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MEASUREMENTS OF EARTH-STATION DELAY INSTABILITIES USING A DELAY-CALIBRATION DEVICE

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ABSTRACT

Delay calibrators were used to measure delay instabilities in the two-way satellite time-and-frequency-transfer earth stations at NIST. Data from the calibrators suggests that the dominant source of earth-station instabilities is group delay errors due to coherent interference and not physical-delay changes. The delay the calibrators measure is correlated with the instabilities in the earth stations but cannot always be used to improve the performance of the system because the correlation factor may be variable.

1. INTRODUCTION

We report on the use of delay-calibration systems to measure the delay instabilities in earth stations that are used for two-way time-and-frequency transfer at the National Institute of Standards and Technology (NIST). Two delay-calibration systems were built to measure the transmitter (TX) and receiver (RX) delays at each of our two earth stations. The first system was installed on a very-small-aperture-terminal (VSAT) earth station and the second system was installed on a 3.7 m (37M) antenna earth station. The RX and TX delays were measured in real-time during two-way time-transfer sessions.

The TX path delay through the earth station is measured by sampling the transmitted signal at the waveguide feed of the antenna with the use of a directional coupler. The sampled signal is down-converted to 70 MHz and the timing information, a one-pulse-per-second signal (1 pps), is decoded in a modem. This 1 pps signal stops the TX counter that was started by the transmitted 1 pps. The reading on the counter measures the propagation delay through the transmit section of the earth station and the calibration unit.

The RX path delay through the earth station is measured by having a 1 pps signal start the RX counter. The 1 pps is encoded on a 70 MHz carrier by a modem. The 70 MHz signal is up-converted in the calibration unit to the receiver frequency of the earth station and coupled into the earth-station antenna feed. The injected signal is down-converted by the earth station to 70 MHz and a modem is used to decode the 1pps signal that stops the RX counter. The reading on the RX counter is the delay through the earth-station receiver plus the delay through the calibration unit.

2. CALIBRATION UNIT STABILITY

The delay calibration system components include: (1) a delay calibration unit with its up and down converters, (2) two NIST modems, (3) a counter to measure the TX delay, (4) a counter to measure the RX delay), (5) the waveguide couplers, (6) the transmit-and-receive-path 70 MHz cables and (7) the temperature control system. The modems are located in the lab along with the counters and clocks. The 70 MHz cables are approximately 50 m long and connect the modems to the delay-calibration unit. The delay-calibration unit upconverts 70 MHz signals to the RX frequency of the earth station and downconverts the TX frequency of the earth station to 70 MHz. The delay-calibration system is described in more detail in a previous publication [1].

The delay-calibration units were tested extensively before being installed on the earth station. The combined receiver and transmitter delay was measured to be 351 ± 1 ns. The calibration unit (receiver – transmitter) temperature coefficient of delay is 10 ± 2 ps/°C. Both calibration units are temperature controlled at 45 °C. The calibration unit temperature was measured to be 45 ± 3 °C for an ambient temperature swing of –20 °C to +38 °C. Peak-to-peak delay variations due to environmental effects are not expected to be larger than 70 ps.

3. MODEM STABILITY

The NIST modems used in the delay calibration system were also characterized.

Table 1. Modem temperature coefficients

Modem	TX	RX	(TX-RX)/2
2	8 ps/°C	30 ps/°C	-11 ps/°C
7	-30 ps/°C	-20 ps/°C	-5 ps/°C
10	-60 ps/°C	-40 ps/°C	-10 ps/°C
11	-45 ps/°C	15 ps/°C	-30 ps/°C

The modem measurement sensitivity to temperature is shown in Table 1. The time delay stability of these modems does not exceed 50 ps for averaging times out to 3 days.

