PRECISION TIME AND FREQUENCY TRANSFER UTILIZING SONET OC-3

Malcolm Calhoun, Paul Kuhnle, and Richard Sydnor
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, California 91109, USA

Sam Stein
Timing Solutions Corporation
Boulder, Colorado 80304, USA

Al Gifford
U.S. Naval Observatory
Washington, DC 20392, USA

Abstract

An innovative method of distributing precise time and reference frequency to users located several kilometers from a frequency standard and master clock has been developed by the Timing Solutions Corporation of Boulder, CO. The Optical Two-Way Time Transfer System (OTWTTS) utilizes a commercial SONET OC-3 facility interface to physically connect a master unit to multiple slave units at remote locations (in this particular implementation, five slave units are supported). Optical fiber is a viable alternative to standard copper cable and microwave transmission. Coaxial cable is lossy with relatively poor temperature stability. Microwave transmission is expensive and may introduce unwanted noise and jitter into the reference signals. Optical fibers are the preferred medium of distribution because of low loss, immunity to EMI/RFI, and temperature stability. At the OTWTTS remote end, a slave local oscillator is locked to the master reference signal by a clock recovery PLL. Data signals are exchanged in both directions in order to calibrate the propagation delay over long distances and to set the slave time precisely to the master on-time 1 pps. The OTWTTS is capable of maintaining, without degradation, the HP 5071 cesium standard stability and spectral purity at distances up to 10 km from the frequency standards central location.

This paper discusses measurements of frequency and timing stability over the OTWTTS. Two reels of optical fiber, each 10.6 km in length, were subjected to sinusoidal temperature variations from −20°C to +50°C over a 24-hour period. The master and slave units were independently subjected to +15°C to +25°C temperature variations (hardware specification). Measurements were made of frequency stability, 1 pps jitter, phase noise, accuracy, and temperature coefficient. Preliminary results indicate that the OTWTTS performs as specified and does not degrade the quality of the cesium reference signal. Worst case environmental tests of the OTWTTS indicate the Allan deviation to be on the order of parts in 10^{14} at averaging times of 1,000 and 10,000 seconds; thus, the link stability degradation due to environmental conditions still maintains HP 5071 cesium standard performance at the user locations.

The OTWTTS described in this paper was designed and built by Timing Solutions Corporation of Boulder, CO. Environmental testing of the hardware and associated optical fibers was performed at Jet Propulsion Laboratory, Pasadena, CA, under contract with the U.S. Navy Fleet Industrial Supply Center, Bremerton, WA.

INTRODUCTION

The Optical Two-Way Time Transfer System (OTWTTS) utilizes a commercial SONET OC-3 facility interface to physically connect a master unit to multiple slave units at remote locations (in this particular implementation, five slave units may be supported).[1] Optical fiber is a viable alternative to standard copper cable and microwave transmission. Coaxial cable is lossy with relatively poor temperature stability. Microwave transmission is expensive and may introduce unwanted noise and jitter into the reference signals. Optical fibers are the preferred medium of distribution because of low loss, immunity to EMI/RFI, and temperature stability.[2] At the OTWTTS remote end, a slave local oscillator is locked to the master reference signal by a clock recovery PLL. Data signals are exchanged in both directions in order to calibrate the propagation delay over long distances and to set the slave time precisely to the master on-time 1 pps. The OTWTTS is capable of maintaining, without degradation, the HP 5071 cesium standard stability and spectral purity at distances up to 10 km from a centrally located frequency standard. In addition to the 5 MHz reference frequency and the on-time 1 pps, IRIG-B time code is transported from the master to the slave units. The OTWTTS performance is reported later in this paper.

OTWTTS OVERVIEW

The OTWTTS functions as a phase-lock loop that controls the time and frequency of a slave clock to agree with a master timing source. The slave may be separated from the master unit by a distance as large as 10 km. The OTWTTS exchanges data and time signals in both directions to set the slave time and to calibrate the delay over the optical fibers. A top-level block diagram of the OTWTTS is shown in Figure 1. The specified operating temperature range for both the slave and master units is +15°C to +25°C. The temperature range for the optical fiber cable is −20°C to +50°C. It is expected that the master and slave units will be located in a controlled environment and will not experience large temperature variations, whereas the optical cable may have long runs that are exposed to the elements. The physical link between the OTWTTS master and the slave is via single-mode optical fibers. The interface between the master/slave electronics and the physical link is a SONET OC-3 assembly. The 155.52 Mb/s clock of the master OC-3 interface is locked to the 5 MHz from the master station frequency standard. The on-time 1 pps from the frequency standard, as well as IRIG-B time code, are inputs to the OTWTTS master unit. A block diagram of the OTWTTS master unit is shown in Figure 2.

