STABILIZATION OF A FIBER-OPTIC LINK USING A TEMPERATURE-CONTROLLED FIBER SEGMENT

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Abstract

The Deep Space Network (DSN) of the National Aeronautics and Space Administration (NASA) is operated by the Jet Propulsion Laboratory (JPL), California Institute of Technology. The DSN uses fiber optics to distribute frequency and time to remote sites that may be as far as 32 kilometers from the Signal Processing Center (SPC) which contains the frequency standards and master clock. The fiber-optic cables are buried 1.5 meters underground. At this depth, the only apparent temperature variations are those due to the annual cycle, having a pseudo-sinusoidal behavior with a 1-year period and a diurnal cycle that is greatly reduced due to the insulation of the earth. Some variation is also caused by the air-conditioning cycling of the fiber-optic cable temperature in the plena of the buildings and the lengths of cable that are in the manhole vaults along the run. The resulting stability of the references at the remote site is well within the requirements of the DSN. However, the radio science requirements for the Cassini mission are much more stringent than the DSN requirements and the existing performance does not meet these requirements. The particular antenna (DSS-25) to be used for the 32 GHz portion of the Cassini radio science mission is 17 kilometers from the main control center and the apparent temperature variation (as measured by the delay variation) is 11°C peak to peak over the annual cycle. By inserting a temperature-controlled section of fiber-optic cable whose temperature is controlled in such a manner as to force the total delay to be constant, the annual variation (and small variations due to storm fronts passing through the area) can be reduced to a negligible amount. The length of this inserted fiber-optic section is > 3.74 kilometers and the temperature variation of this section over the year is 50°C. Details of the design and preliminary results are given.

INTRODUCTION

The Deep Space Network (DSN) of the National Aeronautics and Space Administration is operated by the Jet Propulsion Laboratory of the California Institute of Technology. It consists of three sites located at Goldstone, California; Robledo, Spain; and Tidbinbilla, Australia. Each of these sites has a Signal Processing Center (SPC) and a number of antennas ranging in size from 70 meters to 34 meters in diameter. The frequency and timing standards are located in the SPC and are connected to the various antennas by fiber-optic links. The links can be as

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long as 32 kilometers to the antenna farthest from the SPC. The fiber-optic cables to these remote sites are buried 1.5 meters underground in order to reduce the temperature variations. At this depth, the diurnal component of the temperature variations is greatly reduced. Some effects due to storm fronts, with a period of 4 to 7 days, can be seen, and annual variations are still present.

The station involved in the Cassini radio science experiments at 32 GHz is DSS-25, shown on the map of Figure 1. This station is 17 kilometers from the SPC. The measured annual delay variations in this 17-kilometer cable are the result of a pseudo-sinusoidal annual temperature variation of 11°C peak to peak with a period of 1 year. The diurnal variation results in an Allan deviation of 2×10^{-15} at an averaging time, τ, of $\approx$ 1,000 seconds The fiber-optic cables are standard single-mode cables, with the exception of a few places where the cables are not buried, where the fibers are the "zero temperature fiber" made by Sumitomo. This installation meets the present DSN FTS requirements. This paper covers the effect of the diurnal and annual variations and the use of a thermally controlled section of the cable to stabilize the delay.

DELAY VARIATIONS

The phase variations at the end of the cable due to the temperature variations are:

$$\begin{aligned}
\Delta\phi &= \frac{L}{c_c}(TC)\Delta T \sin(\omega_a t) \\
&= \frac{17\times10^3}{3\times10^8 0.7} 5.5 \sin(199\times10^{-9} t) \\
&= 627 \sin(199\times10^{-9}) \text{ radians.}
\end{aligned}$$

The corresponding frequency variation is given by:

$$\begin{aligned}
\Delta f &= \frac{d\Delta\phi}{dt} \\
&= 125\times10^{-6} \cos(199\times10^{-9}) \text{ radians/second} \\
&= 19.9\times10^{-6} \cos(199\times10^{-9}) \text{ hertz.}
\end{aligned}$$

The resulting peak Allan deviation is: $\sigma_y(\tau) \approx 2\times10^{-15}$ at $\tau = 4$ months. Clearly, the Allan deviation is not large enough to degrade the performance of the reference frequency, but the phase variation of 627 radians can be troublesome for interferometric work.