4. PHASE STABILITY VS DELAY STABILITY IN CABLES

The cables used to send the 70 MHz received and transmitted signals from the calibration unit located on the earth station to the modems located in the laboratory are approximately 60 m long for one system and 50 m long for the second system. Reflections in long cables caused by imperfect termination impedances, dielectric imperfections or kinks can cause group-delay errors [2,3]. These group-delay errors are a function of the phase delay of the cable. The temperature sensitivity of the cable phase-delay is mapped into a group-delay temperature sensitivity. In order to select the best cable for the calibration system the temperature coefficient of the phase and group delays were measured for 3 types of cable. The phase-delay was measured using a phase-bridge technique and the group-delay was measured using one of the NIST modems. The cable temperature coefficients were measured for a temperature range of -10 to 60 °C. The results of the measurements are in Table 2. The cables were terminated very carefully into a 50 Ω load. The return loss of the cable and termination was about -26 dB at 70 MHz.

Table 2. Temperature coefficient for cables

Cable Type	Group Delay	Phase Delay
RG58U	-80 ppm/°C	68 ppm/°C
FSJ1-50	7 ppm/°C	-7 ppm/°C
ISOCORE	21 ppm/°C	-14 ppm/°C

Although the cables were well terminated, the cable phase-delay temperature sensitivity was different than the cable group-delay temperature sensitivity. A mismatch in the cable terminations results in different temperature coefficients for the group-delay. This effect was seen when the FSJ1-50 cable was terminated with a 25 Ω load. The temperature coefficient of delay measured with a 25 Ω load was 33 ppm/°C. Compensation for this group-delay error by measuring the temperature would be very difficult because the temperature coefficient of delay is a function of the phase delay of the cable. A change in cable length will result in a different temperature coefficient of delay.

Based on these measurements we chose to use the FSJ1-50 cables. The cables were installed and all terminations on the calibration unit as well as the modems were measured and adjusted such that all return losses were less than -26 dB.

5. TWO-WAY MEASUREMENTS USING THE CALIBRATION SYSTEM

The stability of the calibration system was measured in loop-back mode for a period of two weeks. The time-delay stability for both earth-station calibrations systems is shown in Fig. 1. The overall time-delay stability $\sigma_x(\tau)$ of the delay calibrations systems is under 100 ps for averaging times of an hour out to 3 days.

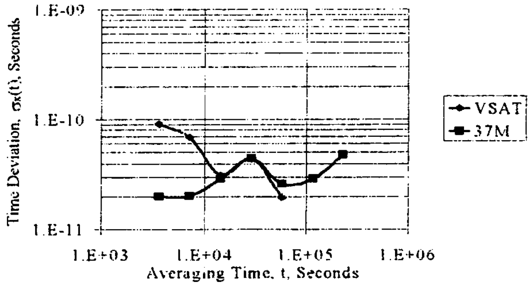

Figure 1. Time stability of calibration systems.

Having verified that the delay calibration system was functional and stable, a two-way common clock time and frequency transfer experiment was conducted using the two earth stations and a stationary transponder located 10 km away. The delay calibration units collected the earth station RX and TX delays in real time during a two-way session. Each two-way session lasted 5 minutes and data was collected once an

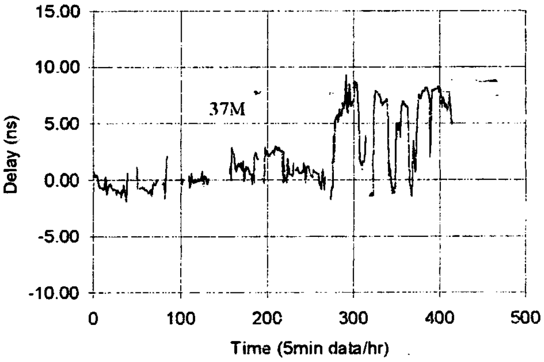

Figure 2. 37M earth station two-way delay data.

hour for a period of 16 days. The figures display the data collected by the calibration systems as well as the regular two-way data. Each point on the graph represents an average of the 300 points taken during a 5 min session. The vertical axis units are ns and the horizontal axes are labeled in hours since the beginning of the experiment. Missing data is indicated by gaps.