The remote slave unit recovers the frequency information from the SONET OC-3 data. The transmitted clock frequency is regenerated by a clock recovery circuit in the slave unit. The clock recovery loop is a digital loop which tracks the phase of the master signal as received at the slave unit including variations in line length between master and slave due to temperature variations. A wideband phase-lock loop is used to filter the SONET data transitions. Time signals are returned to the master unit from the slave in order to set the time of the slave and to stabilize the recovered clock frequency. The OTWTTS is constructed such that the forward delay and the reverse delay are exactly equal, making it possible to calculate the one-way time delay, as well as the master-slave clock difference. The slave unit block diagram is shown in Figure 3.

The SONET OC-3 line interface module directly terminates a single-mode optical fiber.[2] The OC-3 carries the standard ST-3 telecommunications payload and operates at a bit rate of 155.52 Mb/s. The SONET 155.52 Mb/s clock is locked to the 5 MHz of the master frequency standard.

The generated high precision timing markers take advantage of timing which is inherent to the SONET equipment.

TEST CONFIGURATION

For OTWTTS testing, the hardware along with the supporting optical fibers was configured as shown in Figure 4. A hydrogen maser frequency standard was used as the source. The 1 pps was generated by feeding the reference 5 MHz into a time code generator. The master unit, slave unit, and the optical fibers were moved individually into an environmental test chamber as required for the testing. The test chamber used was a Tenney Environmental Systems, Model T20RC-3, which easily accommodates the temperature ranges specified for the OTWTTS. Baseline noise floor and stability tests were conducted on the test system alone, without the OTWTTS, to verify that the test equipment would not contaminate the test data. Next, the Allan deviation was taken with the OTWTTS operating at normal room temperature, which was assumed to be near actual operating conditions for the system hardware. The result of this test is shown in Figure 5.

The on-time 1 pps delay variations were made using a HP 5370B Time Interval Counter. The 1 pps into the master unit was compared with the 1 pps out of the slave unit for delay variations and for pulse jitter. The 1 pps jitter measured at the slave unit is 30 ps for 1,000 averages. For testing, two reels of Corning SMF 28 single mode fibers were used as the physical connections between the master and slave units. This particular optical fiber has a thermal coefficient of delay of approximately 7 ppm/°C. Each reel of fiber was measured precisely to a length of 10.56 km. The fibers used in the testing had no cable jacketing, ensuring relatively fast response to thermal variations.

TEST RESULTS

Figure 6 shows the Allan deviation of the OTWTTS with the two 10.56 km reels of fiber in the environmental test chamber with temperature variations from -20°C to $+50^\circ$C. The temperature variation is sinusoidal with a period of 24 hours in this particular test. Note that there is a diurnal degradation of the 5 MHz stability from parts in 10^{15} to approximately 6×10^{14}. Also observe that the peak-to-peak phase delay variation in the reference frequency is 2.5 ns; thus, the temperature sensitivity of the system to the fiber is 3.3×10^{-12} s/°C/km. The 1 pps delay variations were recorded utilizing this same test configuration. Figure 7 is a plot of the 1 pps delay variations, approximately 2 ns peak to peak. The solid sinusoidal line on the graph represents the controlled temperature variations.

Figures 8 and 9 show the phase noise density as measured at the output of the 5 MHz distribution at the slave unit, 0 to 10 Hz and 0 to 10 KHz, respectively. The noise floor of the OTWTTS is below the HP 5071 specification with some margin. There is a low frequency spur that is related to the digital synthesizer at the slave unit. The spur magnitude was measured to be -80 dBc while the spur specification for the OTWTTS is -75 dBc. Observe the multiple low-frequency spurious responses which are by-products of the SONET digital data transfer. These spurs are multiples of approximately 1/3 Hz. The spur magnitude measured in the SONET OC-3 without the OTWTTS control loop is approximately -70 dBc, whereas the spurs at the output of the OTWTTS have been reduced to -100 dBc or less. Table 1 summarizes some of the test results of the OTWTTS.

