STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

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Abstract

A technique for stabilizing reference frequencies transmitted over fiber optic cable in a frequency distribution system is discussed. The distribution system utilizes fiber optic cable as the transmission medium to distribute precise reference signals from a frequency standard to remote users. The stability goal of the distribution system is to transmit a 100 MHz signal over a 22 km fiber optic cable and maintain a stability of 1 part in 10^{17} for 1000 seconds averaging times. Active stabilization of the link is required to reduce phase variations produced by environmental effects, and is achieved by transmitting the reference signal from the frequency standard to the remote unit and then reflecting back to the reference unit over the same optical fiber. By comparing the phase of the transmitted and reflected signals at the reference unit, phase variations on the remote signal can be measured. An error voltage derived from the phase difference between the two signals is used to add correction phase. An improved version of a previous electronic stabilizer has been built and results of its performance are reported.

Introduction

With the current advances in the development of precise frequency standards, greater emphasis is being placed on frequency distribution systems that can distribute the reference signal derived from a standard without appreciably degrading it. The high cost of developing and maintaining a state-of-the-art frequency standard makes it beneficial to have one precise standard at a complex and to distribute the reference signal from this standard to various users within the complex. Often the reference signal must be distributed tens of kilometers. Furthermore, future scientific experiments may also gain from having coherent signals at several remote locations.

The Deep Space Network, supported by JPL/NASA, is a prime contender for such a distribution system. The DSN consists of three complexes located at Goldstone, California, Madrid, Spain and Canberra, Australia. At each complex there are at least four stations, each supported by a parabolic dish antenna with an ultra- sensitive receiving system requiring a precise frequency reference. Currently each complex is supported by a primary hydrogen maser and a backup hydrogen maser. Projects supported by the DSN that require this type of distribution system include unmanned space flight

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The frequency distribution system at the DSN complex at Goldstone, California must distribute reference frequencies generated by a hydrogen maser over distances as great as 30 km. The 100 MHz signal generated by the maser typically has an Allan deviation of 1 part in 10^-15 for 1000 seconds averaging times. To ensure minimal degradation of the reference signal, the distribution system should be at least ten times more stable than the frequency standard. With expected future improvements in frequency standards, even greater stability of the distribution system will be necessary.

There are two basic limitations in frequency distribution systems. The first is a distance limitation set by the signal-to-noise-ratio (SNR) of the received signal. The SNR is limited by the amount of available input power from the frequency source and the loss in the distribution system. The second limitation is the degradation of the frequency stability due to variations in the group delay of the signal as it is transmitted through the medium. The variations in group delay are caused by physical changes in the transmission medium. A constant rate of change in group delay does not effect the frequency stability, but a change in the rate of group delay does degrade the frequency stability. This is shown in the following equation:

$$\frac{d(\Delta f)}{dt} = f\frac{d^2D}{dt^2} \tag{1}$$

where D is the group delay, Δf is the frequency offset and f is the transmitted frequency. Variations in group delay are due primarily to temperature changes in the transmission medium. Thus they can be reduced by decreasing the temperature change, increasing the time constant of the medium, by choosing a medium with a small thermal coefficient of delay (TCD), or by the use of optical and electronic feedback.

Previous Vs. Current Frequency Distribution Systems

As previously stated, frequency distribution systems have been primarily limited by the distance allowable for distribution and the effects of changing group delay. Coaxial distribution systems are especially subject to these limitations. The loss in 7/8 inch diameter coaxial cable at 100 MHz is 0.5 dB/100 ft and the TCD is greater than 15 ppm/°C at 25°C. The transmission length required to transmit a certain input power through a transmission medium and maintain a certain SNR is given by,

$$L = \frac{Pin - SNR + 204}{32.81\alpha} \tag{2}$$

where,

L = Length in kilometers

Pin = Input power in dBW

SNR = signal-to-noise ratio in dB

α = cable attenuation in dB/100 ft.

Thus, with 1 kilowatt of input signal power, a 100 MHz reference signal can only be distributed 7 km and maintain a SNR of 120 dB, the level required by the fiber optic link. This assumes a thermal noise power in a matched load resistance at 300°K of -204 dBW/Hz.

Microwave distribution systems have also been used in the complex at Goldstone, California. Microwave distribution systems have shortcomings in that they are highly susceptible to interference and require large input powers and repeaters to go several kilometers. Because of the limited bandwidth of microwave systems, the 100 MHz signal cannot be transmitted over microwave links directly.

Fiber optic cable is the best distribution medium for transmitting precise reference frequencies. The loss in typical fiber optic cable is less than 0.5 dB/Km at the optical wavelength of 1300 nm. A typical laser transmitter puts out 0 dBm and is attenuated less than 11 dB over 22 Km. Standard single mode fiber optic cable has a TCD of 7 ppm/°C making it less susceptible to temperature changes than coaxial cable. The fiber optic cable used at the Goldstone complex is buried 1.5 m under the ground, making the fiber quite insensitive to diurnal temperature changes. Fiber optic cable has the additional advantages that the fiber is insensitive to electromagnetic interference (EMI) and radio frequency (RFI) and can be made less sensitive to microphonics using an optical isolator between the laser transmitter and the fiber optic cable. An additional advantage of fiber optic cable as the transmission medium is that the superior performance of the optical components make it quite practical to transmit the signal simultaneously in both directions in the same fiber. This proves to be a key factor in actively stabilizing the distribution system.

