

A Transmission Line Phase Stabilizer

G. Lutes

Communications Systems Research Section

To meet the phase stability requirements of certain experiments performed with the Deep Space Network, transmission lines carrying reference signals must be stabilized to reduce changes in their electrical length due to mechanical movement or changes in ambient temperature. A transmission line phase stabilizer being developed at JPL to perform this function is described in this article.

I. Introduction

Reference signals that are stable to parts in 10^{14} are supplied within the Deep Space Net (DSN) stations by a station reference such as a Hydrogen Maser Frequency Standard.

The stability of these reference signals, as received by the user, is degraded by changes in the propagation lengths of the transmission lines used to distribute them. These changes are due to thermal expansion, generally > 60 parts in 10^7 per $^{\circ}\text{C}$, and mechanical movement of the lines.

These transmission line instabilities are greater than can be tolerated in some critical applications, such as Very Long Baseline Interferometry (VLBI), and interstation clock synchronization, so it is necessary to stabilize the transmission lines carrying these critical reference signals.

A transmission line phase stabilizer to perform this function is being developed at JPL and is described in this article.

II. Basic Considerations

A model for a transmission line distribution system without stabilization is shown in Fig. 1.

The relationship between the reference signal (E_R) and the distributed signal (E_3) is a function of the Voltage Standing Wave Ratio (VSWR) on the line and the propagation delay of the line, and can be found as described below.

For simplicity we will solve for the relationship between E_1 and E_3 and assume that the relationship between E_R and E_1 is constant, as it will be if the load on the reference port is constant.

From Ref. 1,

$$\frac{E_2}{E_3} = \frac{Z_R + Z_0}{2Z_R} (e^{\gamma d} + K e^{-\gamma d}) \quad (1)$$

where

$$K = \frac{Z_R - Z_0}{Z_R + Z_0}$$

d = The length of the line

Z_0 = The characteristic impedance of the line

$\gamma = \alpha + j\beta$ = The complex propagation constant

- α = The loss factor (nepers/meter)
 β = The delay factor (radians/meter)

and from the model

$$\frac{E_1}{E_2} = \frac{Z_s + Z_0}{Z_s} \quad (2)$$

Where, from Ref. 1,

$$Z_s = Z_0 \frac{e^{\gamma d} + Ke^{-\gamma d}}{e^{\gamma d} - Ke^{-\gamma d}} \quad (3)$$

Then substituting Eq. (3) into Eq. (2) and simplifying:

$$\frac{E_1}{E_2} = \frac{2e^{\gamma d}}{e^{\gamma d} + Ke^{-\gamma d}} \quad (4)$$

and multiplying Eq. (4) and Eq. (1) we get:

$$\begin{aligned} \frac{E_1}{E_3} &= \frac{Z_R + Z_0}{Z_R} e^{\gamma d} \\ &= \frac{Z_R + Z_0}{Z_R} e^{d(\alpha + j\beta)} \\ &= \frac{Z_R + Z_0}{Z_R} e^{d\alpha} (\cos d\beta + j \sin d\beta) \\ \frac{E_1}{E_3} &= \frac{Z_R + Z_0}{Z_R} e^{d\alpha} \angle d\beta \end{aligned} \quad (5)$$

It can be seen from Eq. (5) that the relationship between the phase of E_1 and E_3 is a function of the length of the cable only, and is not affected by VSWR. The amplitude relationship is a function of VSWR and line length.

The purpose of the line stabilizer is to set and hold the phase relationship between E_R and E_3 constant under all conditions likely to be encountered in the field.

III. Description

The transmission line stabilizer consists of two basic parts: a transmitter and a receiver.

The transmitter is located near the station reference at one end of the transmission line to be stabilized. It transmits a reference signal up the line and receives a return signal coming down the same line from the receiver. These two signals are compared in phase, and an error voltage is generated that is used to reduce the error by controlling a voltage controlled phase shifter in series with the line.

The receiver is located at the far end of the stabilized transmission line near the user's equipment. It receives the reference signal from the transmitter, processes it so it can be separated from the reference signal, and sends the processed signal back down the line to the transmitter. It also supplies a stable reference signal to the user.

