STABILIZED PHOTONIC LINKS FOR DEEP SPACE TRACKING, NAVIGATION, AND RADIO SCIENCE APPLICATIONS[1]

S. Huang and R. L. Tjoelker
Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, CA USA
Email: Shouhua.Huang@jpl.nasa.gov

Abstract

Stable fiber optic links have been operational in NASA's DSN for over 20 years providing distribution limited fractional frequency stability below 10^{-14} at one second and reaching 10^{-18} at ~10,000 seconds. We summarize recent stabilized photonic link developments for DSN operation capable of high performance and reliability, and at much lower cost than previous systems. Recent research has focused on two applications, 1) actively stabilized links to transport 100 MHz metrology frequency references to sites up to 30 km from the central atomic frequency standard, and 2) stabilized links transporting broadband S, X, and Ka band signals used in deep space tracking and navigation and antenna arraying applications.

INTRODUCTION

Low phase noise and long term stable reference signals originating from state of the art atomic frequency standards require an ultra-stable transmission medium for long distance transport. Some of the earliest metrology applications of stable fiber optic links were developed for use in NASA's Deep Space Network to provide coherent frequency references at antennas located some distance from a centrally located frequency standard. Open and closed loop distribution approaches were researched at JPL starting in the 1980's **[1-3]** and low noise links have been implemented in the DSN for over twenty years **[4]**.

Fiber optic signal distribution is conceptually simple and the optimum approach is highly dependent on the intended application. Examples of different photonic link requirements:

- Signal: Frequency or time comparison; syntonization or synchronization, phase alignment
- Band: microwave or optical
- Differential stabilization or absolute calibration
- Short or long term stability
- Distance
- Operability/complexity/reliability
- Cost

Noise processes in the basic link components (photonic transmitter, receiver, and fiber optic cable) limit achieved system performance at different time scales. For actively stabilized systems there are several methods to probe/measure link perturbations and generally the higher the frequency and more precise the probe, the better the phase delay measurement and compensation. Correcting fiber optic distribution related phase variations is accomplished with one or a combination of methods that vary in complexity and response time. Common methods include using a quartz oscillator to provide electronic delay compensation, or physical compensation through use of piezo stretchers, thermally controlled fiber optic spools, or variable (mechanical) optical phase shifters.

PHOTONIC LINKS IN THE DEEP SPACE NETWORK

The NASA Deep Space Network (DSN) consists of three deep space communication complexes (DSCCs) that require multiple transmission links to distribute the stable, low noise frequency standard and clock reference signals to each antenna. These references support spacecraft range and Doppler tracking, delta differential one way range tracking, and accurate time tagging for VLBI observations. The distance from the central frequency standard to each antenna ranges from a few hundred meters up to thirty kilometers.

JPL has previously researched several different approaches to minimize link noise and stabilize link performance through passive and active means and both open and closed loop Fiber Optic Distribution Assembly (FODA) systems have been implemented in the DSN (for a summary, see **[4]**). Passive approaches minimize the magnitude/impact of external thermal perturbations on the fiber optic cable. Standard telecom fiber optic cable inherently has a low thermal sensitivity of 7 ppm/°C, and specialized fibers with a thermal sensitivity of 0.1 ppm/°C are used in some applications. Furthermore burying fiber optic cable deeper than ~1.5 meters in the ground provides thermal isolation from diurnal temperature variations.

For applications demanding additional stability, stabilized approaches must be implemented. Low noise, 16 km long stabilized links were implemented in the DSN to enable gravity wave searches with the radio link to the Cassini spacecraft. The fiber optic link perturbations were compensated using a thermally controlled 4 km long fiber optic spool, achieving long term stability at the 10^{-18} level **[5,6]**. While very reliable, these stabilized systems are large and expensive and not amenable to large scale implementation in multiple antennas or antenna array applications.

The lasers in the current DSN FODA and Stabilized-FODA (SFODA) systems are near end of life and have motivated new development for high performance, highly reliable, and cost effective stabilized photonic link systems. In this work, we report developments on two stabilized photonic link approaches. The first method incorporates a Variable Optical Phase Shifter (VOPS) to directly compensate phase fluctuations of the transmission line. In a second method we revisited using electronic "phase conjugation" first studied at JPL in the 1980s **[1, 2]**.

