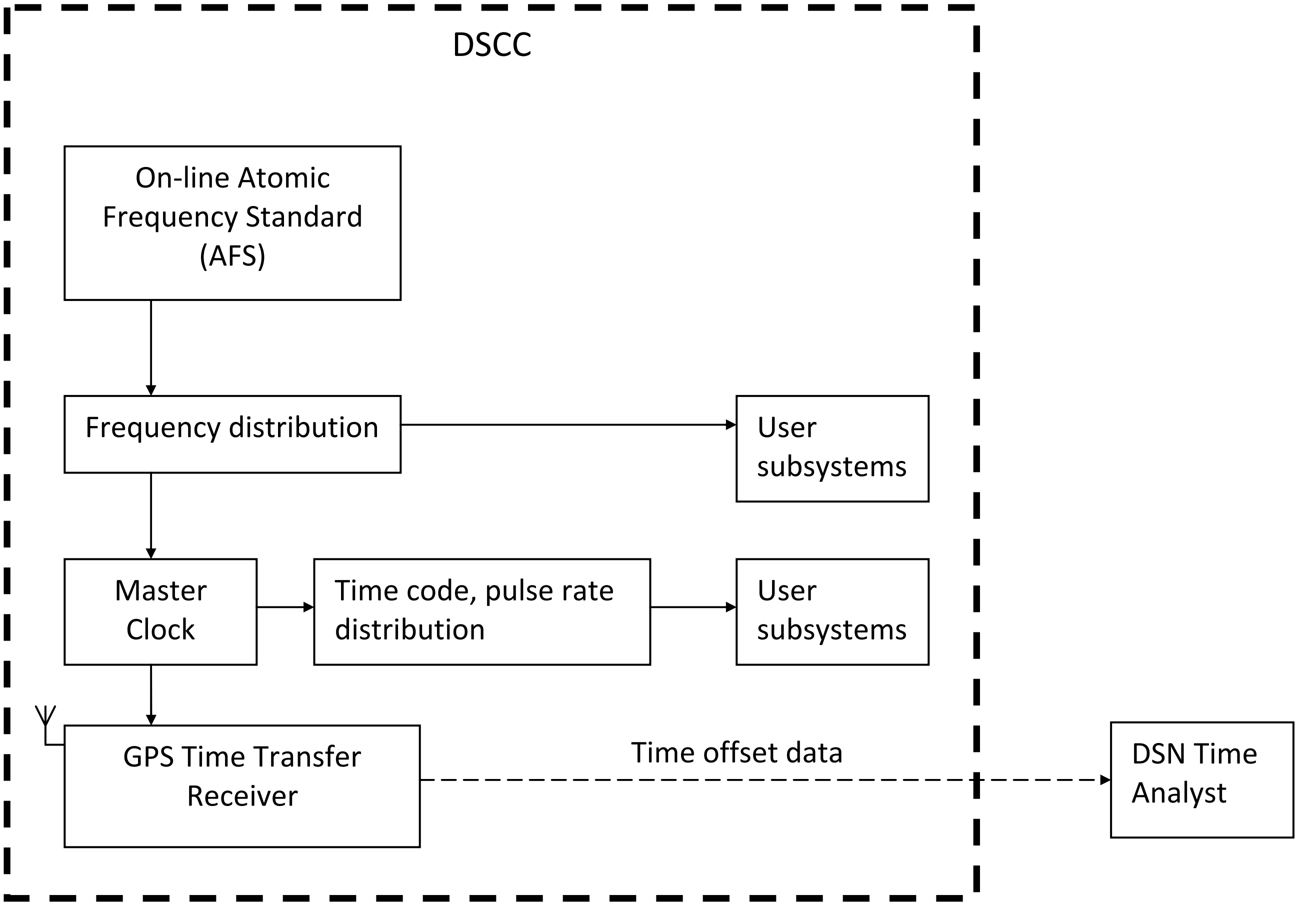

Figure 1. DSN Frequency and Timing – Simplified Block Diagram

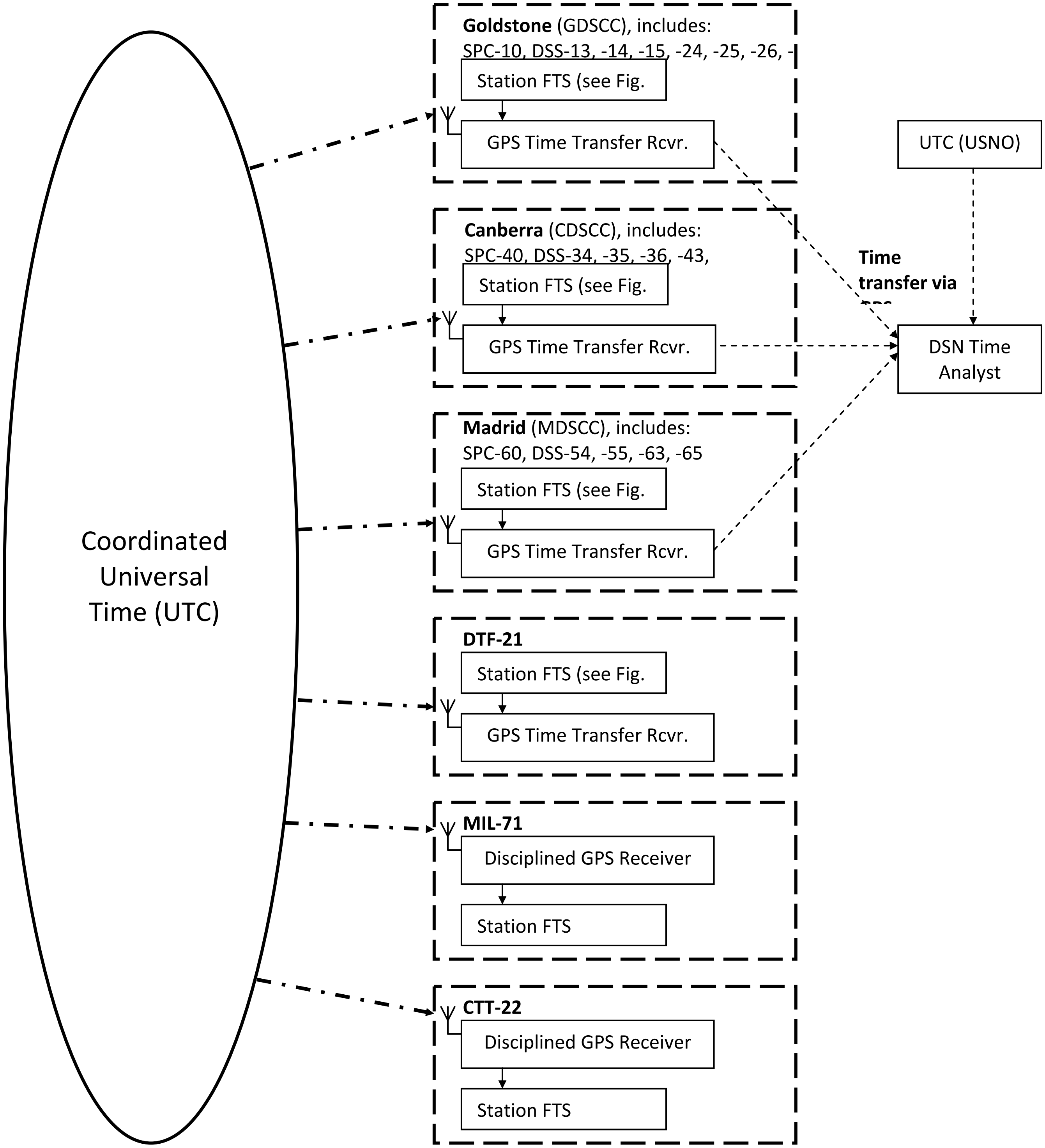

Figure 2. DSN Time Transfer

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 (USNO)
3) Generate phase calibration tones for very-long baseline interferometry (VLBI) via phase calibration generators. See paragraph 2.2.12 for further details

2.2 Components

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

2.2.1 Atomic Frequency Standards

Two types of atomic frequency standards are nominally 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 3 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 may be made available for special experiments. See paragraph 2.2.3 for additional details.