IV. Analysis

As shown in Fig. 2, a reference signal ($A_1 \sin \omega t$) from the station standard is split into three equal signals ($A_2 \sin \omega t$) by three-way power splitter HY-1.

Two of these signals are used as local references in the transmitter and are applied to the LO ports of mixers A2 and A3.

The third signal is sent through a hybrid, a voltage controlled phase shifter, a manual phase shifter and then to the receiver through the transmission line being stabilized.

At the receiver, the received signal goes through another hybrid and then through a narrow (100-Hz) tracking filter that greatly reduces leakages of the control signal to the output reference and restores the amplitude of the reference signal.

The signal out of the tracking filter is split by power splitter HY-2 into three equal signals [$A_2 \sin (\omega t + \phi)$] where ϕ is phase delay from the input reference to the output.

One signal is used as the stabilized output and provides a reference to the user.

Another signal drives the frequency divider, which divides the reference frequency by 1000.

The third signal goes through mixer A1 where it is modulated by the output of the frequency divider, which is

$$A_3 \sin \left(\frac{\omega t + \phi + \theta}{1000} \right) \quad (6)$$

where $\theta/1000$ = phase delay through the divider.

The signal out of mixer A1 consists of two spectral lines around a suppressed carrier.

$$A_4 \left[\cos \left(\frac{999(\omega t + \phi) - \theta}{1000} \right) - \cos \left(\frac{1001(\omega t + \phi) + \theta}{1000} \right) \right] \quad (7)$$

The signal is sent through the hybrid down the transmission line back to the transmitter.

At the transmitter, the return signal goes through the manual phase shifter, the voltage controlled phase shifter, and the hybrid, to a quadrature hybrid where it is split into two equal signals in quadrature. The outputs of the quadrature hybrid are

$$A_5 \left[\cos \left(\frac{999(\omega t + \phi + \xi) - \theta}{1000} \right) - \cos \left(\frac{1001(\omega t + \phi + \xi) + \theta}{1000} \right) \right] \quad (8)$$

$$A_5 \left[\sin \left(\frac{1001(\omega t + \phi + \xi) + \theta}{1000} \right) - \sin \left(\frac{999(\omega t + \phi + \xi) - \theta}{1000} \right) \right] \quad (9)$$

where ξ = the return delay down the transmission line.

These signals are mixed with the reference signals ($\sin \omega t$) in mixers A2 and A3.

The outputs of mixers A2 and A3 after low-pass filtering are respectively

$$A_6 \left[\sin \left(\frac{\omega t + \phi + \xi + \theta}{1000} \right) \sin(\phi + \xi) \right] \quad (10)$$

$$A_7 \left[\sin \left(\frac{\omega t + \phi + \xi + \theta}{1000} \right) \cos(\phi + \xi) \right] \quad (11)$$

and are applied to the final mixer (A4).

The filtered signal out of mixer A4 is

$$A_8 \sin 2(\phi + \xi) \quad (12)$$

a dc voltage equal to the product of Eqs. (10) and (11). This signal is applied to the voltage controlled phase shifter to reduce the phase error.

V. Stable Operating Area

Adjustment of the manual phase shifter, which acts like a narrowband line stretcher, is required to set the operating point of the system near the center of a stable operating area.

Two conditions on the slope of the control voltage versus line length curve must be met for stable operation.

- (1) The slope does not equal zero or change sign.
- (2) The slope has the opposite sign to the slope of the voltage controlled phase shifter (phase versus control voltage).

The stable operating points can be found by plotting the control signal Eq. (12) versus line length (ϕ). See Fig. 3.

Since $\phi \approx \xi$, then Eq. (12) becomes

$$A_8 \sin 2(\phi + \xi) \approx A_8 \sin 4\phi \quad (13)$$

It can be seen from Fig. 3 that the stable operating areas are

$$(n-1) \frac{\pi}{8} < \phi < (n+1) \frac{\pi}{8} \quad (14)$$

where

$$n = 0, 4, 8, 12, \dots \quad (15)$$

It can also be seen that a stable operating point occurs every $\pi/2$ radians of line length.