Table 1. OTWTTS Performance Measurement

UNIT UNDER TEST	Δ T (oC)	Δ 1 pps	5 MHz Δ t/t
OPTICAL CABLE	−20 to +50	2 ns p-p	2.5 ns p-p
OTWTTS MASTER	+15 to +25	800 ps p-p	800 ps p-p
OTWTTS SLAVE	+15 to +25	900 ps p-p	300 ps p-p

SUMMARY

The measured performance of the OTWTTS meets the stated specifications of a controlled slave clock such that its time and frequency agree with the master unit. The slave unit maintains high performance cesium quality stability and signal characteristics at the remote slave location under worst case environmental variations. The two-way master/slave 1 pps jitter is less than 100 ps. The commercial SONET OC-3 interface performs as a vehicle for precise time and frequency transfers.

ACKNOWLEDGMENT

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REFERENCES

[1] *"Optical two-way time transfer system"* (product description), TS96.0097, Timing Solutions Corporation, Boulder, Colorado 80304, USA.

[2] M. Calhoun, P. Kuhnle, and J. Law 1993, *"Environmental effects on the stability of optical fibers used for reference frequency distribution,"* Proceedings of the 39th Annual Meeting of the Institute of Environmental Sciences, May 1983, Las Vegas, Nevada, USA.

[3] OC-3 ATM LIMO, preliminary publication, Odetics, Inc., Anaheim, California 92808, USA.