STABILIZED PHOTONIC LINKS (SPL)

FREQUENCY INDEPENDENT COMPENSATION

The frequency independent Stabilized Photonic Link (SPL) using a variable optical phase shifter (VOPS) as the fiber compensating element has been previously described **[4]**. This simple approach can be used to distribute arbitrary frequency references over a very large frequency band or signals with modulation structure superimposed. The approach is particularly amenable to large scale downlink/uplink array application. It also would be effective in antenna remoting applications where a broadband high frequency signal is transported directly to a central control room before signal demodulation.

Figure 1 shows a possible link configuration for an uplink array. With a slightly different transmitter, receiver, and E/O modulator configuration the same technology can also be used in downlink, and antenna remoting applications. The main features of this link technology are:

- A low-cost laser transmitter (calibration channel) is modulated by a fixed frequency reference signal (~400 MHz) originating from a DSN hydrogen maser.
- A variable optical phase shifter (VOPS) is used to compensate the link phase change as measured by the calibration channel.
- Wavelength-division multiplexing (WDM) technology is used to reduce crosstalk between the main signal channel and the calibration channel. Since the calibration / compensation channel has been separated from the main signal channel, the link may transfer any frequency from 10 MHz to 40 GHz (limited by the RF components and E/O modulator).
- A high power laser can simultaneously drive 16 parallel distribution links.

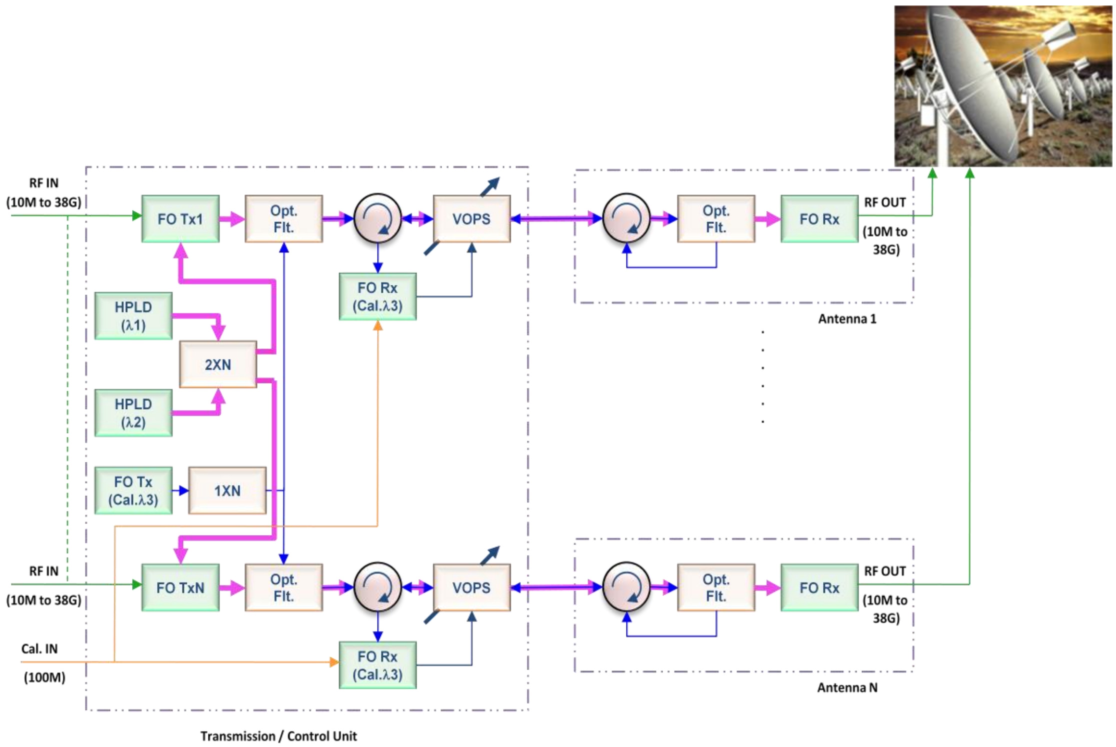

Figure 1. Frequency independent SPL in an uplink array configuration.

Figure 2 shows the degree of stabilization obtained when transmitting X-band signals through a 2 km test fiber exposed to a 7 °C peak to peak diurnal thermal perturbation. When operating open loop, a phase voltage change of 150 mV is measured corresponding to a 480 ps time delay. When the loop was closed (phase stabilized), the phase voltage change was less than 43 μV, corresponding to a fiber delay change reduced to < 0.138 ps representing a stability improvement of >3500. Since the link is frequency independent, in a 10 GHz transmission link over a 2 km fiber the delay fluctuation (with 7 °C temperature change) will cause a signal phase change as high as 4.8 cycles of the signal (i.e. 1728°, or 30.16 rad.) for open loop operation. For a closed (phase stabilized) loop, the fluctuation is reduced to less than 0.5° (or 0.009 rad.). We have also built a polarization maintaining Ka-band modulator system for demonstration at Ka band.