VI. Correction Factor

The correction factor for a perfectly matched system can be found by setting

$$\epsilon_0 - G \sin 2(\phi + \xi) = \epsilon_c \quad (16)$$

where

ϵ_0 = the open loop error

ϵ_c = the closed loop error

$G = AK_D K_\phi$

AK_D = total voltage gain in the signal path from mixer A1 output to the voltage control phase shifter input times the phase factor (volts/radian)

$$= A_8 \sin 2(\phi + \xi) \quad (12)$$

K_D = the detector gain (not solved for explicitly in this analysis)

K_ϕ = gain of the phase shifter (radians/volt)

A stable operating point, assuming the phase shifter has the proper slope, is where $\phi \approx \pi/2$, and since $\phi \approx \xi$,

$$(\phi + \xi) \approx (\pi/2 + \pi/2 + \epsilon_c) = (\pi + \epsilon_c) \quad (17)$$

Substituting Eq. (17) into Eq. (12) and simplifying,

$$\sin 2(\phi + \xi) = \sin 2\epsilon_c \quad (18)$$

substituting Eq. (18) into Eq. (16),

$$\epsilon_0 - G \sin 2\epsilon_c = \epsilon_c \quad (19)$$

for small ϵ_c , Eq. (19) becomes

$$\approx \epsilon_0 - 2G\epsilon_c = \epsilon_c$$

Therefore, the correction factor is:

$$\frac{\epsilon_c}{\epsilon_0} = \frac{1}{1 + 2G} \quad (20)$$

VII. Problems

The dominant remaining problem with the present system is the detector sensitivity to changes in amplitude of the signal returned from the stabilizer's receiver. These changes are due primarily to changes in VSWR on the transmission line as pointed out previously in Eq. (5). This problem can be reduced by redesigning the detector or by adding an automatic level control circuit to the present system.

Another source of error is the contamination of the reference signals by leakage, such as that which occurs between the ports of the hybrids. Since hybrid isolation is a function of VSWR on the line, this problem can be reduced by controlling the quality of the transmission line as much as practical, as well as improving the shielding and power supply decoupling.

In some applications, the leakage of the 5-kHz sidebands into the signal supplied to the user must be reduced to

extremely low levels. In the present system, these sidebands are approximately 100 dB below the output signal. With extreme care in shielding and grounding, it may be possible to improve this.

Thermal stability of the system is degraded because of the numerous cables that must be used to get signals in and out of the ovens. An improved thermal design would improve the long-term stability.

Miscellaneous problems related to testing, measuring, and monitoring the system have not yet been addressed.

VIII. Test Results

Preliminary short-term tests have been run, and proper operation of the system has been verified.

A line stretcher, placed in series with a 1-km length of coaxial cable (RG 223), was used to change the line length by 25 cm (883 ps). This change was reduced by the transmission line stabilizer to a worse-case change of <0.3 cm (10 ps), a correction of >83 times.

Preliminary tests indicate that the phase noise of the system should not appreciably degrade the distributed signal from the station reference.

IX. Conclusion

Preliminary tests indicate that the basic design of the system is sound, but there are several problems that still need attention.

Work is underway to reduce the sensitivity to changes in VSWR on the transmission line so that system performance can be guaranteed.

A new packaging design should be considered to improve long-term stability and accuracy.

Test and monitoring methods and equipment must be developed if line stabilizers are to be used in the DSN on a regular basis.

Transmission line stabilizers will be required if reference signals are to be distributed with phase stabilities in the order of 10 ps or less since there are no other transmission media available at the present time that are this stable without compensation.