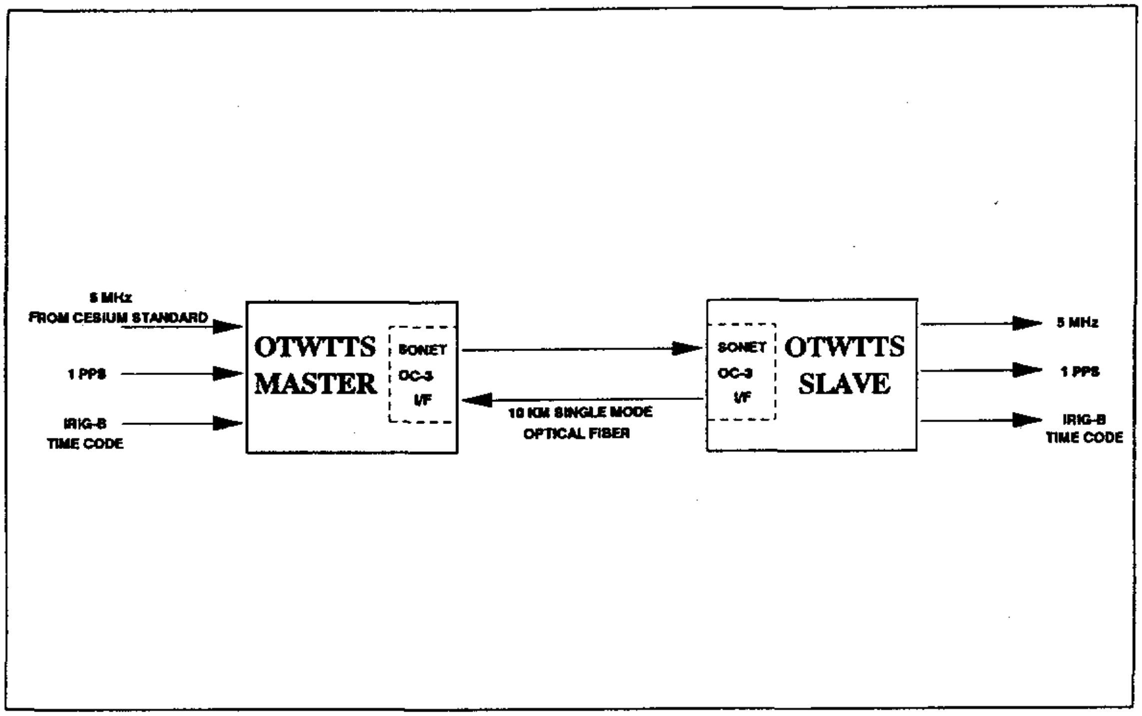

Figure 1. Block Diagram of the Optical Two-Way Time Transfer System

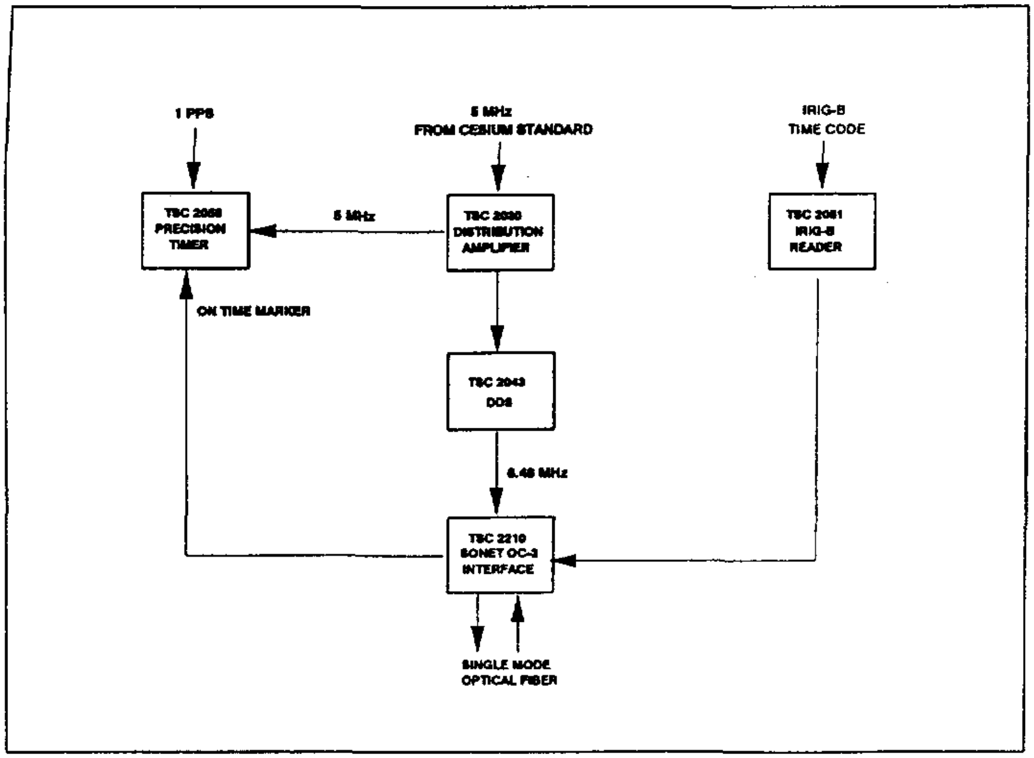

Figure 2. OTWTTS Master Unit Block Diagram

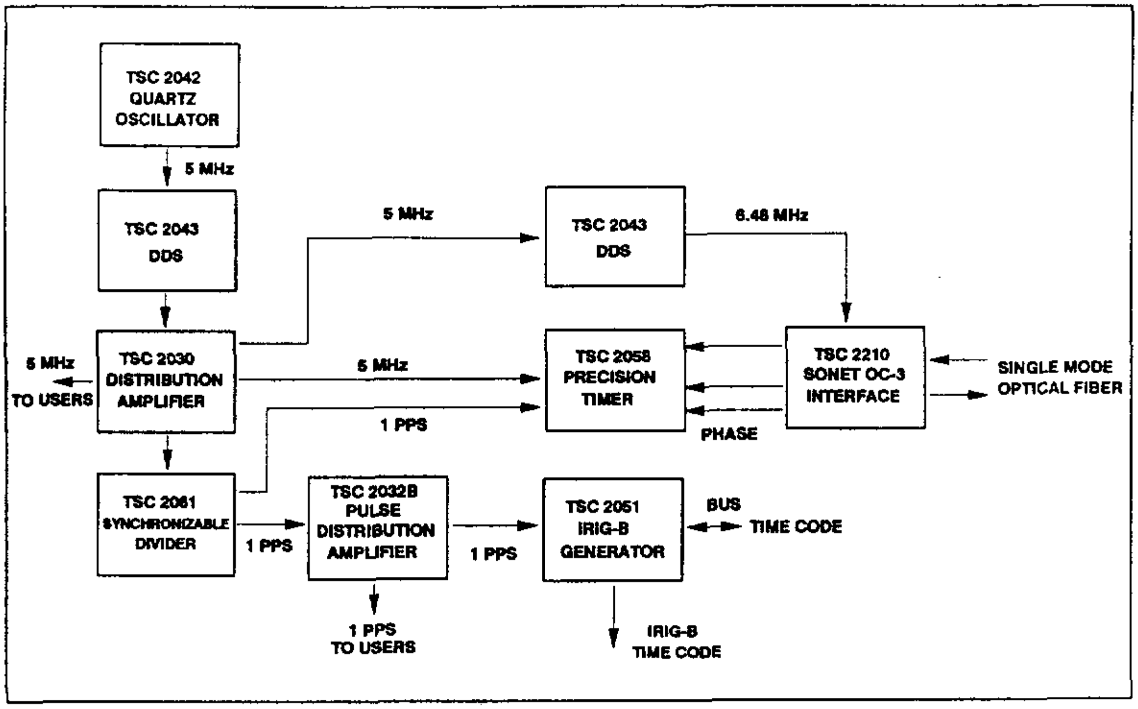

Figure 3. OTWTTS Slave Unit Block Diagram

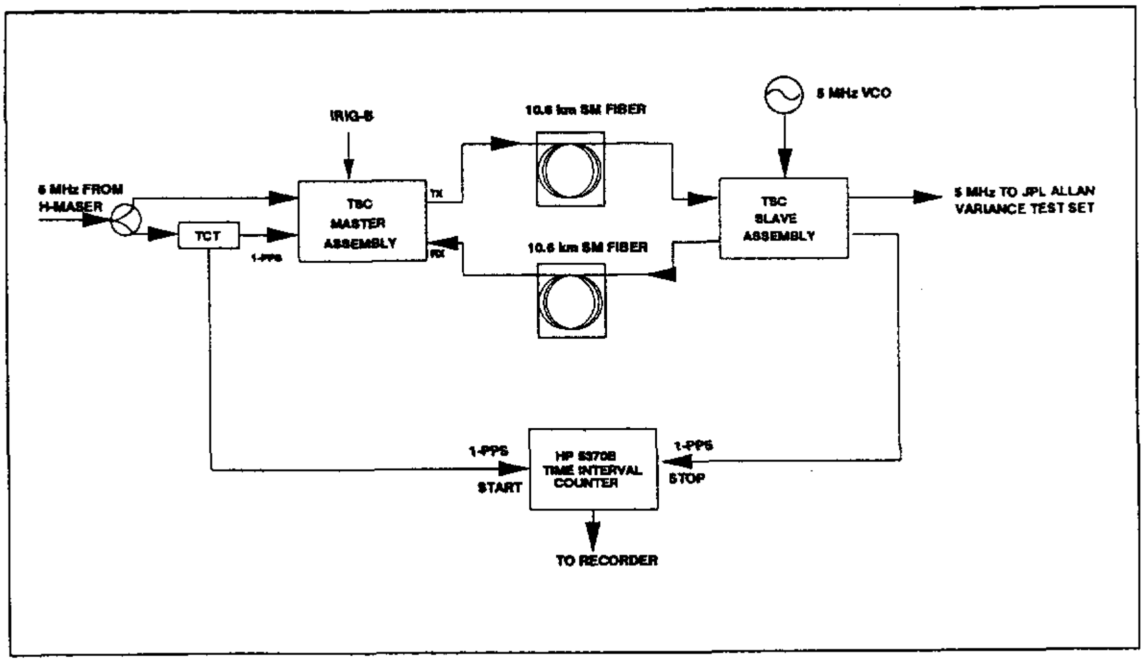