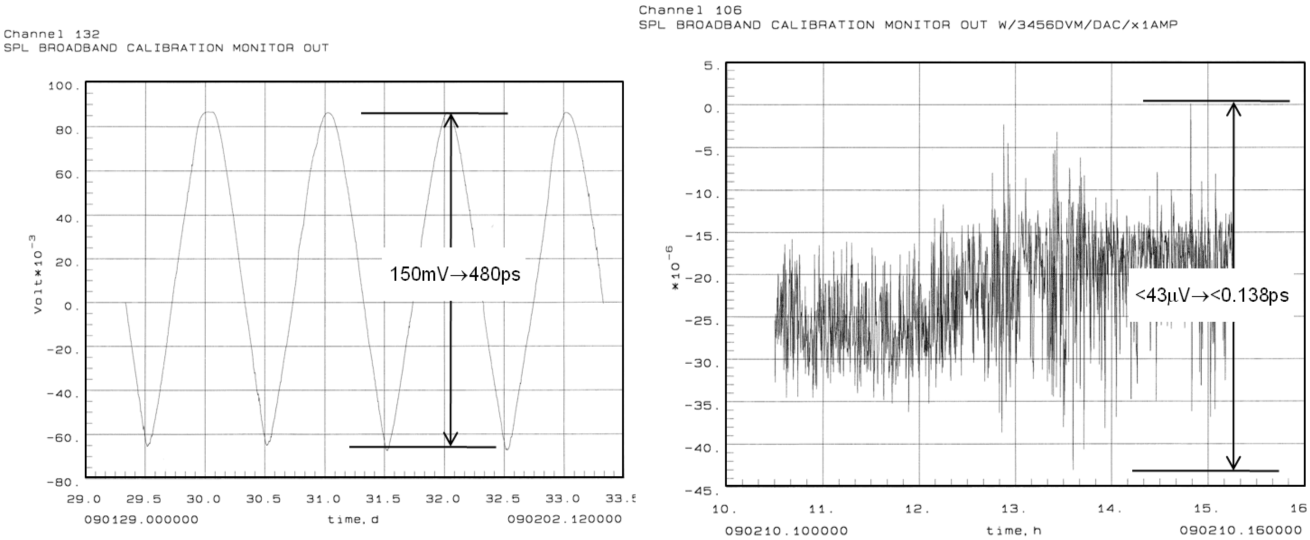

Figure 2. a) Open loop variations with a 7 °C peak to peak thermal perturbation applied to a 2 km fiber optic cable. b) with the loop closed the variation is significantly reduced, demonstrating a gain >3500.

Electronic Compensation - Phase Conjugation

Electronic stabilization to compensate for fiber optic cable related delays relying on the conjugate phase was first demonstrated at JPL in the 1980s, but was not implemented in the DSN due to component performance limitations at that time. This method is attractive for small, low cost applications transmitting a fixed frequency, e.g. 100 MHz metrology reference signals to each DSN antenna.

The principle of phase conjugation assumes a high degree of symmetry and that the distribution phase delay at the midpoint is half of the round trip delay:

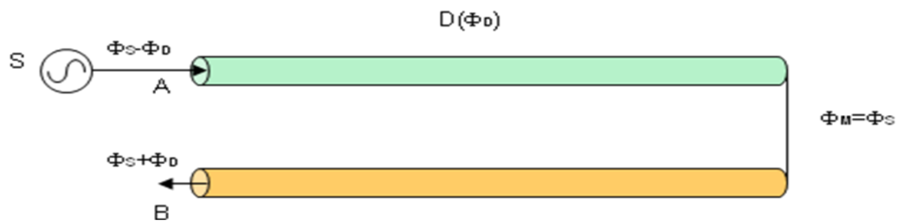

Figure 3. Phase conjugation, ideal system.