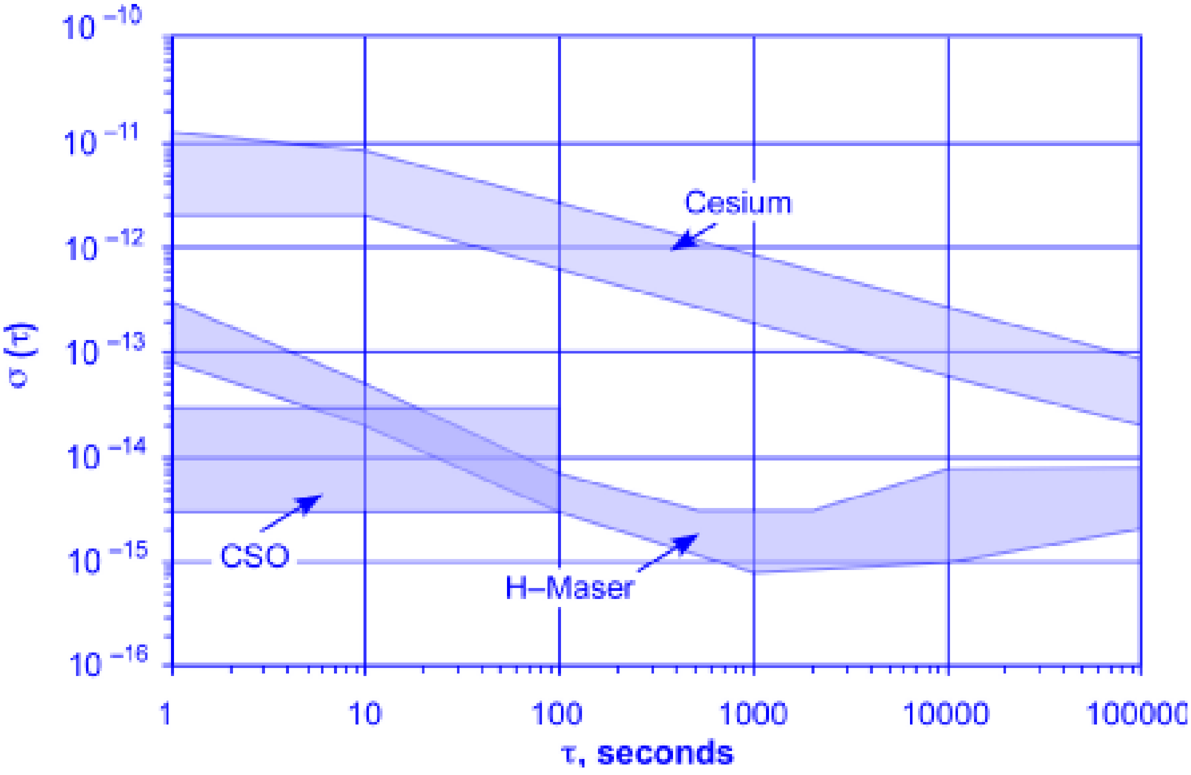

Figure 3. Allan Deviation of Frequency Standards.

Hydrogen masers have been employed as the prime 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 reference must be multiplied up to local oscillator frequencies as required by DSN transmit and receive equipment. The frequency 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 and timing signals 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	
Typical	$<3 \times 10^{-13}$
Resolution reconstructed by analysis ($3\ \sigma$)	$<1 \times 10^{-13}$
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 3
SSB Phase Noise at 100 MHz, in 1Hz bandwidth, 1Hz from the carrier	
Hydrogen Maser	–97 to –104 dBc/Hz
Cesium Standard	–65 to –85 dBc/Hz For other frequencies, add 20 log (f/100) to these values, where f is the desired frequency in MHz.
Availability	> 0.9999

2.2.2 *Frequency Standards at the DSCCs*

The present complement of standards at each DSCC nominally 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 FSTL and DSS-25 Cryogenic Sapphire Oscillator

Cryogenic oscillators provide the ultra-high short-term stability and low phase noise 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 3 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.

