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A Stabilized 100-Megahertz and 1-Gigahertz Reference Frequency Distribution for Cassini Radio Science

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The development of the stabilized fiber-optic distribution assembly (SFODA) is reported. The system was developed to enable gravitational wave searches and atmospheric occultation experiments between the Cassini spacecraft and the NASA Deep Space Network. These experiments are conducted at 32-GHz (Ka-band) frequencies and demand the highest possible short-term and long-term frequency stability at Deep Space Station 25, a remote antenna 16-km distant from the frequency reference source.

This article presents the final design of the SFODA and test results transmitting a 1-GHz reference signal over a 16-km optical fiber under controlled test conditions. The SFODA utilizes active feedback with a temperature-compensating fiber-optic reel to compensate for thermally induced phase variations over the 16-km fiber cable. Test data show a factor of 1000 improvement in long-term stability when the active phase compensator is used, thus enabling degradation-free distribution from the highest performing atomic frequency standards.

I. Introduction

The Deep Space Network (DSN) frequency and timing subsystem (FTS) must generate low-noise and ultrastable reference frequencies and distribute them at distances up to 30 km. The frequency source of the reference signal is a high-performance atomic frequency standard, typically a hydrogen maser or a linear ion-trap frequency standard (LITS). These atomic frequency standards operate in an environmentally controlled room at the Signal Processing Center (SPC). The end users of these low-noise, stable signals typically are located at spacecraft tracking antennas that may be thousands of meters from the signal source. The distribution system that carries the reference signal to the antennas is often subject to harsh environmental conditions: extremes of temperature, electromagnetic and radio-frequency interference, and vibration. The distribution challenge is twofold in nature: (1) to preserve the frequency standard stability throughout the distribution system and, if necessary, (2) to clean up the phase noise of the frequency standard and the distribution system. The distribution of atomic-frequency-standard-quality reference signals free of degradation at a distance of tens of kilometers is the primary goal of the stabilized

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fiber-optic distribution assembly (SFODA). Phase-noise cleanup is accomplished at Deep Space Station 25 (DSS 25) using a cryogenic sapphire oscillator (CSO) [1]. Figure 1 illustrates the reference frequency distribution system between SPC 10 and the pedestal of DSS 25.

Cassini radio science experiments such as planetary occultation and gravity wave measurements place stability requirements on the frequency distribution system of 1.5×10^{-16} at 1000-s and 10,000-s averaging times. The greatest deterrent to meeting the long-term stability requirements is the exposure of distribution components, primarily cabling, to the temperature variations between the SPC and the remote antenna.

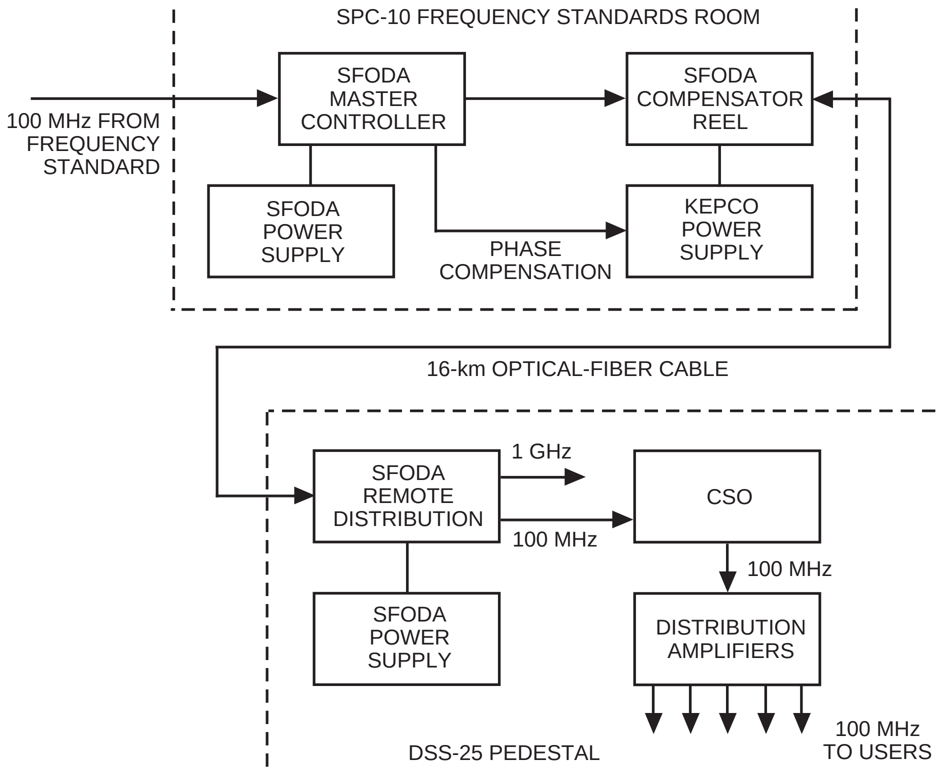

Fig. 1. The 100-MHz reference frequency distribution of DSS 25.

