DISTRIBUTION OF ULTRA–STABLE REFERENCE FREQUENCY SIGNALS OVER FIBER OPTIC CABLE*

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Abstract

Radio telescope systems, which operate primarily at microwave frequencies, are used for radio and radar astronomy, very large baseline interferometry (VLBI), geodynamic measurements, and spacecraft navigation. Experimenters have struggled for years to overcome the deficiencies of metallic coaxial cables and wave–guides which have limited the stability and accuracy of measurements made with radio telescope systems. Recent advances in fiber optic technology are on the verge of eliminating transmission lines as the major source of error in these systems. This paper describes high stability fiber optic links developed at JPL which are used to distribute reference frequencies over distances as far as 29 kilometers. Reference signals generated by hydrogen masers are distributed over these links and maintain a stability of 1 part in 10^{15} for 1000 second averaging times.

INTRODUCTION

For applications including coherently arrayed antennas, radio and radar astronomy, very long baseline interferometry (VLBI) and geodynamic measurements, an ultra–stable distribution system capable of distributing RF signals over distances up to tens of kilometers can greatly enhance the performance of radio telescopes [1]. Fiber optic distribution systems provide a reliable, cost efficient means of disseminating ultra–stable RF signals to remote antenna locations without degrading the stability of the signal.

The Time and Frequency Systems Research Group for the development of techniques for distributing ultra–stable signals throughout the NASA/JPL Deep Space Network (DSN) complex at Goldstone, California as well as the development of new frequency standards with improved stability. The fiber optic distribution system at Goldstone has provided the necessary distribution stability for hydrogen maser signals to be used in such diverse applications as gravitational wave detection, spacecraft navigation, telemetry arraying, connected element interferometry and debris radar [2].

The Goldstone complex consists of four stations, each supported by a parabolic dish antenna with an ultra–sensitive receiving system requiring a precise frequency reference. The stations are supported by a primary hydrogen maser with a stability of 1 part in 10^{15} for 1000 second averaging times (at 100 MHz). The hydrogen maser signal has been distributed over a 29 kilometer link without appreciably degrading its stability [2].

Future frequency standards such as the trapped mercury ion standard and the superconducting cavity maser will have improved short and long term stability and operate in the 1–100 GHz range. With the development of these new standards, the stability of the distribution system must also improve. In general, the stability of the distribution system should be at least ten times more stable than the reference signal being transmitted.

There are many advantages to using fiber optic cable as the distribution medium for ultra–stable reference frequencies, including its low loss, immunity to EMI and RFI, light weight, high bandwidth and low thermal coefficient of delay (TCD). Therefore, for applications dependent on the stability of the distributed signal, optical fiber is superior to traditional distribution mediums such as coaxial cable, waveguide and terrestrial microwave. This paper will discuss the considerations pertaining to the development of ultra–stable distribution systems and the improve- ments that can be made for better short and long term distribution stability.

SYSTEM DESCRIPTION

A generalized model of a fiber optic link is shown in Figure 1. A basic fiber optic link consists of some or all of the

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following components: laser, optical isolator, modulator, fiber optic cable, photodiode detector, output matching network and amplifier.

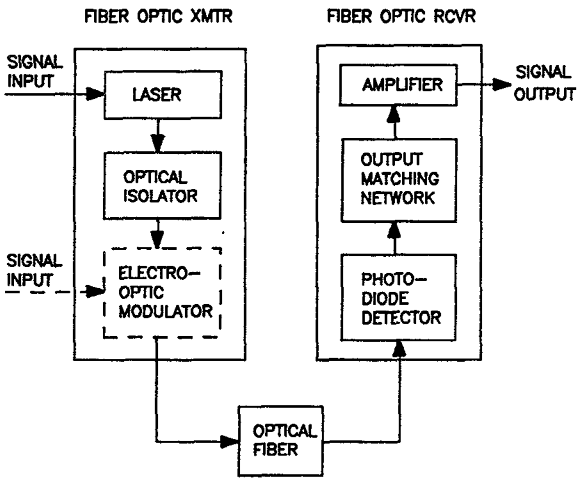

Figure 1: Model of fiber optic link.

- Various types of lasers including semiconductor distributed feedback (DFB), Fabry–Perot and diode laser pumped solid-state Nd:YAG lasers are being evaluated at JPL for their stability.
- Optical isolators are used to prevent light reflected from connectors and splices from entering the laser cavity and degrading the stability.
- Microwave signals may be distributed over fiber optic cable by modulating the optical signal from the laser at the microwave frequency. The optical signal is modulated either by directly modulating the current on the laser or externally modulating the intensity of the light in an electro–optic external modulator.
- Fiber optic cable is a low loss medium with low thermal coefficient of delay and thus is an ideal medium for distributing signals over long distances in adverse environments.
- The photodiode detector, output matching network and follow–on amplifiers make up the optical receiver.