Active Stabilization Of A Fiber Optic Frequency Distribution System

Passive stabilization of fiber optic transmission links, such as burial of the cable, is not sufficient for maintaining stabilities in the range required for many applications. When stabilities higher than a part in 10^{15} are required the link must be actively stabilized.

The phase conjugator is the key element of the actively controlled fiber optic distribution system. The frequency distribution system consists of a reference unit, containing the frequency standard, and a remote unit, where the frequency standard is to be transmitted. The method for actively controlling the phase variations in the fiber is based on maintaining a constant phase relation between the input phase and the phase of the received signal.

A signal passing through the fiber optic cable in both directions experiences identical delay in the two directions. The midpoint of the signal is at the far end of the cable and experiences exactly half of the round trip delay. 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 (see Figure 1). 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 is called a phase conjugator (see Figure 2).

The reference unit consists of the frequency standard, the phase conjugator, a fiber optic transmitter, a fiber optic receiver, an optical coupler and a phase-lock loop (PLL) (see Figure 3). The remote unit consists of a 50/50 mirror, a fiber optic receiver and a PLL.

The phase conjugator compares the phase of the transmitted and received signals in the reference unit and an error voltage derived from the phased difference is used to control a voltage-controlled oscillator (VCO) (see Figure 4). The particular design of this phase conjugator requires a 100 MHz reference signal and a 20 MHz auxiliary signal. A previous design used a single 100 MHz reference signal, but required two precisely matched phase detectors and tightly controlled signal levels. By using the 20 MHz auxiliary signal, a single phase detector can be used to measure phase error.

The 100 MHz signal and the 20 MHz signals are multiplied together in mixer M1 to produce 80 MHz and 120 MHz signals. A power splitter (S1) separates the signal out of the mixer (M1) into two signal paths. Band pass filters in each signal path separate the 80 MHz and 120 MHz signals. The 80

MHz signal and the 100 MHz signal from the VCO are multiplied in mixer (M2) to produce a 20 MHz intermediate (IF) signal. The 20 MHz IF signal contains the instantaneous phase difference between the VCO signal and the 80 MHz signal.

The 120 MHz signal and the 100 MHz signal reflected from the remote unit are multiplied together in mixer (M3) to produce another IF signal. This 20 MHz IF signal contains the instantaneous phase difference between the reflected signal (100 MHz) and the 120 MHz signal.

The phase detector (PD) receives the two 20 MHz IF signals and produces an error voltage that is proportional to the phase difference between them. The error voltage is applied to the VCO control input through the inner loop filter (ILF). Delay changes in the fiber optic cable result in changes in the control voltage. This voltage controls the phase of the VCO relative to the reference 100 MHz signal.

The output of the VCO is divided into two signals in the RF power splitter (S2). One of the signals is received by mixer M2 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. The 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 100 MHz RF signal. A PLL filters the signal to be used at the remote unit. The reflected optical signal returns to the reference unit where it passes through the optical coupler and is detected by another optical receiver. This signal is also filtered by another PLL and provides a constant amplitude signal into mixer M3. With the signal back at the reference unit, the system loop is closed.

Stabilizer Test Setup

The latest version of the stabilizer consists of each element packaged in an aluminum shield box with 60 dB of power supply filtering. A new laser that is less sensitive to refections back into the laser was also used. The 80 MHz and 120 MHz band pass filters were also improved.

The stabilizer does require initialization using a manual phase shifter (see Figure 4). The phase shifter is used to compensate for the delays in the fiber optic transmitter and fiber optic receiver, to ensure that the phases of the transmitted and received signals are conjugate at the input to the fiber.

The stabilizer was tested with a 4 km link of fiber which was placed on a fiber optic test rack (see Figure 5). The test rack allows better air circulation and thus a shorter time constant for our tests. The entire rack was placed in a test chamber where the humidity, temperature, and pressure could be varied. The temperature in the chamber was varied in temperature steps of various sizes and over various time intervals. The phase at the receiver and the transmitter in the reference unit and the phase at the remote unit receiver were compared to the 100 MHz reference signal (see Figure 6).

Results

Several tests were performed with the stabilizer. By measuring the response of the stabilizer to a step change in temperature and to a linear variation in temperature, the correction factor of the stabilizer was determined. For a step change in temperature from 15°C to 35°C, the phase at the transmitter and receiver in the reference unit changed by 90 degrees and the phase at the remote unit changed by about 2 degrees, thus the stabilizer provided a 45 times improvement (see Figure 7). The glitch in the curve is probably due to optical leakage of the 100 MHz through the coupler directly into the reference unit receiver, causing a cross modulation of the leakage signal and the reflected signal. If the results of this experiment are considered over the first hour, the reference phases changed by 25 degrees while the remote phase changed by 0.5 degrees, for a 50 times improvement (see Figure 8). Results from the test with a linear change in temperature show 20 degrees of phase change at the reference unit and 0.1 degrees of phase change at the remote unit, resulting in a 200 times improvement (see Figure 9). The ripple effect in the remote unit phase is probably due to reflections from the end of the fiber into the fiber optic transmitter. With more optical isolation this effect should be reduced.