2.2.4 Frequency References for Test Facilities

Reference frequencies at DTF-21 are derived from a Cesium Beam standard (see Figure 3 for nominal stability). Reference frequencies at MIL-71 and CTT-22 are derived from a disciplined GPS Receiver. For testing at JPL locations that requiring high 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.

The Network Operations Control Center (NOCC) at JPL does not require reference frequencies but receives time code via the JPL Calibration Laboratory.

2.2.5 Signal Processing Centers

Reference frequencies at the DSCCs are distributed via a system of high-quality distribution amplifiers and coax cables that are designed to minimize degradation to the frequency standard performance. Outputs from the selected frequency standard are routed 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.

2.2.6 34M High Efficiency Antennas and 70M Antennas

The frequency references for the Receiver Downconverters at the 34M High Efficiency (HEF) and 70M antennas are provided by a fiber optic transmission system, the *Photonic Frequency Distribution* (PFD), designed to preserve the stability equivalent to that of a hydrogen maser at the distribution point within the antennas. The PFD 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 can experience significant changes in temperature both from the environment and when antenna motion exposes them or shields them from the sun.

2.2.7 34M Beam Waveguide Antennas

The frequency references for the Exciters and Receiver Downconverters at the 34M beam waveguide (BWG) antennas are provided via PFDs. Standard temperature coefficient, singlemode fiber is used for frequency distribution to all of the DSN BWG antennas. 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. Diurnal phase variations at DSS-24 and DSS-25 are nominally the same as DSS-26 as the signal distribution follows an almost identical path to that of DSS-26. All equipment requiring frequency references at the BWG antennas is located within the antenna pedestals so antenna motion has no effect on frequency stability.

2.2.8 Time Standards

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

2.2.9 DSCC Time Standard

Each DSCC contains a Master Clock whose rate is determined by the selected on-line frequency standard. In the rare circumstance of a switchover between online standards, an in-series, low noise flywheel oscillator continues to provide a frequency reference to the Master Clock during the switching period (typically < 5ms). This technique ensures that the maximum clock error after a frequency standard switchover 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 (USNO) is maintained at < 3 μs from UTC with a knowledge < 20 ns. Synchronization between the DSCCs and UTC is accomplished using "common-view" or "all-in-view" GPS time transfer between USNO and the DSCCs.

Table 2. DSCC Time Standard Characteristics

Parameter	Value
Time Reference	UTC (USNO)
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

2.2.10 DTF-21, CTT-22, MIL-71 and NOCC Time Standards

Timing signals and day-of-year 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 are traceable to UTC with an accuracy of ≤ 100 ns. At MIL-71 and CTT-22, clock rates are determined by disciplined GPS receivers.

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 the NOCC to be synchronized within 0.1 s of UTC.

2.2.11 Time Distribution

Station time information is distributed from the Master Clock, via fiber optic cables up to 30km in length, to Time Code Translators (TCTs) that are typically located in racks of user subsystems that require precision time or pulse rate signals. TCTs can be calibrated to compensate for fixed 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).

Certain monitor and control computers that do not require precision timing (> 0.1s accuracy) are synchronized to local NTP servers, independent of the station FTS.

2.2.12 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.

On the 70M and HEF antennas, 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). On the 70M antennas, a similar spectrum can also be injected into the waveguide ahead of the L-band LNAs.

Receiver and comb generator stability tests on the S- and X-band PCGs 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.

X/Ka PCGs are planned to be implemented on several of the BWG antennas in the future (see paragraph 3.1 below).