If Φ_S is the phase at the source and the distribution distance D introduces a phase delay of Φ_D, then the relative phase relationship at point A is (Φ_S-Φ_D) and at point B (Φ_S+Φ_D). The corresponding signals at A and B are:

$$S_A(t) = S_O e^{-i(\omega t+\Phi_S-\Phi_D)} \quad \text{at point A} \quad (1)$$

$$S_B(t) = S_O e^{-i(\omega t+\Phi_S+\Phi_D)} \quad \text{at point B.} \quad (2)$$

This phase relationship is referred to as the conjugated phase, or "phase conjugation". With the user located at the midpoint (denoted by *M*) in this ideal system the phase at the midpoint Φ_M is independent of any change in Φ_D.

$$\Phi_M = (\Phi_S - \Phi_D) + \frac{[(\Phi_S+\Phi_D)-(\Phi_S-\Phi_D)]}{2} = \Phi_S \quad (3)$$

Figure 4 shows a phase conjugation system implemented with an optical transmitter and receiver, and an optical fiber as the transmission (delay) line. A VCO serves as the loop frequency discriminator and compensating element. Typically the noise of the VCO and the optical devices (transmitter and receiver) will be much higher than the RF components, so for a noisy VCO, we have

$$\Phi_M = \Phi_S + \Delta\Phi_V + \Delta\Phi_T + \Delta\Phi_R \tag{4}$$

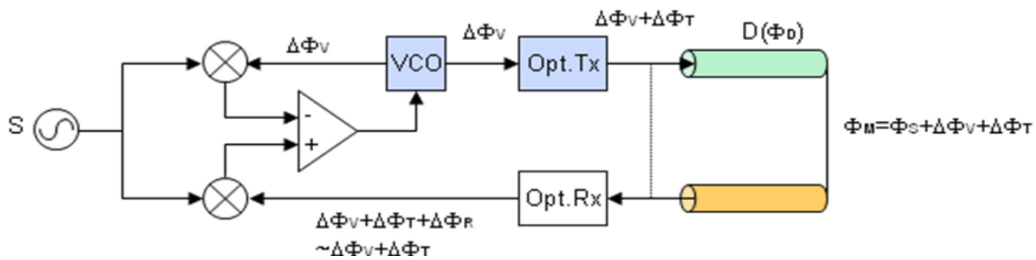

Figure 4. Block diagram of phase conjugation system with a noisy VCO.

Since the VCO noise and transmitter laser noise (RIN, non-zero linewidth) are much higher than other components and asymmetric in the loop, short term instabilities are not fully compensated by the conjugate phase assumption. The component noise therefore limits achievable short term stability.

Several VCO's of vastly different cost (20 to 10,000$) and phase noise/stability performance were examined in a phase conjugation stabilized photonic link. As expected, the lower performing oscillators significantly degraded the SPL phase noise and short term stability. Similarly, several commercially available and highly reliable laser diode transmitter and receiver components were examined. The laser diode transmitter is the most critical component and must be carefully selected based on the application, transmission distance (power), and noise properties of the laser. The open loop stability noise floor resulting from the Tx and Rx components selected for our application are shown in Figure 5.

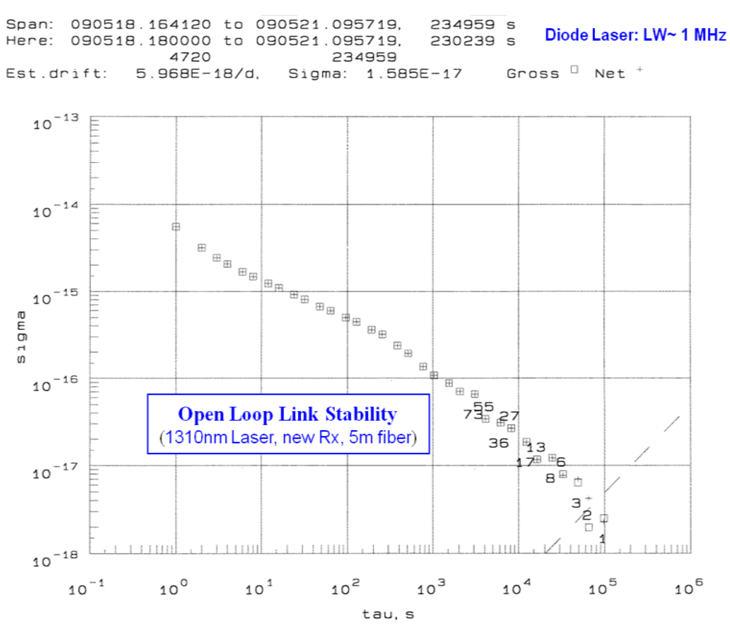

Figure 5. Measured noise floor resulting from the photonic and receiver components (short fiber in a controlled thermal environment).