Future Improvements

The results of initial tests on the stabilizer are encouraging. The factor of 10 times reduction in phase variations with the stabilizer seems to be readily attainable, with potential for even greater improvements. New tests with a sinusoidal variation in temperature over diurnal time periods need to be performed to simulate more realistic time and temperature variations. Current tests have put the stabilizer through conditions too severe to realistically simulate field conditions.

The first step in improving the stabilizer is to reduce the losses in the system. Once losses are reduced, the return signal will be much larger than the leakage signal through the coupler. Specifically if the return signal is 40 dB greater than the leakage signal, the resulting phase variation will be 0.57 degrees. By reducing the losses and making the return signal 60 dB greater than the leakage signal, the resulting phase variation will be 0.057 degrees.

After the losses have been reduced any further problems with leakage may be eliminated by using techniques such as transmitter/receiver switching. By not allowing the transmitter and receiver to be on at the same time eliminates the interference problem of the leakage signal.

Conclusion

A method of active stabilization of frequencies distributed over fiber optic cable has been demonstrated and proves to be more than adequate for current frequency standards and distribution lengths. Current frequency standards require a ten times reduction in phase variations, and the described stabilizer provides at least 40 times reduction over a 4 Km link. Theoretical calculations predict phase reduction factors of 500 will be attainable by reducing optical losses and leakage.

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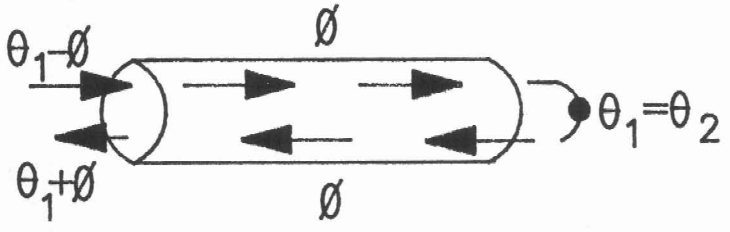