II. Thermal Variations on Distribution Fibers

The cables that distribute the reference signals to the antenna at DSS 25 are buried underground but are partially exposed to extreme temperature variations. In order to characterize the ground temperature effects on the optical cables, a study was conducted at the Goldstone Deep Space Communications Center (GDSCC) [2]. The temperature profile of the Earth was measured by placing thermocouples in the ground at depths of 0.6 m, 0.9 m, 1.2 m, 1.5 m, and 1.8 m, employing a data logger with a computer. The results of these measurements are shown in Fig. 2. Measurements were begun on day of year (DOY) 46 and terminated on DOY 178 at a site near SPC 10. A similar experiment was conducted at DSS 13, at some 27-km distance from SPC 10, with corroborating results. Note in Fig. 2 that the line with the larger variations from day to day is the surface temperature averaged over a 24-hour period. Figure 3 shows the same temperature data as Fig. 2, but expanded to show detail over the period from DOY 150 through DOY 178. Figure 4 is a plot of surface temperatures at GDSCC recorded every 4 hours for the period from DOY 163 through DOY 166. Note the extremes from a low of about 12 deg C to a high near 55 deg C with an average ΔT of 35 deg C.

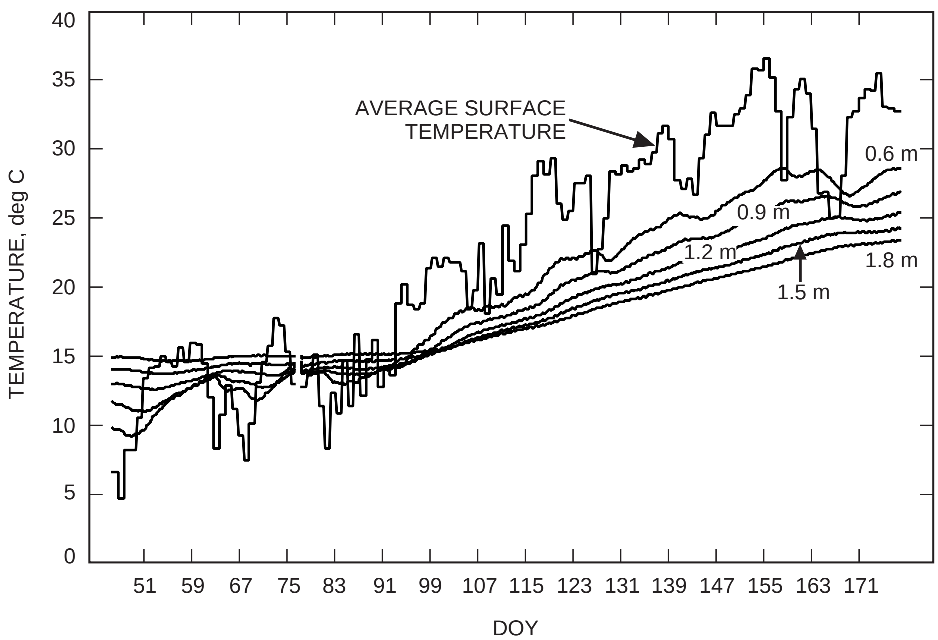

Fig. 2. Ground temperature at GDSCC.