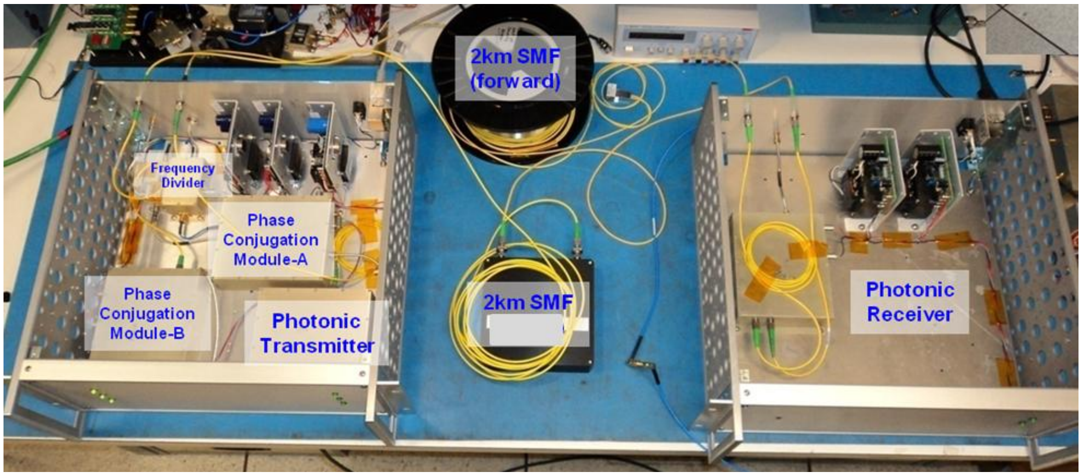

Figure 6. Phase conjugation based stabilized photonic link.

Figure 6 shows the complete stabilized link development model connected to a 2 km test fiber. Figure 7 shows the 2 km link performance with the loop open and the 2 km telecom grade fiber in a thermal chamber experiencing a 15 C diurnal thermal perturbation. Figure 8 shows the link stability when the phase conjugation loop is closed. For short averaging times (< 100 seconds), the phase conjugated closed loop stability is degraded from the open loop link noise floor shown observed in Figures 5 and 7. This is primarily due to VCO noise from the inexpensive (~$100) oscillator used in this demonstration. For averaging times (>10^4 seconds) the closed loop phase conjugation link provides 100-1000x improvement.

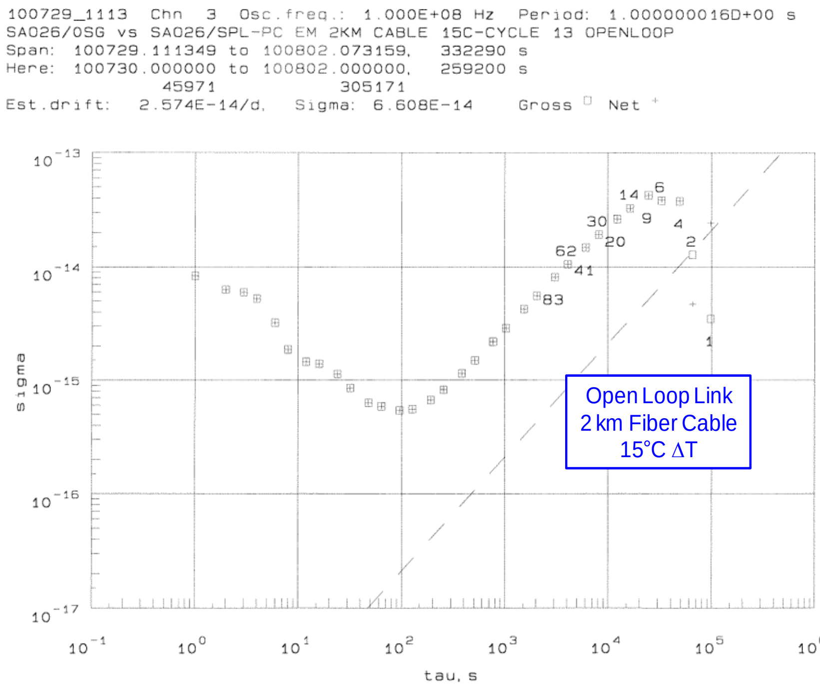

Figure 7. Open loop link stability with a 2 km fiber exposed to 15 °C diurnal perturbation.