$$\theta_2=(\theta_1-\phi)+\frac{(\theta_1+\phi)-(\theta_1-\phi)}{2}=\theta_1$$

FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

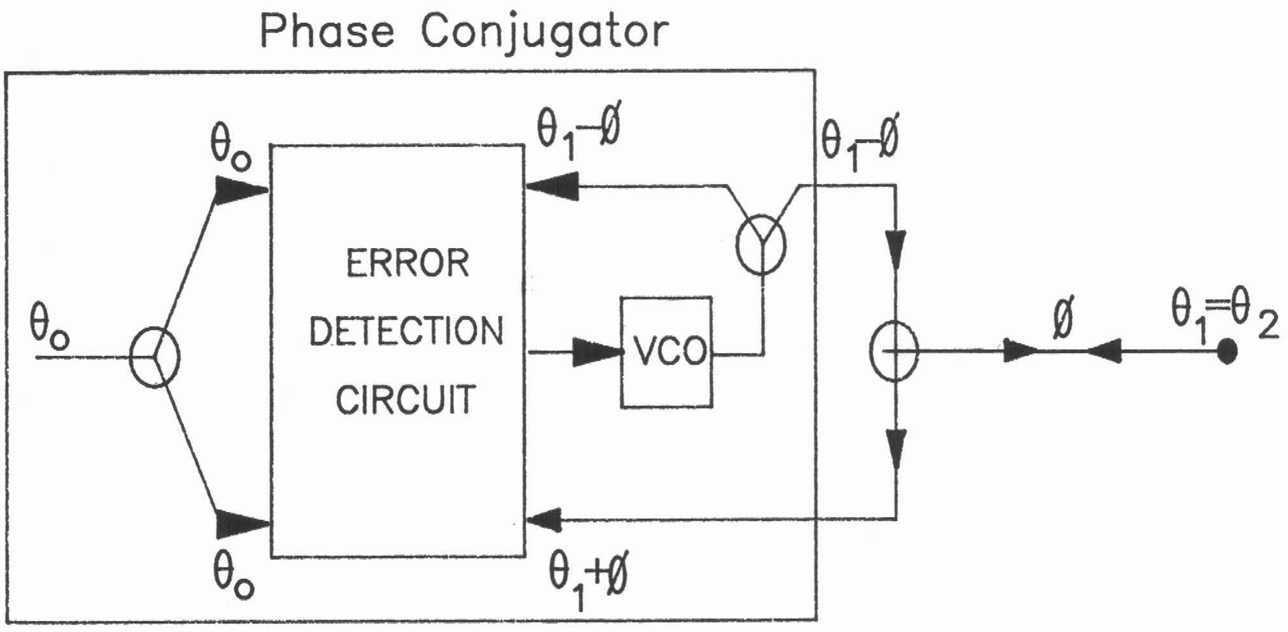