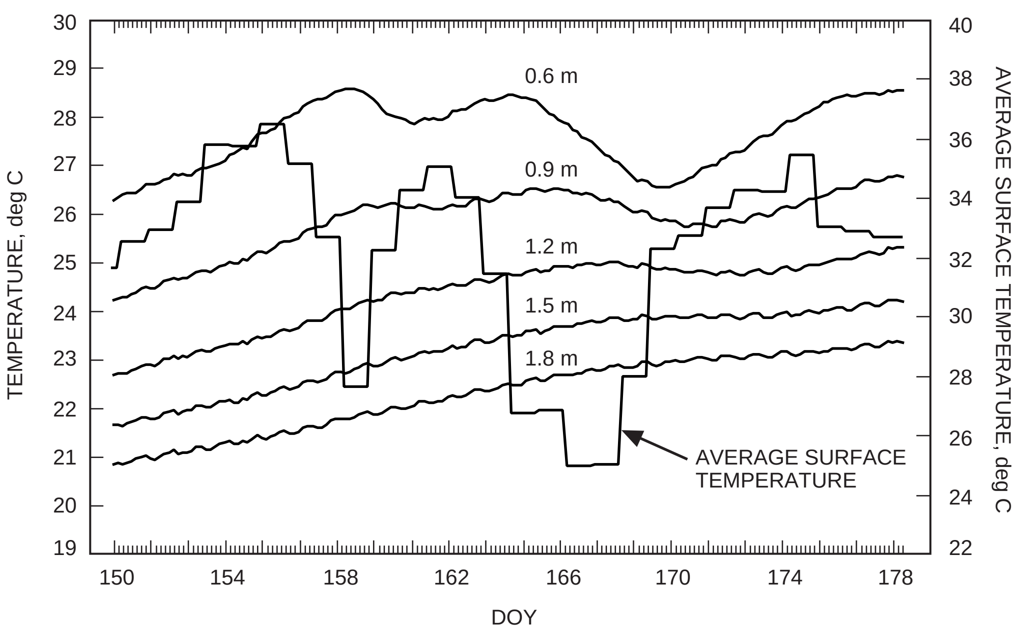

Fig. 3. Expanded graph of the ground temperature measured at GDSCC.

A curve-fitting routine was used to determine a temperature-versus-depth attenuation model. A best-fit equation based on the recorded temperature data shows that temperature variations are attenuated by 21 dB at a depth of 0.9 m, 30 dB at 1.2 m, and 45 dB at 1.5 m.

The burial depth of the cable run from the SPC to the remote antenna site is approximately 1.5 m. At this depth, the temperature variation is sufficiently attenuated as to not degrade the frequency distribution. However, along the 16-km path of buried fiber are four vaults, each of which has approximately 10 m of coiled cable. These vaults have steel covers and are exposed to extremes of temperature variation as

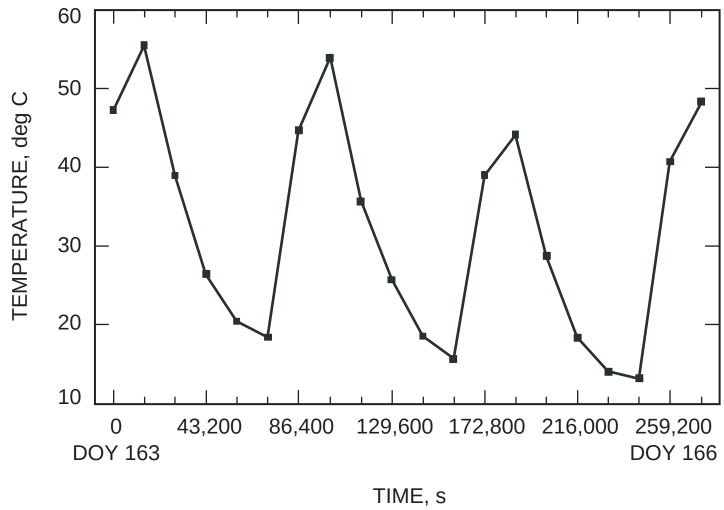

Fig. 4. Ground surface temperature measured at GDSCC over a 3-day interval.

great as 50 deg C peak-to-peak daily. Additionally, the fiber cables pass through the plenum at SPC 10, the plenum at Apollo station, and the DSS-25 pedestal. Temperature cycling in the plenums and pedestal varies, but has been observed to be as great as 3 deg C peak to peak over varying periods, typically in the 2000- to 4000-s range. All of these factors can contribute to phase-delay variations measured at the user end of the distribution system.

III. Frequency and Phase Stability Versus Temperature

The electrical phase variation in the fiber is

$$\Delta\Phi = \frac{\Delta L \times 360 \text{ deg}}{\lambda_m}$$

where $\Delta L = Lk\Delta T$, $\Delta\Phi$ is the change in phase delay introduced by the temperature variation ΔT, k is the thermal coefficient of delay of the fiber in ppm/deg C, and λ_m is the wavelength of the reference signal in the medium (at 100 MHz in optical fiber, λ_m is 2.1 m). Calculating the phase change for a 10-deg C peak-to-peak temperature excursion over a 6-month period yields a peak-to-peak phase variation of 192 electrical degrees at 100 MHz. The rate of change of the phase is relatively constant over this seasonal temperature variation, and thus presents no stability problem. However, the diurnal temperature variations in the vaults and the more rapid plenum variations create a stability problem at the remote site—hence, a need for active stabilization.

Assuming a peak-to-peak temperature change, ΔT, of 50 deg C in the vaults, approximately 40 m of cable exposed to this variation, and $k = 7$ ppm/deg C in glass fiber,

$$\Delta L = Lk\Delta T = 0.014 \text{ m}$$

$$\Delta\Phi = \frac{\Delta L \times 360 \text{ deg}}{\lambda_m} = 2.4 \text{ deg electrical phase}$$

A 2.4-deg phase at 100 MHz is equivalent to a 66.5-ps time-delay variation. Averaged over 12 hours, this delay variation yields a fractional frequency variation of approximately 1.5×10^{-15}, much larger than the Cassini radio science distribution stability requirement of 1.5×10^{-16} for averaging times greater than 1000 s.