The delay data from signals received by the 37M earth station are displayed in Fig. 2. These data are the sum of the VSAT TX delay, path delay from the VSAT to the 37M earth-station, and the 37M earth-station RX delay. Peak-to-peak delay variations in the data set are about 5 ns for the first 280 hr experiment and change to 10 ns for the remainder of the experiment. The 37M TX and RX delays, as measured by the calibration system are displayed in Fig. 3. The RX and TX delays through the 37M earth station as measured by the delay calibration system have peak-to-peak variations that do not exceed 2 ns. The large delay variations seen by the 37M earth station in Fig. 2 do not appear to be caused by delay variations in the RX path of the earth station.

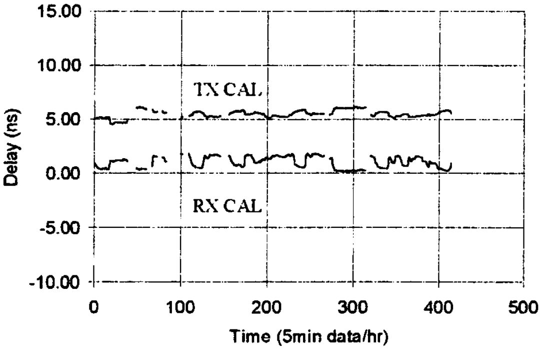

Figure 3. 37M RX and TX delays as measured by the 37M earth station calibration system.

The delay data from signals received by the VSAT earth station are displayed in Fig. 4. These data are the sum of the 37M TX delay, the path delay from the 37M to the VSAT earth station and the VSAT earth-station RX delay. Peak-to-peak delay variations in this data set are about 5 ns. From a qualitative observation there appears to be some correlation between the 37M transmit delay and the delay data from the signals received by the VSAT earth station. The VSAT earth-station TX and RX delays, as measured by the calibration system, are shown in Fig. 5. The VSAT TX delay, as measured by the VSAT calibration system has large 15 ns peak-to-peak excursions. The VSAT transmit path appears to be unstable and accounts for the large delay variations that were seen by the 37M earth station. The VSAT RX path appears to be well behaved with variations not exceeding 2 ns. If the delay variations through the earth stations are real physical delay changes the calibration system should be able to measure them with a stability of better than 100 ps. In this case the data from the calibration systems could be used to improve the stability of the two-way link.

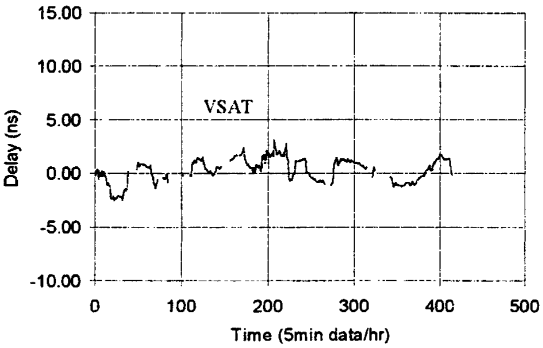

Figure 4. VSAT earth station two-way data.

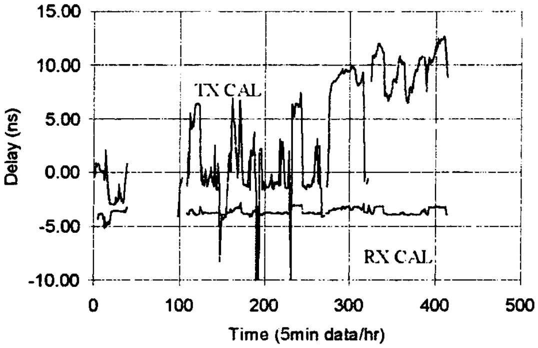

Figure 5. VSAT RX and TX delays as measured by the VSAT calibration system.