The stability of the distributed signal is dependent on all the components of the link, as will be discussed.

STABILITY CONSIDERATIONS

An ideal distribution system would distribute signals without any degradation of phase or amplitude stability. For reference frequency distribution, the phase stability of the distributed signal is of primary concern. Phase fluctuations of the transmitted signal can be examined in three regimes: high frequency (greater than 10 Hz), mid–frequency (0.1 to 10 Hz) and low frequency (less than 0.1 Hz).

There are two complimentary methods of measuring the stability of a reference signal; the phase noise of the signal and its Allan deviation [3]. For phase noise measurements, the transmitted signal is mixed down to DC in quadrature with the input, so that the phase noise at offset frequencies greater than 1 Hz from the carrier may be examined. For Allan deviation measurements, a two–sample deviation that describes the frequency stability at averaging times greater than 1 second is measured.

The short term stability corresponds to phase fluctuations at high offset frequencies from the carrier. It is set by the amount of phase noise added to the signal by the fiber optic link and is typically limited by the signal–to–noise ratio (SNR) of the fiber optic link. The long term stability corresponds to phase fluctuations at low offset frequencies. The long term stability is degraded by group delay variations in the signal path due to temperature variations along the fiber, or other low frequency noise sources in the system. The mid–term stability corresponds to phase noise at frequencies in the range of 0.1 to 1 Hz. This phase noise seems to be determined by the characteristics of the particular laser transmitter and optical receiver used, and has a $1/f^n$ character which varies between system types. Current research focusses on the noise characteristics of the various components in the mid–term regime.

Short Term Stability

The short term stability of a fiber optic link is generally limited by the phase noise of the received signal. For offset frequencies greater than 10 to 100 Hz, the single side band (SSB) phase noise in dBc is typically equal to the SNR of the link measured in a 1 Hz bandwidth. In an optical distribution system, the SNR for a single frequency carrier is [4],

$$SNR = \frac{(m \cdot r)^2 \cdot R_L \cdot (10^{\frac{-P_L}{10}} \cdot P_O)^2}{(2 \cdot P_N)} \qquad (1)$$

where,

SNR = signal to noise ratio [dB − Hz],
m = optical modulation index,
r = responstivity of the photodiode [A/W],
R_L = load resistance across photodiode [Ω],
P_L = optical loss [dB],
P_O = average optical power in fiber [Watts] and

P_N = thermal and shot noise [W/Hz].

According to this equation, the SNR and thus the short term stability may be improved by increasing the amount of optical power coupled into the fiber, the modulation index and photodiode responsivity, and by reducing the optical losses in the system and the electronic system noise. Typically, these systems are limited by the laser relative intensity noise (RIN) for directly modulated semiconductor lasers, or by the quantum limit of photon–induced shot noise for the Nd:YAG–based systems. With present DFB lasers, a SNR of 130 dB-Hz can be attained at 100 MHz, but decreases with higher modulation frequencies. With present solid state lasers such as the Nd:YAG coupled to external electro–optic modulators, a SNR of 140 to 150 dB-Hz up to microwave frequencies can be achieved.

Long Term Stability

The long term stability of a distribution link is also limited by the SNR of the distributed signal but is usually degraded by group delay variations of the fiber due to temperature excursions and low frequency noise characteristics of the laser.

Group delay variations are typically caused by temperature variations on the cable. For fiber optic cable buried 1.5 meters underground, the temperature variation may be 1–10 milli–°C over a 24 hour period. The Allan deviation as a function of a sinusoidal temperature variation is given by [5],

$$\sigma_y(\tau) = \frac{L \cdot \alpha \cdot \delta T \cdot n}{c \cdot \tau} \cdot \left[\sin^2\left(\frac{\pi\tau}{P_T}\right)\right] \qquad (2)$$

where,

τ = averaging time [seconds],
α = thermal coefficient delay (TCD) [ppm/°C],
L = length of the cable [meters],
δT = peak to peak temperature change [°C],
n = index of refraction of the fiber,
C = speed of light [3×10^8m/sec] and
P_T = period of temperature change [seconds].

From equation (3), it is evident that the long term stability can be increased by decreasing the temperature change or using fiber with a lower thermal coefficient of delay. Standard single mode optical fiber inherently has a low TCD of approximately 7 ppm/°C and new fiber with a TCD of 0.1 ppm/°C is being considered for such applications.

Mid-Term Stability

The observed phase stability of fiber optic systems between 0.1 and 10 Hz typically follows a $1/f^n$ power spectrum, where n is typically between 1 and 3. It has been found that low frequency fluctuations in bias current stability in this frequency range will appear as phase noise sidebands on the distributed signal. However, when the bias current fluctuations are reduced to an adequately low level, a 1/f phase noise response is still observed. Methods of reducing this phase noise through electronic feedback are currently being evaluated.