Similarly, for shorter averaging times, plenum and pedestal temperature variations degrade stability. For example, there is a fiber cable 50 m in length in the pedestal at DSS 25. Measurements have shown the temperature to vary as much as 2 deg C peak to peak with a period of 45 minutes. Repeating the previous calculations yields

$$\Delta L = Lk\Delta T = 0.0007 \text{ m}$$

then

$$\Delta\Phi = \frac{\Delta L \times 360 \text{ deg}}{\lambda_m} = 0.12 \text{ deg electrical phase}$$

A 0.12-deg phase is equivalent to a 3.3-ps time-delay variation. Averaged over 45 minutes, this yields a fractional frequency variation of approximately 1.2×10^{-15} at 2400 s, which again does not meet the SFODA stability requirement for the Cassini gravity wave experiment.

In addition to the pedestal temperature variation, the plenums in the Apollo site and SPC 10 cause delay variations of similar magnitudes and periods. The variation in the periodic cycling of the plenum and pedestal temperatures causes a broad hump in the measured Allan deviation, and Fig. 5 clearly shows the effects of these temperature variations. Figure 5 is the 100-MHz Allan deviation measured at DSS 25 with an uncompensated open-loop fiber-optic distribution system.

For antennas located near the SPC, a cost-effective solution has been to install a special optical fiber with a low thermal coefficient of delay (LTCD). The thermal coefficient of delay for this fiber is less than 1 ppm/deg C for temperatures below 35 deg C, and on the order of 0.1 ppm/deg C over the range from 10 deg C to 25 deg C, which accounts for most plenum and tunnel temperature variations. Note that the thermal coefficient of standard single-mode optical fiber is on the order of 7 ppm/deg C. The existing cable runs of this specialized fiber are limited to the nearby 34-m high-efficiency (HEF) antenna and the 70-m antennas. This is due in part to the cost of the cable and to the fact that it is not a direct burial cable as is used for the long runs to the remote antennas.

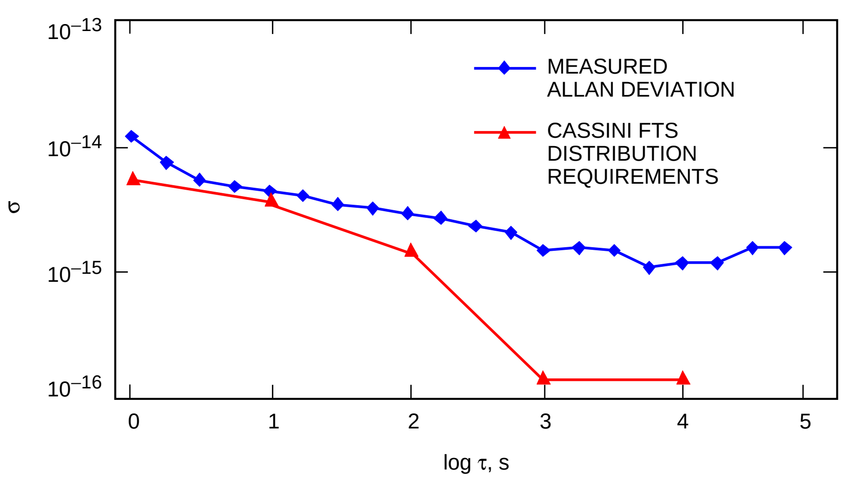

Fig. 5. Allan deviation of the existing open-loop reference frequency distribution assembly measured at the remote antenna DSS 25.

The remote 34-m beam-waveguide antennas at Goldstone are not equipped with the LTCD fiber and consequently do not meet the very stringent stability requirements for Cassini radio science experiments. Since DSS 25 was selected to support the Cassini spacecraft for gravity wave and planetary occultation experiments and is located 16 km from SPC 10, temperature compensation is accomplished with a closed-loop, active feedback system, referred to as the stabilized fiber-optic distribution assembly (SFODA) [3].

IV. Stabilization Technique

The block diagram of the SFODA system that was used to stabilize the reference signal distribution to the remote sites is shown in Fig. 6. In this diagram, the 100-MHz reference signal (f_0) is multiplied to 1 GHz and sent to the remote site over the fiber link to be compensated. At the remote site, a 100-MHz voltage-controlled crystal oscillator (VCXO) is multiplied to 1 GHz and phase locked to the incoming signal. The 1-GHz signal is biphase modulated by the 100 MHz signal to produce the two side bands, 900 MHz and 1100 MHz, with the carrier suppressed. A notch filter is inserted to further suppress the carrier since any residual carrier will degrade the performance of the control loop. These side bands are sent back on the fiber to the sending site, where they are mixed with the carrier to extract the 100-MHz modulation frequency. This signal is phase detected by the local 100-MHz station reference to produce a signal that is used to control the delay of the signals through the fiber-optic reel (by varying the temperature of the reel) in order to maintain constant phase delay of the overall frequency distribution system.