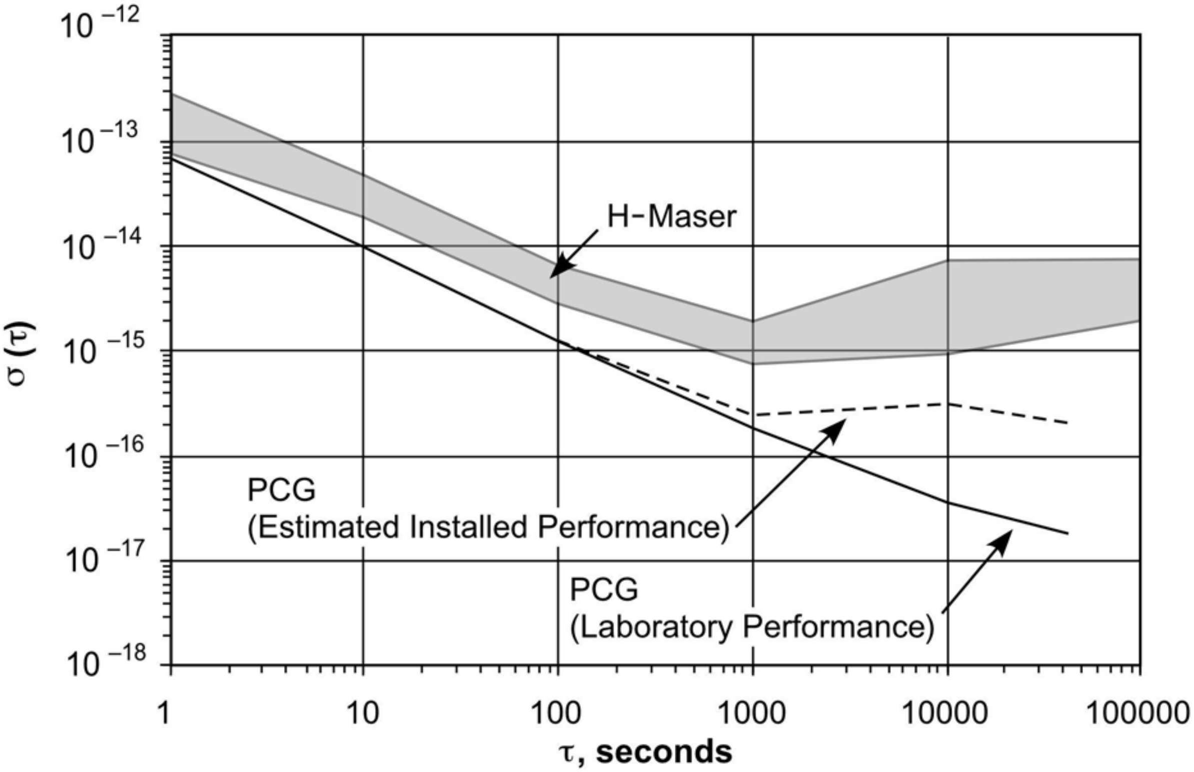

Figure 4. S-band and X-band Phase Calibration Generator Stability.

2.3 *Frequency and Time Synchronization*

DSN frequency and time synchronization is referenced to UTC using "common-view" or "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. USNO maintains a similar database between UTC(USNO) and all GPS satellites. The USNO 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 required frequency and time specification limits.