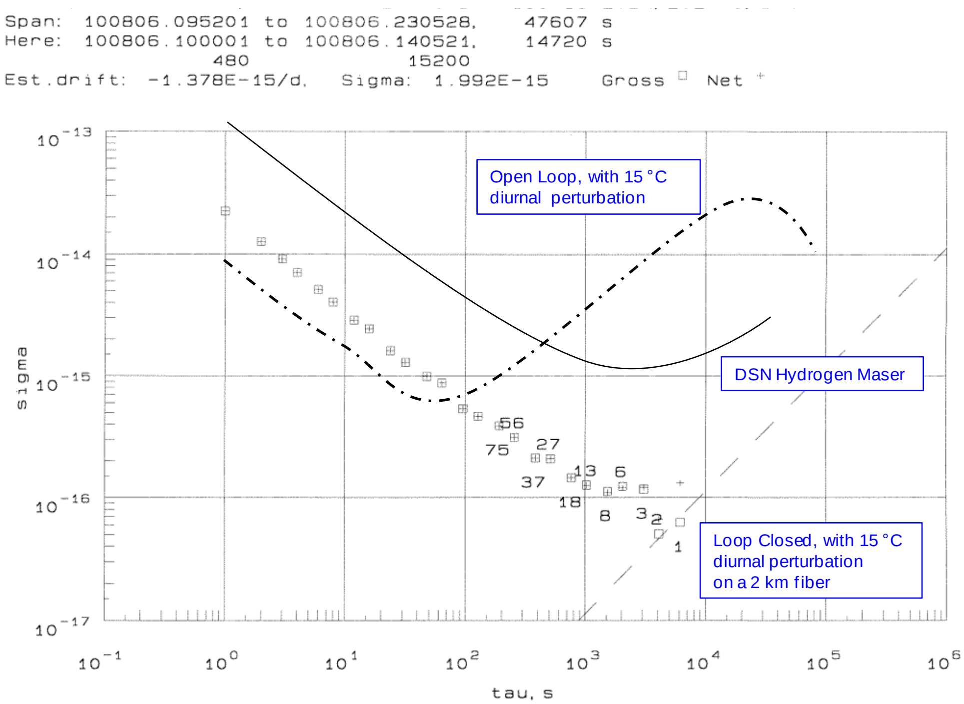

Figure 8. Open and closed loop phase conjugation system stability (Allan deviation) with a 2km fiber exposed to a large 15 °C diurnal thermal perturbation. Typical DSN hydrogen maser performance is shown for reference.

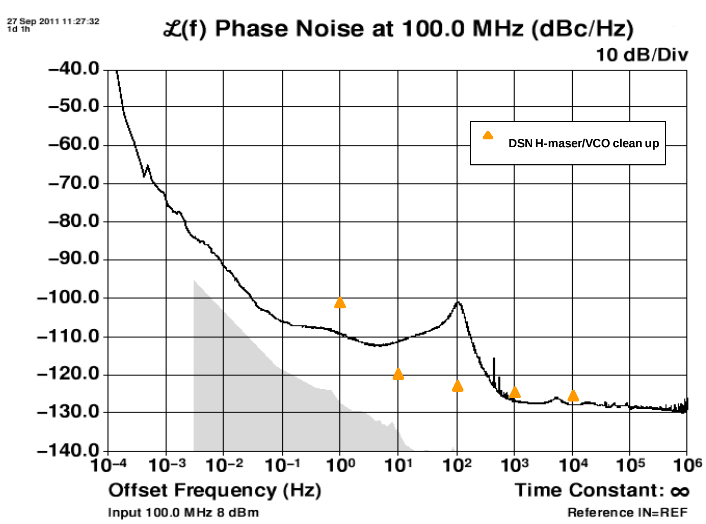

Figure 9. Phase noise measured in the phase conjugated stabilized photonic link with low cost VCO and selected photonic components.

Figure 9 shows the phase noise of the closed loop system. The degradation at 100 Hz offset results from using a noisy VCO in the phase conjugation loop operating with a 100 Hz loop bandwidth. Also shown is the phase noise of a typical DSN hydrogen maser which incorporates a very expensive clean up oscillator.

SUMMARY

To meet current NASA DSN photonic link needs and future array requirements, two stabilized link approaches have been further developed:

1) A frequency independent stabilized photonic link
    - 3500x improved phase stability, capable of distributing signals from 10 MHz ~ 38GHz.

2) 100 MHz phase conjugation photonic link
    - Active stabilization improves long term stability ~1000x
    - Short term stability achieved with careful screening of laser diode transmitter and VCO quality.

Both systems deliver the stability achieved in previous SFODA implementations, while much simpler, smaller, and at lower cost.

ACKNOWLEDGEMENTS

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