The three main considerations that governed the design of the system are as follows:

(1) Although the input and output frequencies are 100 MHz, the frequency used as the carrier over the fiber-optic link is 1 GHz. This change was made because the noise added by the fiber-optic system produces the same phase noise at all frequencies. The signal-to-phase noise ratio is then $\approx (\omega^2/S_\phi)$. By using 1 GHz instead of 100 MHz, the signal-to-phase noise contribution from the fiber-optic components is reduced by 20 dB.

(2) The modulation frequency in the system is the same as the reference frequency and is available with no additional complexity such as frequency dividers.

(3) The variable delay element is a reel of fiber-optic cable with delay controlled by temperature variation.

Over a 6-month period of time, the buried fiber-optic cable at Goldstone sees a temperature variation of 10 deg C over the 16-km run. The thermoelectric devices that are used to control the delay-control reel can produce a temperature range of ± 25 deg C. This is five times the measured change in the cable run, so a reel with one-fifth the length of fiber is sufficient. The final reel of fiber uses 4 km of fiber, sufficient to compensate a 20-km cable run without requiring any additional phase shifters.

The delay-compensation reel design uses a 20.32-cm diameter, 20.32-cm long, aluminum cylinder. The diameter was chosen so that the bending of the cable would not cause excessive signal loss due to light leakage. The length was chosen such that the thickness of the multiple layers of fiber-optic cable wrap would not be enough to cause appreciable thermal delay in the response of the reel.

Since the temperature coefficient of expansion of the fiber-optic cable is much smaller than that of the aluminum cylinder,[2] and since the reel had to be wound at room temperature, the higher temperature control points would stress the cable and lead to lower lifetime, signal loss, and the possibility of premature

[2] The linear temperature coefficient of expansion of aluminum is 23×10^{-6} per deg C, while that of the fiber-optic cable is 5.7×10^{-7} per deg C. With a temperature change from 25 deg C (room temperature) to 50 deg C, the difference in circumference of the aluminum reel and the optical fiber is 0.036 cm.