FIGURE 2. PHASE CONJUGATOR

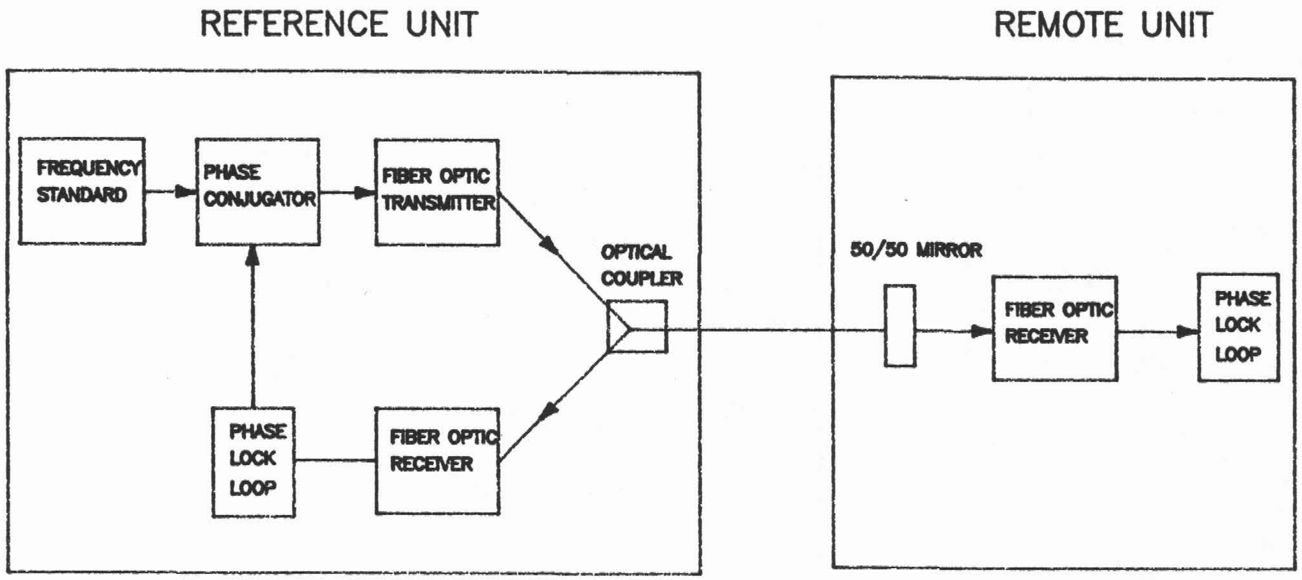


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

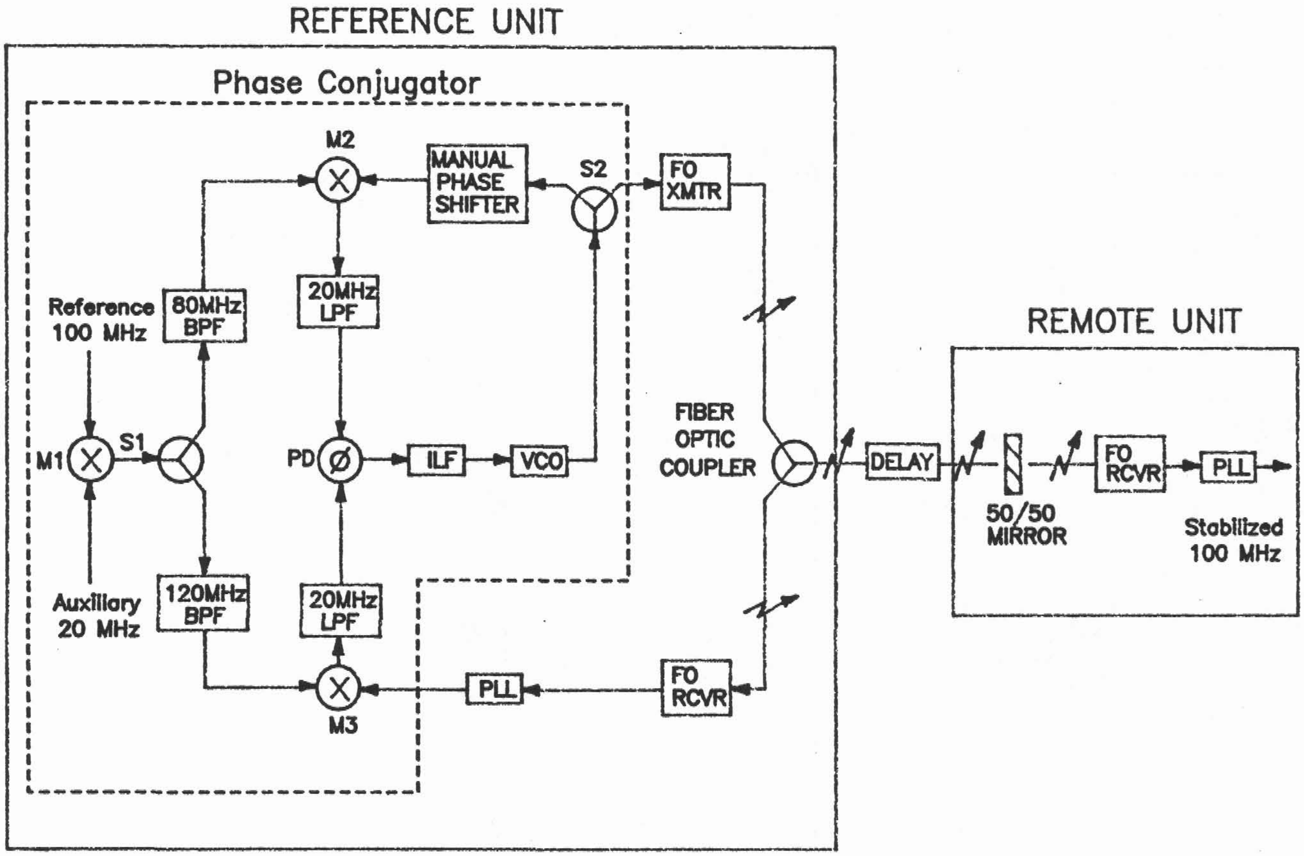


FIGURE 4. BLOCK DIAGRAM OF FIBER OPTIC STABILIZER