Using the same equation for the diurnal variations, we find that the apparent mean temperature variation of 10 millidegrees gives a phase variation of 0.62 radians, a frequency variation of 4.5×10^{-5} hertz, and an Allan deviation of 2×10^{-15} for a τ of 1,000 seconds. This is worse than the required stability and is the main reason for the development of the thermal cable stabilizer.

For the Cassini mission we will use a cryogenic, sapphire-stabilized oscillator/flywheel with the JPL-developed Linear Ion Trap Standard (LITS). This combination will produce a much more stable reference than the hydrogen maser. Several changes in the distribution system are being made to retain this stability. The stabilized fiber-optic cable is just one of them.

The concept of the stabilizer involves inserting a section of fiber-optic cable in the distribution system with a length sufficient that, with a temperature variation of 50°C, it will compensate for the delay variations of the 17 km of buried fiber. Since the annual temperature variation of the buried fiber is 11°C, the length of the controlled section must be $(\frac{11}{50})\times 17 = 3.74$ kilometers.

A diagram of the planned system is shown in Figure 2. In this figure, the reference signal (100 MHz) in SPC 10 is multiplied to 1 GHz in order to reduce the phase noise contributed by the link. The 1 GHz reference signal is then used to modulate a 1,310 nm laser. This laser has an internal isolator and another isolator is added to obtain the necessary isolation to produce low interaction between the laser and the reflections on the fiber. The optical signal then goes through the compensation fiber reel and then to the remote site.

At the remote site the signal is detected to reproduce the 1 GHz reference signal. A phase-locked loop is used to generate the necessary reference signal for the remote site (100 MHz). The 100 MHz is also used to modulate the 1 GHz signal. This produces the two sidebands with a suppressed carrier. The carrier is further reduced with a notch filter and the signal then modulates an 1,310 nm laser that also has additional isolation. The output of this laser is sent back to the original site over the same fiber that was used to send the original signal to the remote site. At the main site, the signal is down-converted to 100 MHz and then to base-band to produce an error signal. This error signal is filtered to remove the residual 100 MHz and to produce the correct dynamic and static stability for the loop. The output of the filter drives the temperature driver electronics to controls the temperature of the fiber-optic reel to vary the delay in such a manner to keep the error at zero, i.e., to maintain a constant delay in the system.

The temperature compensation fiber reel consists of 4 km of fiber wound on an aluminum reel 20 cm long and 20 cm in diameter. A Peltier cooler/heater is fastened to each end of the reel to minimize gradients and to decrease the response time. The normal operating temperature varies from 0°C to 50°C.

Preliminary tests in the laboratory show a reduction of delay variations by a factor of > 300. This is enough to ensure that the contribution of phase variations due to the fiber-optic link will not degrade the frequency standards. The response time of the system is approximately 60 seconds. This is fast enough to reduce the variations due to air-conditioning cycle effects in the plena to acceptable levels.