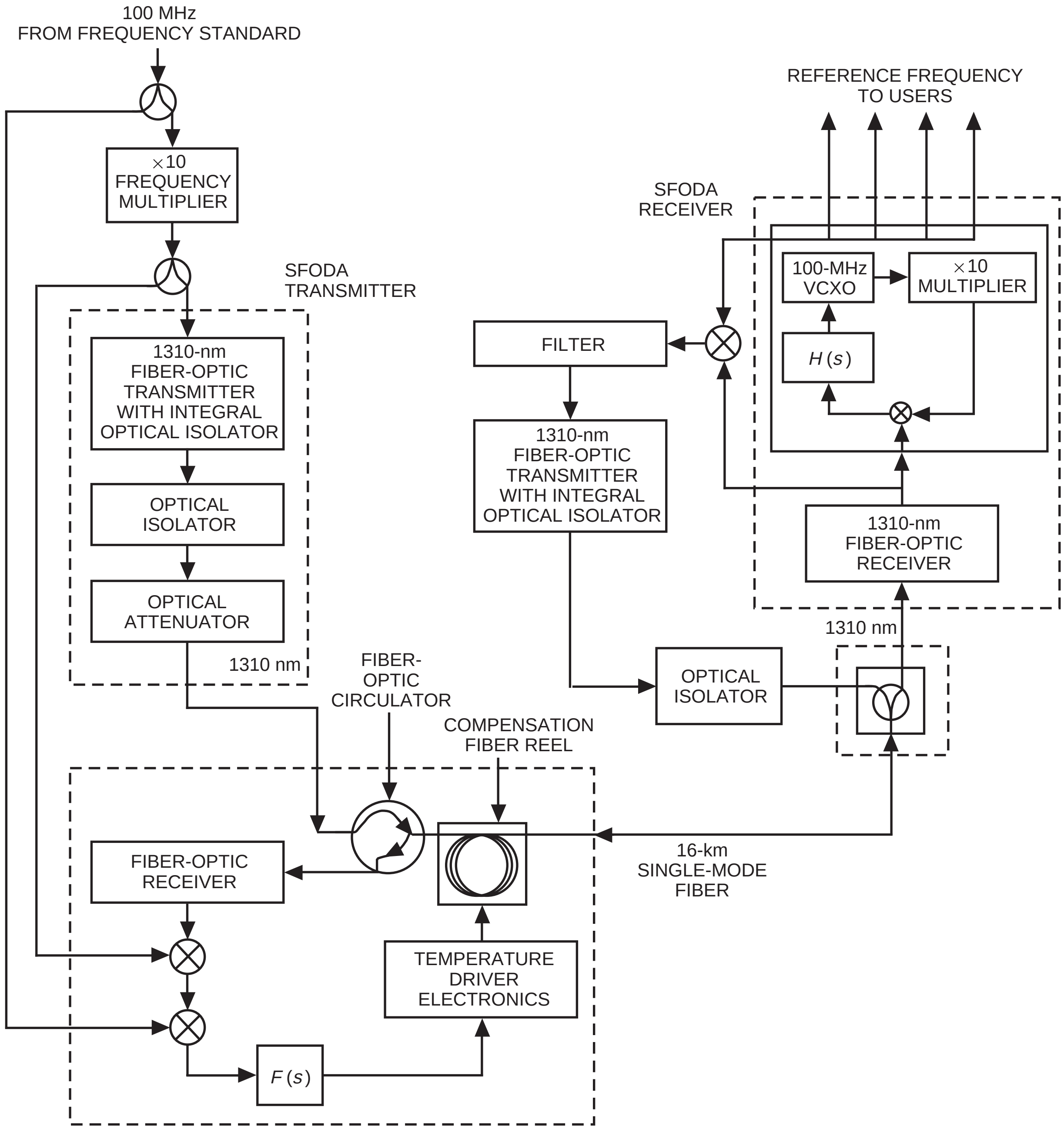

Fig. 6. The stabilized fiber-optic distribution assembly.

failure. To eliminate this problem, the side of the aluminum cylinder was slit to leave a gap of 0.05 cm. This gap was shimmed open during the winding of the reel, and the shims were removed after the winding was completed. This process ensures that the fiber is not stressed when the reel is at the highest design temperature.

The error signal from the phase detector is applied to a commercial process controller that controls the bipolar power to drive the reel temperature-control elements. The reel is mounted between two thermoelectric units so that the temperature of the reel is uniform and the response time is minimized.

V. Test Results

The SFODA was tested extensively at JPL's Frequency Standards Test Laboratory (FSTL) before delivery and installation at GDSCC. The test bed included a 16-km reel of optical fiber enclosed in a temperature-controlled chamber. The test setup for the SFODA stability measurement at the FSTL is shown in Fig. 7. A 16-km reel of commercial single-mode optical fiber (SMF 28) was temperature cycled in a commercial temperature chamber. The test results in Fig. 8 show the measured SFODA Allan deviation at 100 MHz versus the Cassini radio science requirements. Figure 9 shows the SFODA stability with and without compensation with the thermal chamber cycled ±1 deg C peak to peak, with a 24-hour period. For this test, the compensator reel was turned off and held at a constant temperature. The stability with compensation shows improvement by a factor of 1000 over the uncompensated fiber. Figure 10 shows the measured Allan deviation of the SFODA installation between SPC 10 and DSS 25. Note that the test setup for this measurement includes the forward link to DSS 25 as well as a second independent SFODA to return the signal to SPC 10 for comparison with the source reference signal. The 1-s Allan deviation of the SFODA alone does not meet Cassini radio science requirements; however, this deficiency is overcome with the addition of the CSO as a clean-up loop at DSS 25.

VI. Operational Applications

The SFODA was developed specifically to support Cassini radio science experiments at DSS 25. One spare SFODA has been fabricated and is operated as a hot spare and a test link for verification of performance.

A modified version of the SFODA, called the stabilized uplink fiber-optic assembly (SULFO) is used to stabilize the 3.8 GHz (S-band) signal that is sent from SPC 10 to the DSS 25 pedestal for the 32-GHz (Ka-band) exciter. This S-band signal is used in turn to generate the Ka-band uplink signal. The basic