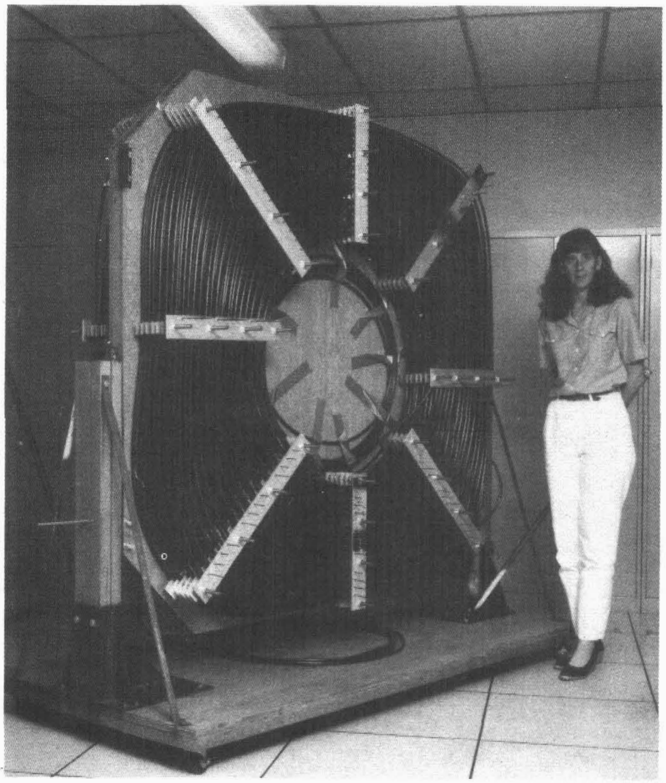


FIGURE 5. TEST RACK FOR FIBER OPTIC CABLE

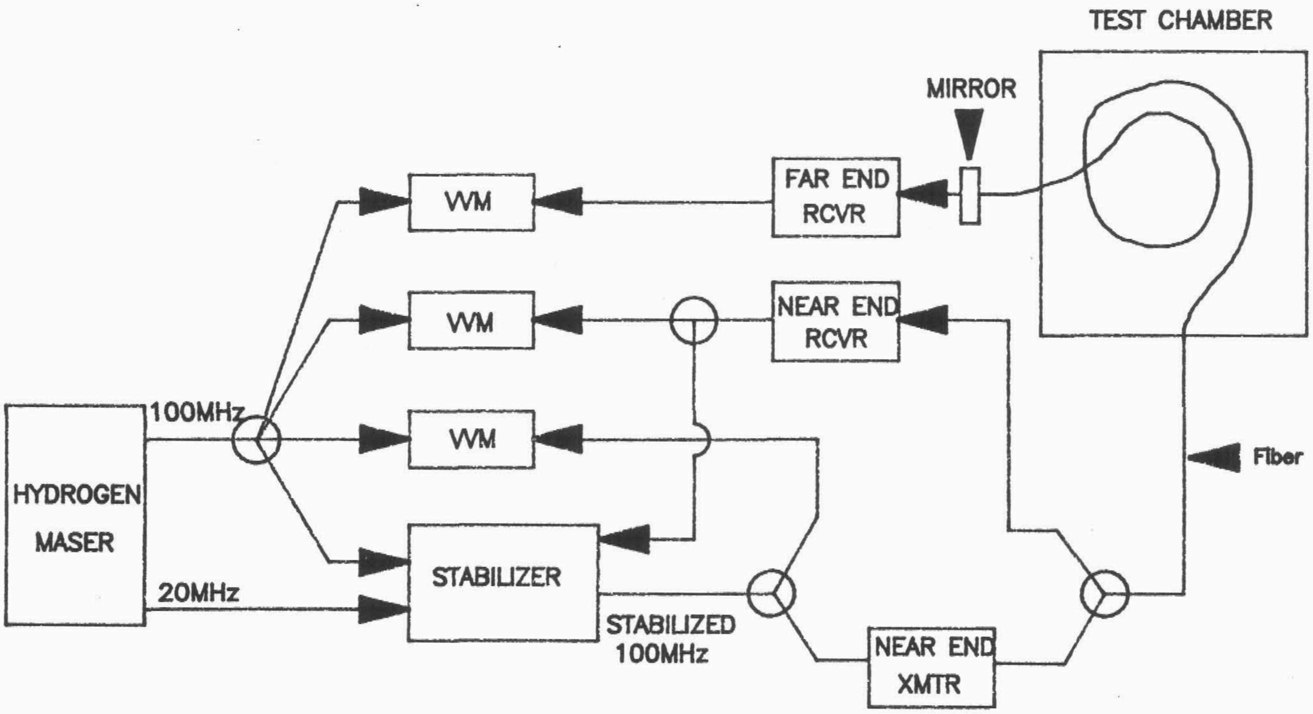
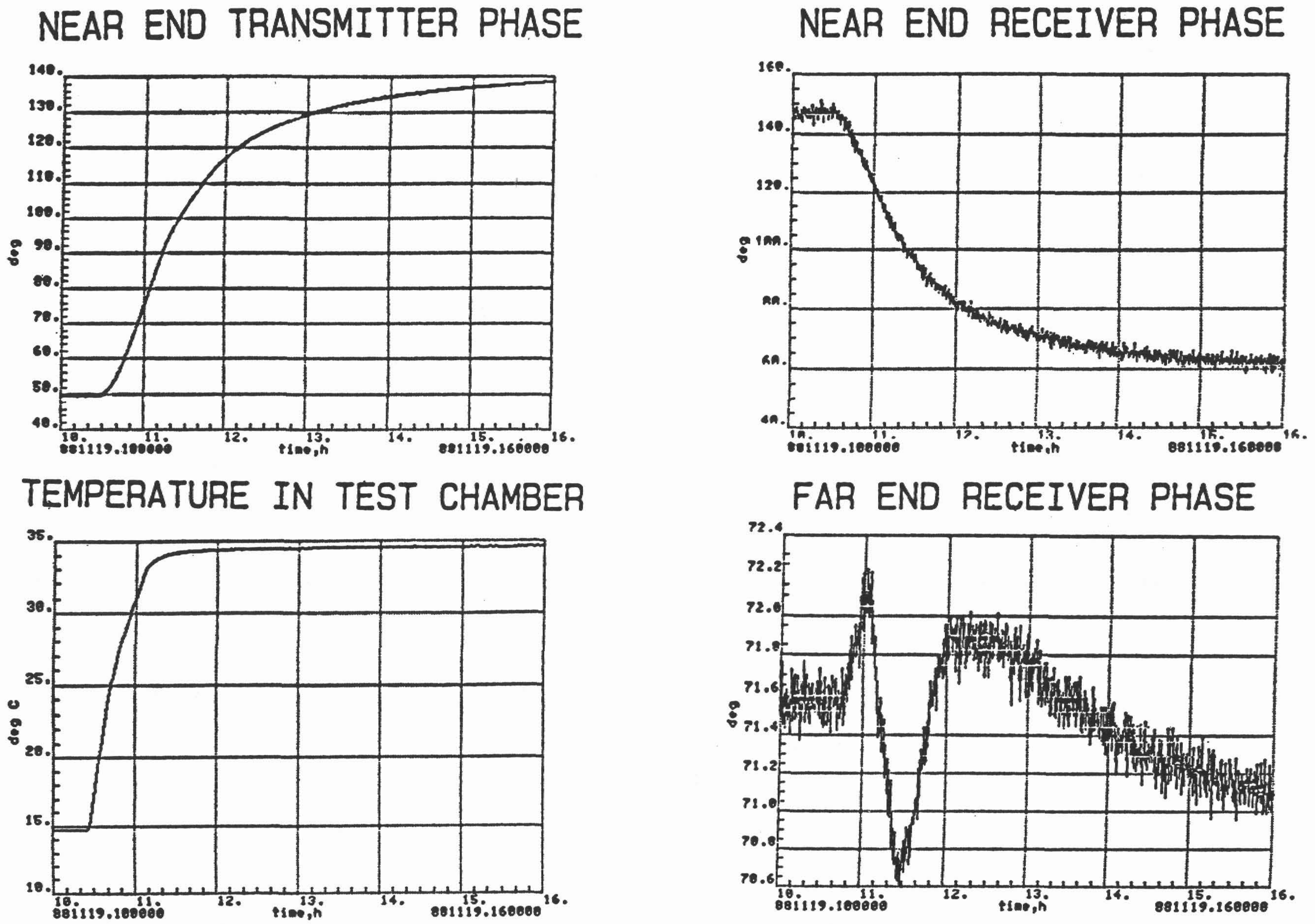