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

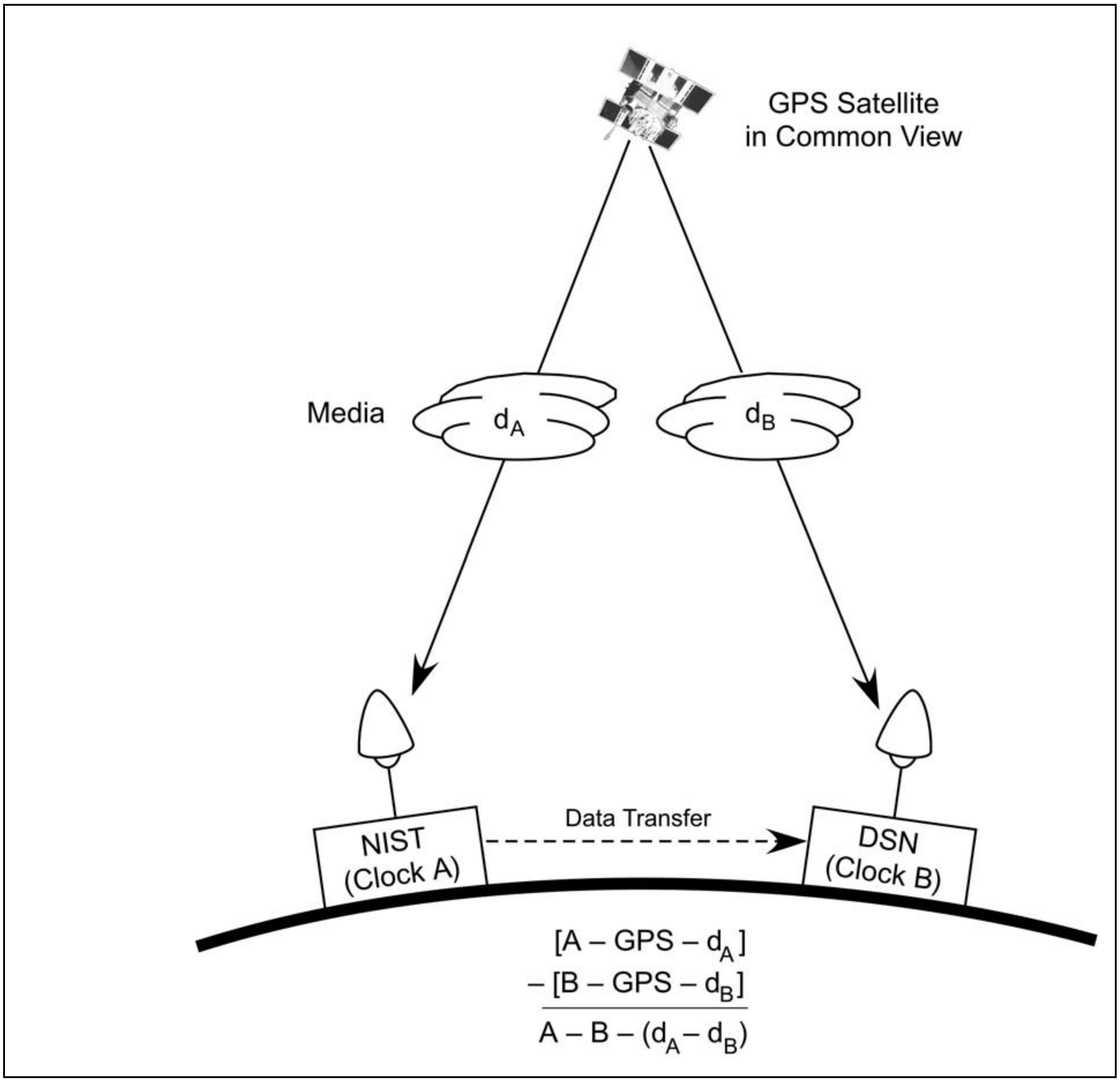

Figure 5. Common-View GPS Time Transfer

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 X/Ka-band Phase Calibration Generator

An X/Ka-band phase calibration generator has been developed and tested at DSS-25 with the ultimate intention of implementing this capability on several of the 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. X/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 s < τ < 100,000 s	$<5 \times 10^{-17}$
Amplitude Flatness	±1.7 dB, 32 — 33 GHz
Comb Spacing	1 MHz, 2 MHz, or 4 MHz selectable

3.2 Stabilized Photonic Frequency Distribution (S-PFD)

The existing PFD implementation for frequency reference distribution to the antennas provides a return link that facilitates performance verification at the user port. Nevertheless, the PFD frequency distribution system is open loop. I.e. there is no provision to actively compensate for distribution link induced phase variations (e.g. due to environmental thermal variations) – potentially significant at the remote antennas at Goldstone where the distribution link can be up to 30 km. A closed-loop modification to the PFD hardware has been developed which does actively compensate for induced phase variations on the distribution link. Initial testing at JPL indicates a 50- to 100-times improvement in stability at averaging times greater than 100s.