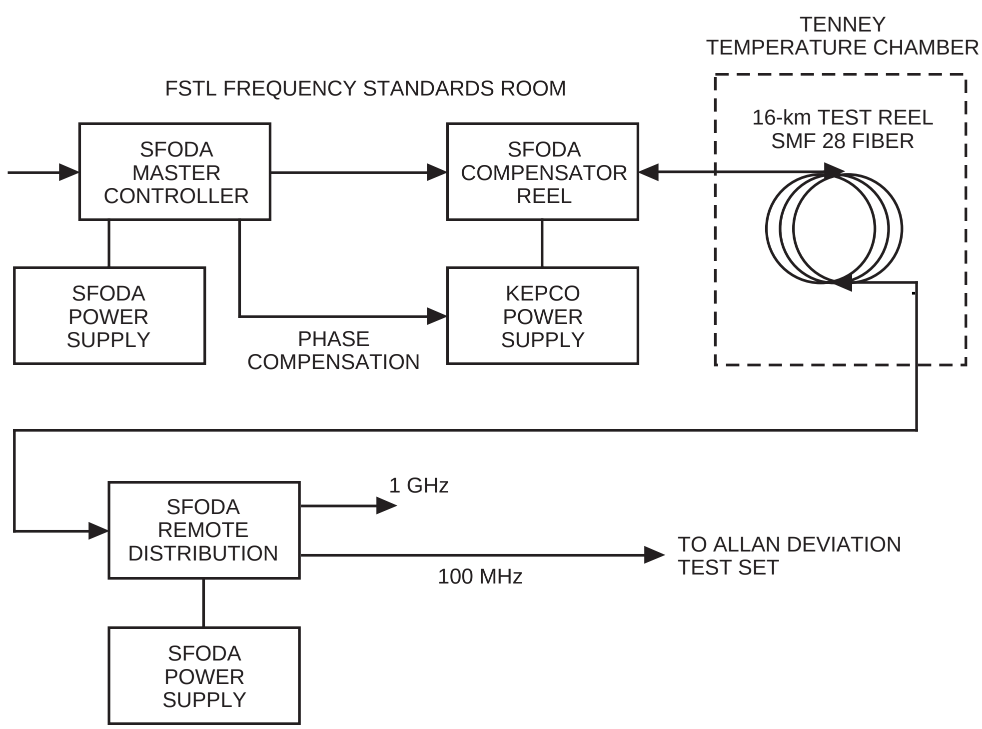

Fig. 7. Test setup for the SFODA Allan deviation measurement.

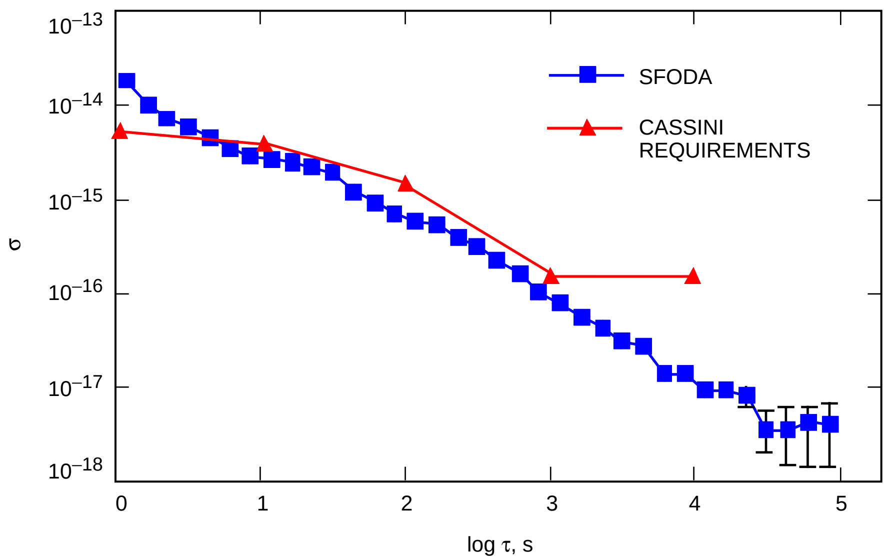

Fig. 8. Allan deviation of the SFODA over a 16-km fiber-optic link.

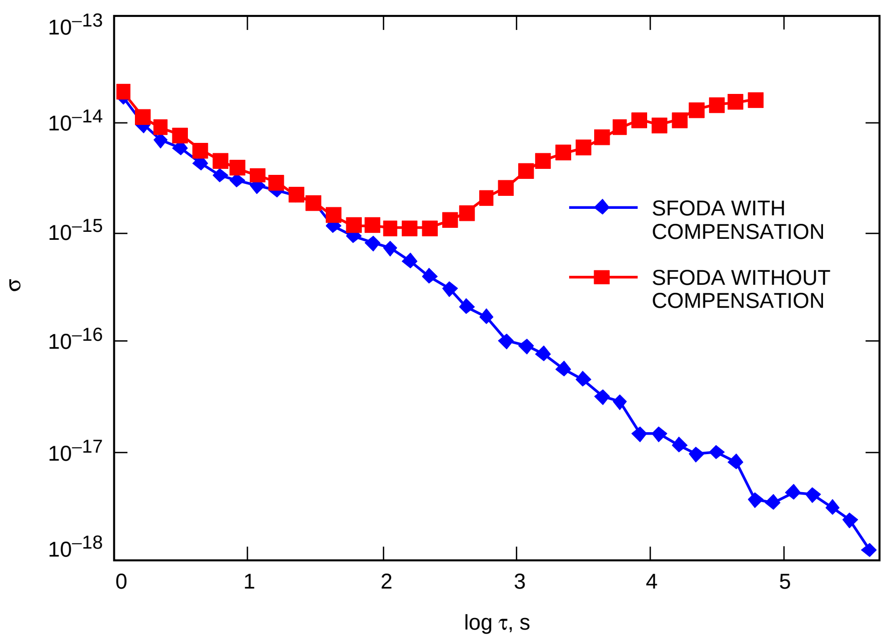

Fig. 9. Allan deviation of the SFODA with and without active phase compensation.

stabilization technique of the SULFO is the same as that for the SFODA. The major differences between the SFODA and the SULFO involve diplexing the SFODA 1-GHz signal and the S-band signal (~4 GHz) at the source and remote ends of the link.