FIGURE 6. FIBER OPTIC STABILIZER MEASUREMENT SETUP

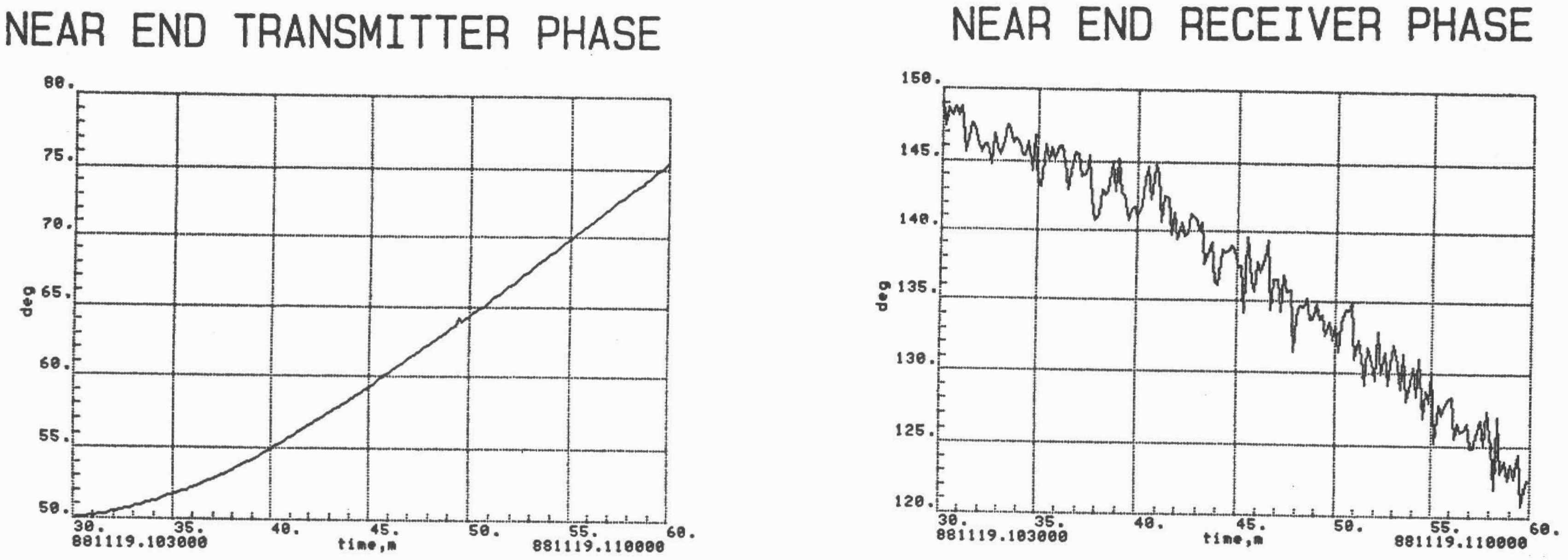

NEAR END TRANSMITTER PHASE

NEAR END RECEIVER PHASE

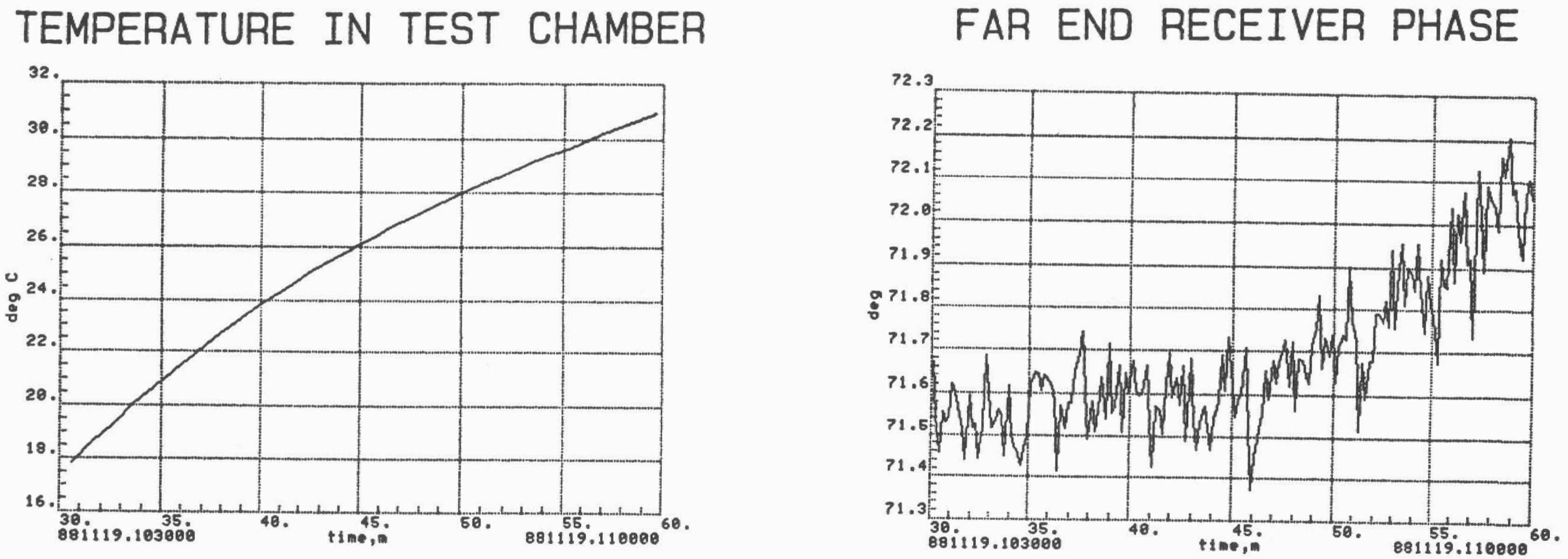
TEMPERATURE IN TEST CHAMBER

FAR END RECEIVER PHASE

FIGURE 7. FIBER OPTIC TEST RESULTS STEP CHANGE IN TEMPERATURE 15°C TO 35°c