The top trace displayed in Fig. 6 is the difference of the two-way data received by the 37M earth station and the VSAT earth station. Since the clock noise is common to both earth stations these data represent only the noise of the two-way time-and-frequency transfer system. The bottom trace in Fig. 6 is the noise of the two-way time-transfer system corrected for delay variations measured by the calibration systems. The corrected two-way time-transfer data are no better than the uncorrected two-way data. In some parts of the data set the calibration system corrections actually make the two-way noise larger.

The instabilities in the TWSTFT system at NIST are dominated not by physical delay instabilities in the earth station but perhaps by apparent delay errors caused by delayed coherent interference as discussed earlier by Acarrunz, et al. [3].

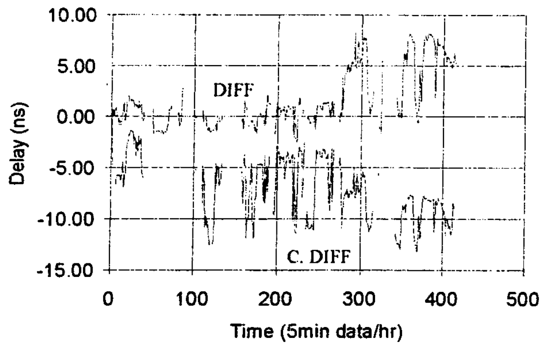

Figure 6. VSAT/37M two-way data and VSAT/37M two-way data corrected by data measured using the calibration system.

The following experiment illustrates the effect of delayed coherent interference upon a delay measurement using a spread-spectrum modem at a chip rate of 2.5 MHz, and at a chip rate of 20 MHz. The carrier signal frequency is 70 MHz. The modem transmitter signal was attenuated by 20 dB before being split into two paths. The first path is the direct signal path and was created with a cable delay of 154 ns. The second path had an initial delay of 435 ns. This second path was attenuated such that the delayed signal was -28 dB lower in level than the direct signal. The direct and delayed, attenuated signal were summed in a signal combiner and attenuated an additional 10 dB before going to the receive port of the modem. The path delay of the delayed interfering signal was increased in increments of 2.7 ns. The delay data from the modem with a 2.5 MHz chip rate is displayed in Fig. 7. The modem group-delay measurement of the direct signal has a bias that depends on the time delay between the direct and interfering signal. The modem group-delay measurement at the higher chip rate of 20 MHz does not appear to have a bias.

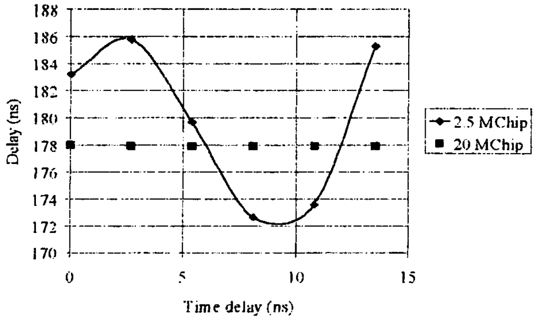

Figure 7. Comparison of delay measurements for modem chip rates of 2.5 MHz and 20 MHz.

CONCLUSIONS

The delay calibration system is a diagnostic tool that can be useful in identifying anomalous behavior in earth-station components. However, the calibration system at NIST cannot reliably be used to improve the stability or accuracy of the TWSTFT system. The dominant source of instability in the NIST earth station is delayed coherent interference that causes correlator errors. The calibration systems are sensitive to these apparent delay errors. However the delay errors are a vector phenomenon and the calibrator may not give the correct sign or magnitude information to allow their use in the correction of these errors.

The level of delayed coherent interference in the system cannot be reduced any further by practical means. Decreasing the sensitivity of the measurements to delayed coherent interference is the suggested method of improving the stability of this TWSTFT system. This can be accomplished by using higher-chip-rate modems or modems that employ fractional correlators.

ACKNOWLEDGEMENTS

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