A third application of the SFODA technology is for reference frequency distribution from SPC 10 to DSS 13, a distance of 27 km. A fully operational SFODA was installed and performance verified to support very long baseline interferometry (VLBI) and water vapor radiometer (WVR) connected-element interferometry (CEI) experiments between DSS 15 and DSS 13 [4].

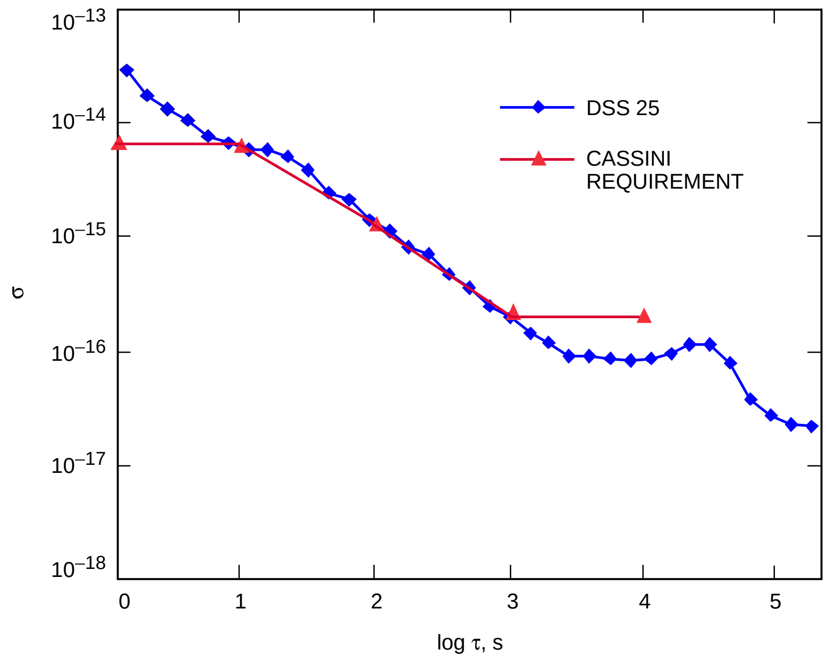

Fig. 10. SFODA Allan deviation, SPC 10 to DSS 25, two-way measurement (two SFODAs).

VII. Conclusions

The SFODA has been developed, tested, and installed at GDSCC. A second operational unit serves as a return link for performance verification and will be operated as a hot spare during critical observation times. The original engineering model SFODA was upgraded and installed for reference frequency distribution at DSS 13. This improved stability at DSS 13 allowed VLBI experiments for verification of the Cassini water vapor radiometers.

Stability measurements indicate that the 100-MHz reference frequency signal for Cassini radio science experiments meets or exceeds requirements. Environmental temperature effects have been reduced by providing active phase compensation over the 16-km fiber link. Additionally, provision of thermoelectric temperature control for the terminal equipment reduces the effects of temperature in the spaces where the electronics equipment are located. The FTS combination of an atomic frequency standard, the SFODA, and the CSO provides high performance at both short and long averaging times for radio science experiments requiring the most stringent stability and noise requirements.

Acknowledgments

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References

[1] G. J. Dick and R. T. Wang, "Design of a Cryocooled Sapphire Oscillator for the Cassini Ka-Band Experiment," *The Telecommunications and Mission Operations Progress Report 42-134, April–June 1998*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–10, August 15, 1998.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-134/134I.pdf

[2] M. Calhoun, J. C. Law, and P. F. Kuhnle, "Environmental Effects on Optical Fibers Used for Reference Frequency Distribution," *Proceedings of the Institute of Environmental Sciences Applications Meeting*, Paper 242, Las Vegas, Nevada, May 1993.

[3] M. Calhoun, G. J. Dick, and R. T. Wang, "Frequency Transfer and Cleanup System for Ultra High Stability at Both Long and Short Times for Cassini Ka-Band Experiment," *Proceedings of the 30th Annual Precise Time and Time Interval and Applications Meeting (PTTI)*, Reston, Virginia, pp. 405–412, December 1998.

[4] G. M. Resch, J. E. Clark, S. J. Keihm, G. E. Lanyi, C. J. Naudet, A. L. Riley, H. W. Rosenberger, and A. B. Tanner, "The Media Calibration System for Cassini Radio Science: Part II," *The Telecommunications and Mission Operations Progress Report 42-145, January–March 2001*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–20, May 15, 2001.
http://tmo.jpl.nasa.gov/tmo/progress_report/42-145/145J.pdf