Reference

1. John D. Ryder, *Network Lines and Fields*, Prentice Hall, 1949, Chapters 5 and 6.

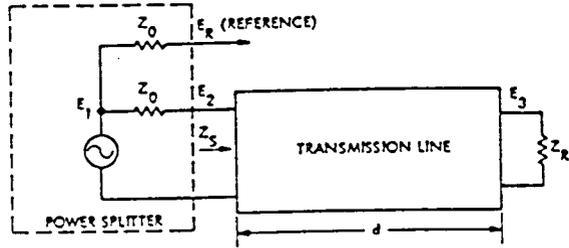


Fig. 1. Transmission line distribution system model

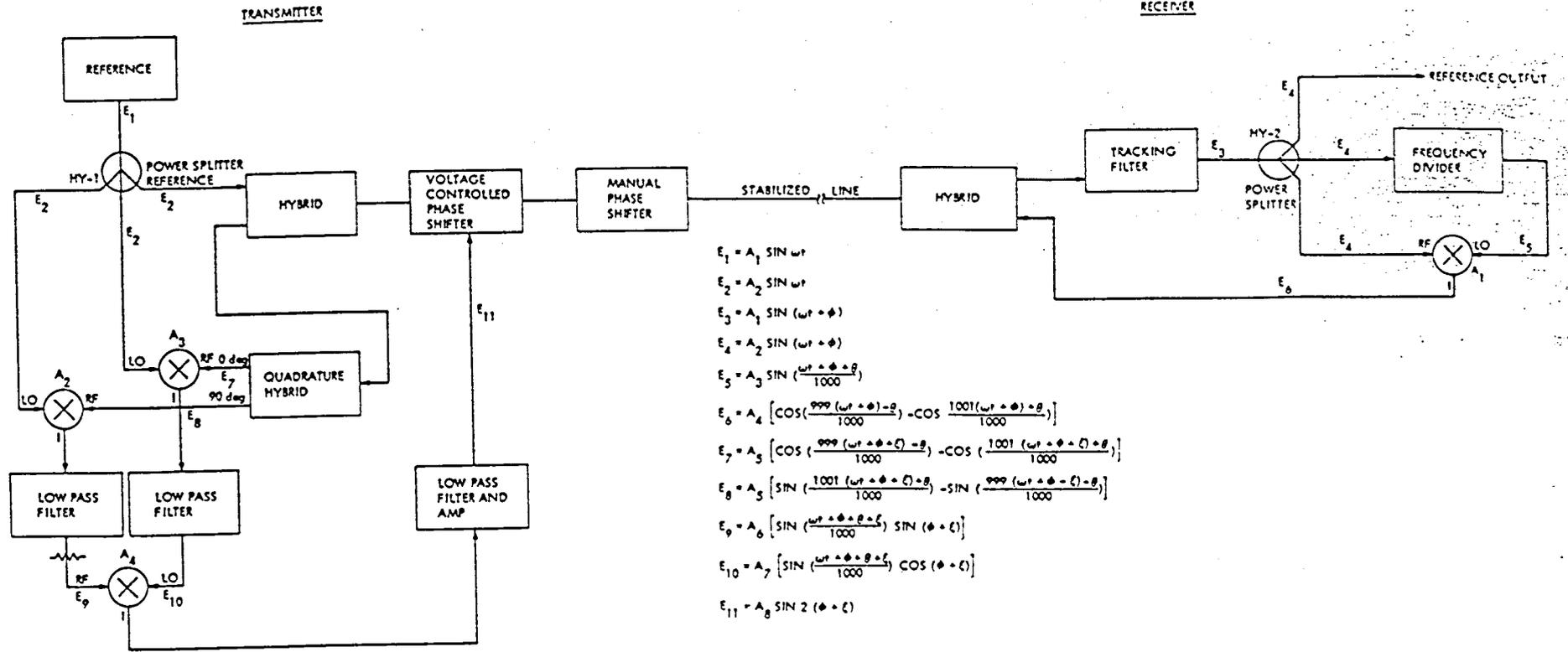


Fig. 2. Simplified block diagram of transmission line stabilizer

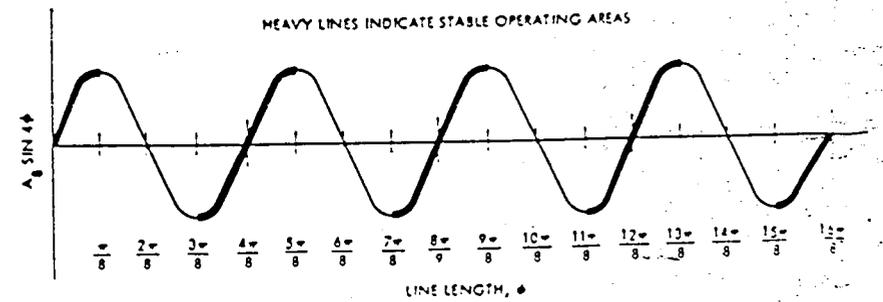


Fig. 3. Open loop error voltage in transmission line stabilizer