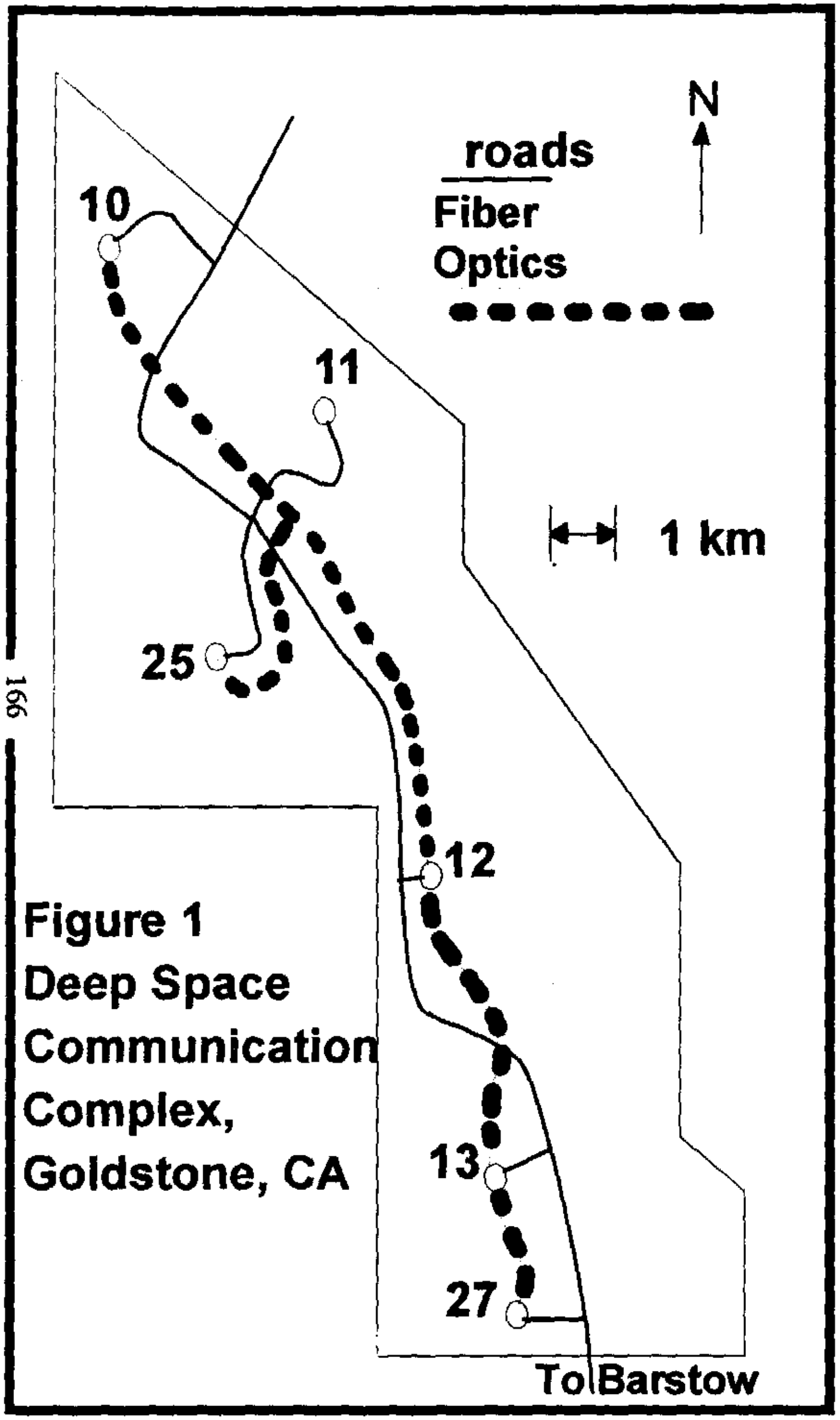

Figure 1
Deep Space Communication Complex, Goldstone, CA

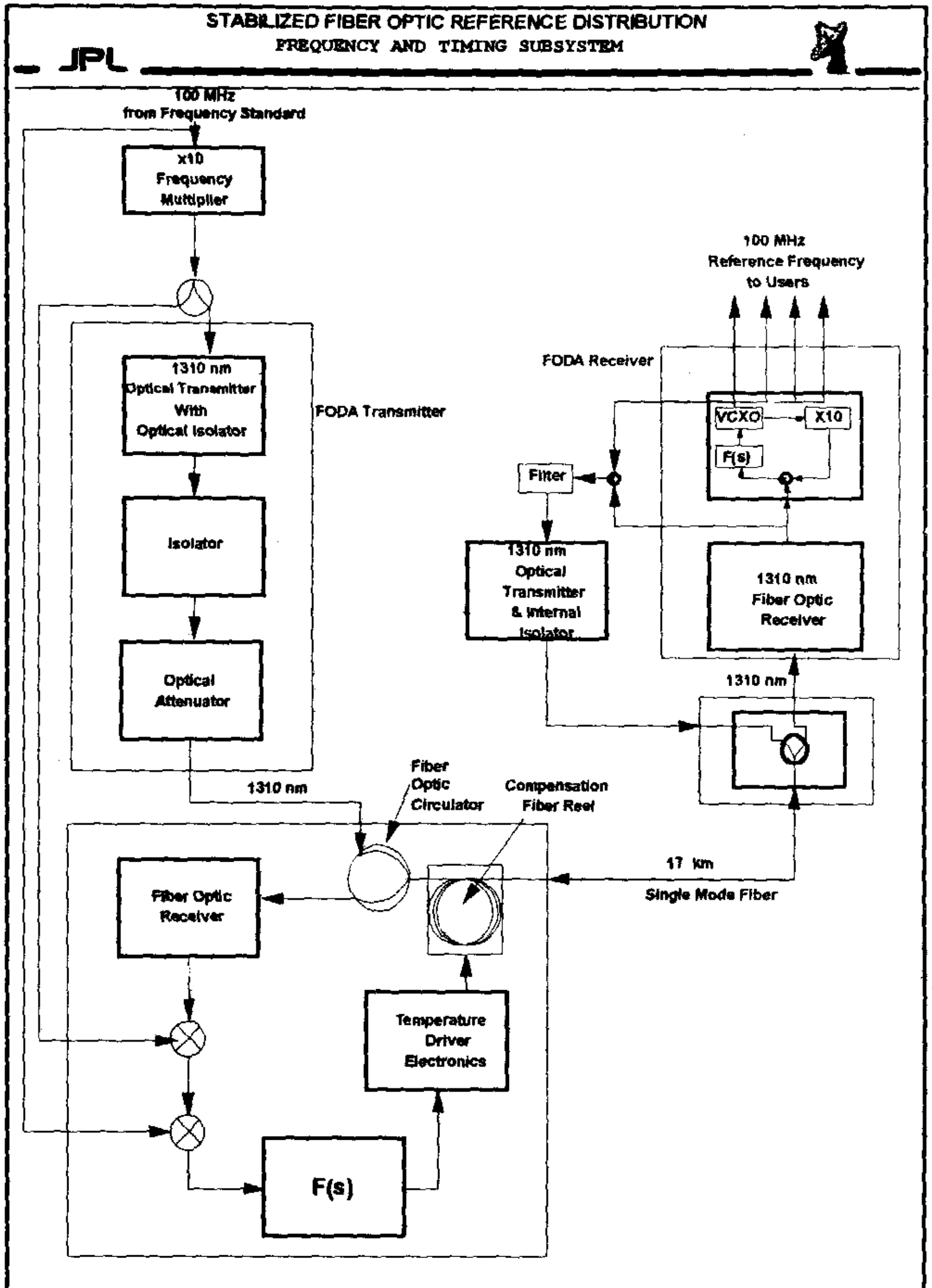

Figure 2 Phase Stabilized Fiber Optic Reference Frequency Distribution Transmission Frequency 1 GHz, Pound System

Questions and Answers

MARC WEISS (NIST): If you know the fluctuations, you've measured the change in the physical length of the cable, or actually the frequency offset, why not steer it with a microphasestepper instead of using all the hysteresis involved with the temperature?

RICHARD SYDNOR: Microphasesteppers put in little slopes and things which gives us degradation of the performance of the frequency standard. And besides, this system, since it's controlling the actual delay – not the phase delay, the actual time delay – now we can use that fiber for any other frequency we want to send through there, and they're all stabilized. It's a broadband system.

We've done what you've suggested at times in the past. But it's a single frequency device. You use up a fiber with one signal on it that's many gigahertz of bandwidth. And this is a much more practical thing, we think, than doing it that way.

MARC WEISS: Do you find any problem with hysteresis of the temperature cycle? You store heat in it and then you have to lose it.

RICHARD SYDNOR: Since it's a control loop, we haven't seen any problems with hysteresis.

BOYD MOORE (KAMAN SCIENCES CORP.): What kind of a response time are you seeing with this system?

RICHARD SYDNOR: We're trying to compensate for the diurnal variations primarily. And the response time that we're using now – I think we're running at 1-minute response time. The thermal time constant of the control spool is the main limiting thing. The roundtrip delay time is very small compared to the thermal response time of the spool, even though it's been made as fast as we could make it.