Figure 4. Test Configuration for the TSC Master-Slave Time Transfer System

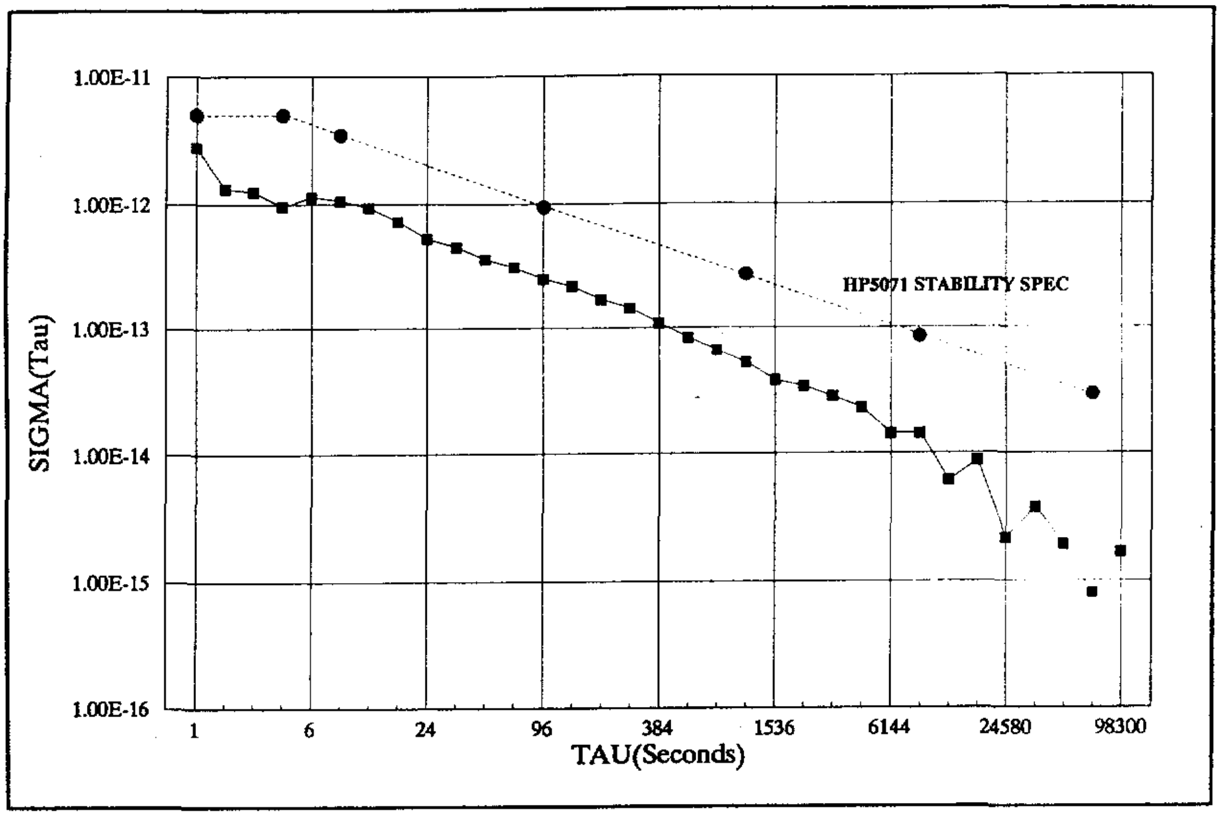

Figure 5. Allan Deviation, OTWTTS 5 MHz Distribution

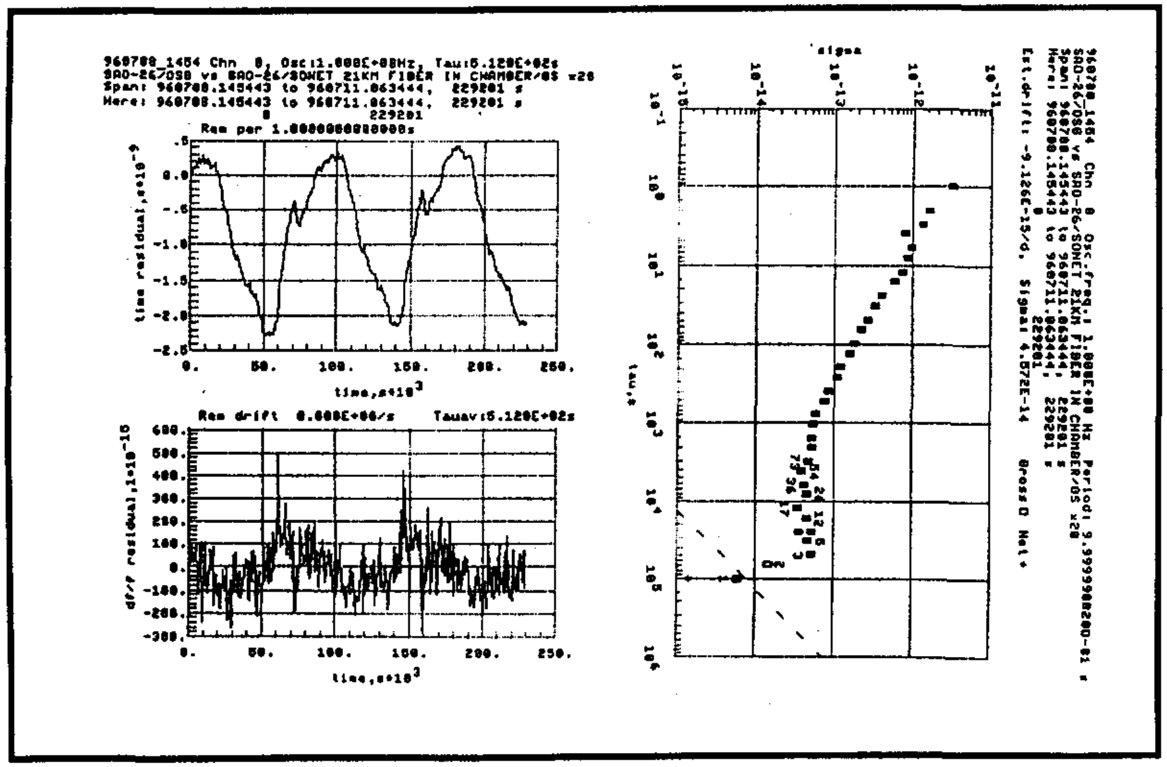

Figure 6. Allan Deviation, OTWTTS with 10.56 km Fiber Temperature Cycled

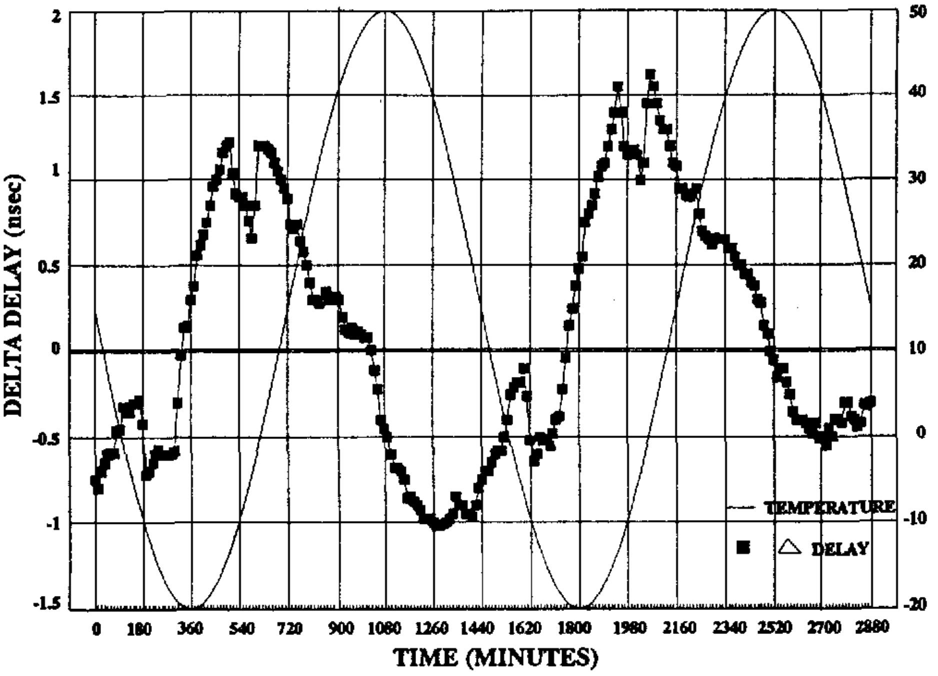