NEAR END TRANSMITTER PHASE

NEAR END RECEIVER PHASE


TEMPERATURE IN TEST CHAMBER

FAR END RECEIVER PHASE

FIGURE 8. FIBER OPTIC TEST RESULTS STEP CHANGE IN TEMPERATURE 15°C TO 35°C

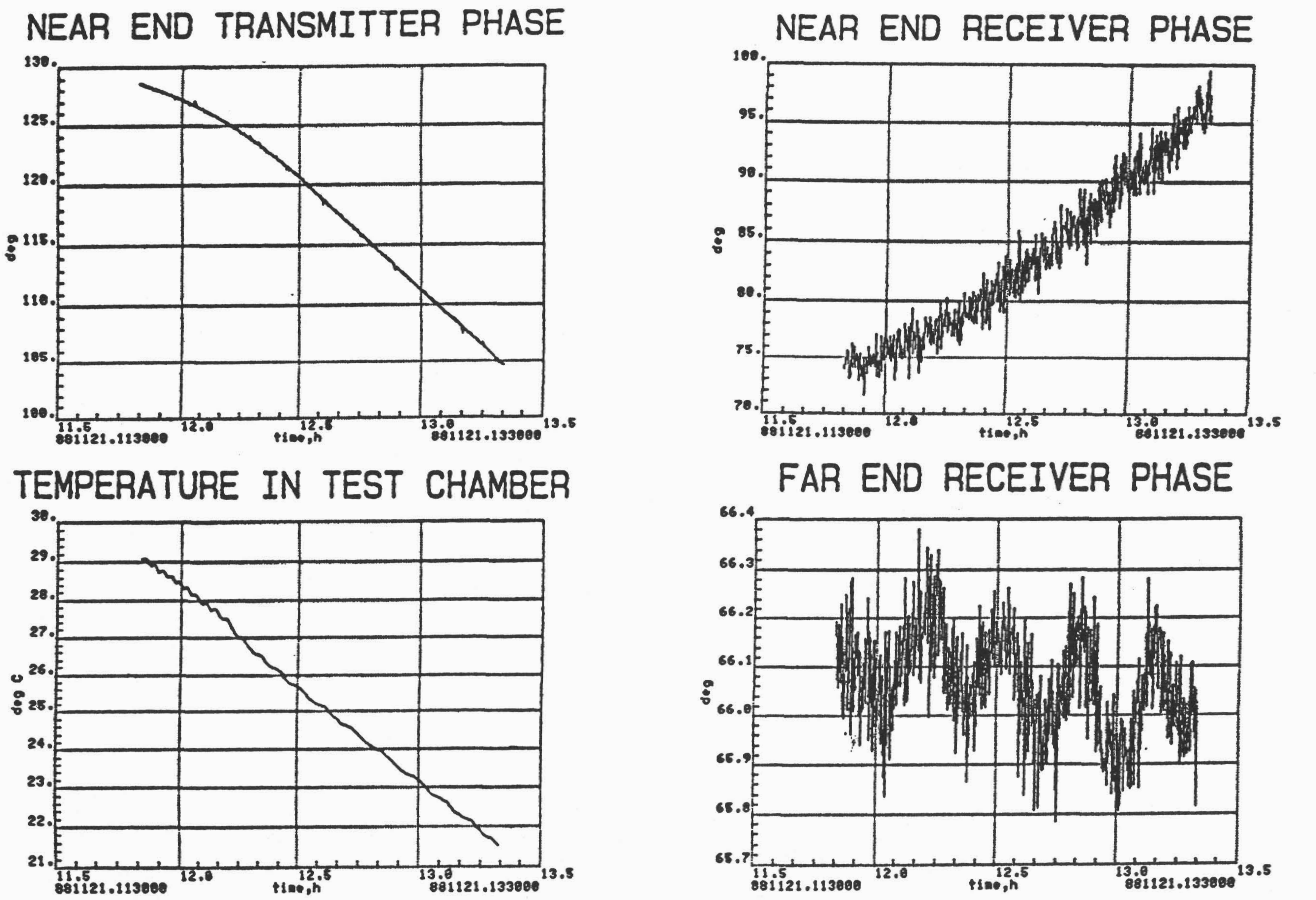


FIGURE 9. FIBER OPTIC TEST RESULTS LINEAR CHANGE IN TEMPERATURE 29°C TO 22°C