STABILIZED FIBER OPTIC DISTRIBUTION LINK

Temperature variations on the fiber optic cable are the largest cause of degradation of frequency stability. Burying the fiber optic cable underground reduces most of the temperature variations on the cable and thus the fiber optic system is passively very stable. When even greater stability is required, the temperature variations can be compensated by adding a corrective amount of phase. A cable delay compensator (CDC) has been built and tested at JPL [6],[7].

The basic operation of the stabilized fiber optic link is that the reference signal is transmitted both ways through the same fiber by reflecting half of the signal at the remote unit. The signal experiences identical delay in the two directions so that the midpoint of the signal delay is at the far end of the cable. If the phases of the transmitted and received signals at the reference end of the cable are conjugate, the phase at the remote end is independent of phase delays in the medium. The CDC is an electronic device that detects the phases of the transmitted and received signals at the input to the fiber and adds enough phase to maintain conjugation and thus stabilize the signal at the remote unit (Figure 2).

The CDC compares the phase of the transmitted and received signals in the reference unit and derives an error voltage from the phase difference. This voltage is then used to control a voltage–controlled oscillator (VCO). The output of the VCO is divided into two signals. One of the signals is received by the CDC and the other modulates the optical carrier emitted from the laser transmitter. The modulated optical signal is transmitted to the remote unit through the optical coupler. A 50/50 mirror at the remote unit reflects half of the optical signal back toward the reference unit while the other half passes through the mirror to the optical receiver. The receiver demodulates the optical signal and amplifies the resulting RF signal. The reflected optical signal returns to the reference unit where it passes through the optical coupler and is detected by another optical receiver and sent to the CDC.

The CDC was designed to work with a 1300 nm DFB laser modulated at 100 MHz. It was tested with a 4 kilometer link of fiber in an environmental test chamber. The temperature of the fiber optic cable was varied sinusoidally 10 °C over a 24 hour period. The Allan deviations of the

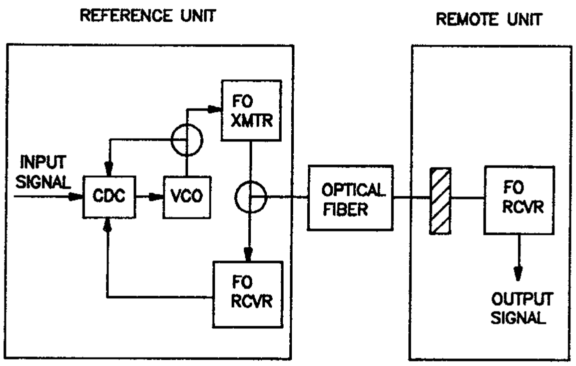

Figure 2: Block diagram of cable delay compensator.

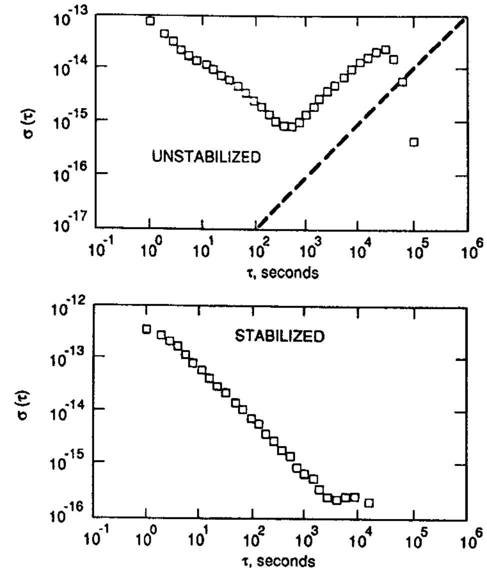

Figure 3: Allan deviation for unstabilized and stabilized 4 kilometer fiber optic link.

stabilized and unstabilized links are shown in Figure 3. These plots show a 400 times reduction of phase deviations caused by the temperature change on the link at 10000 second averaging times.

FUTURE DIRECTIONS

Future plans at JPL include using a Nd:YAG laser with an external modulator in the cable stabilizer. This should provide longer stabilized links due to the higher power, narrower linewidth and lower noise. A 1 GHz distribution system is being developed, with plans to develop distribution systems that operate up to Ka band. An additional application of fiber optic distribution systems currently under investigation is the direct transmission of microwave signals from the cone of an antenna to a control room for processing [4]. This eliminates the need for providing a LO in the cone and down conversion the signal.

CONCLUSION

Fiber optic distribution systems are the only distribution systems that can disseminate ultra-stable frequencies over tens of kilometers. The applications of such a distribution system cover a wide range of scientific research. As systems with lower SNR and group delay variations are developed, distribution systems with improved short and long term stability can be realized. Active stabilization with a cable delay compen- sator (CDC) has been shown to reduce phase variations by 400 times and improved methods of active stabilization will further enhance the use of fiber optic distribution systems.

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