Figure 7. OTWTTS Slave 1 PPS Delay Variations with Temperature Cycling

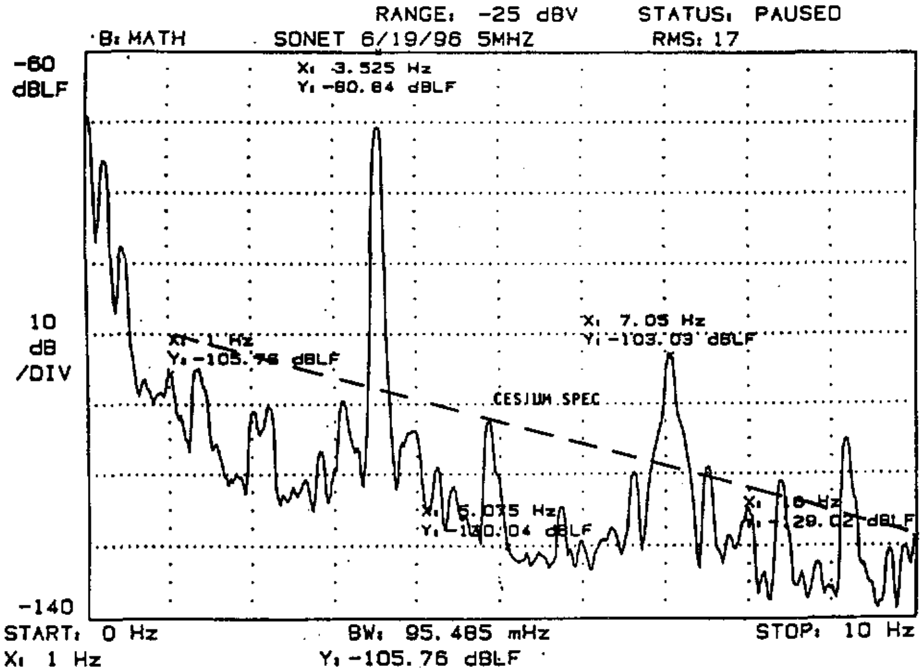

Figure 8. OTWTTS Slave Phase Noise Density, 0 to 10 Hz

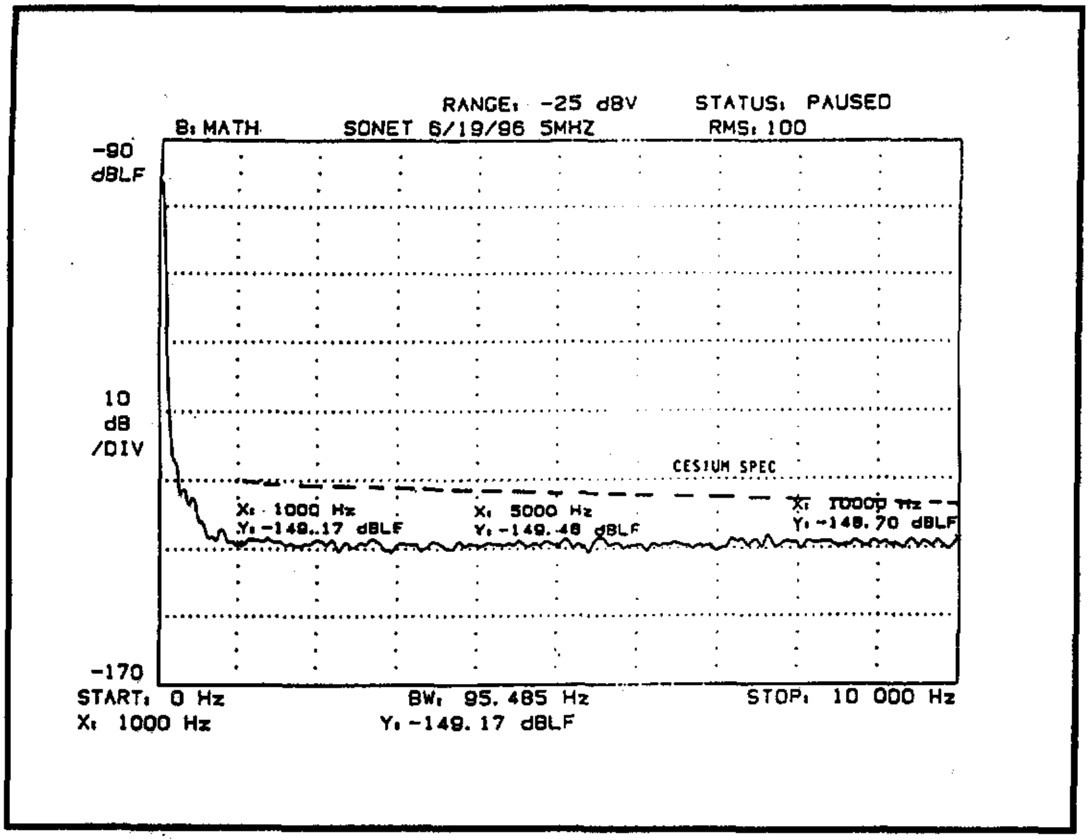

Figure 9. OTWTTS Slave Phase Noise Density, 0 to 10 KHz

Questions and Answers

MICHAEL GARVEY (FREQUENCY AND TIME SYSTEMS, INC.): Malcolm, you showed a plot of Allan deviation, I believe. And I wasn't quite sure what the measurement configuration there was, but it looked like the link shows white frequency noise.

MALCOLM CALHOUN: Yes.

MICHAEL GARVEY: Naively, I would have expected some form of phase noise.

MALCOLM CALHOUN: Actually it's the same data except for the longer averaging times. There are some noise contributions from the SONET which I'm not sure we ever totally characterized. We made some measurements on just the raw SONET devices themselves before Sam's phase-lock loop and cleanup, and there were some horrendous spurs at roughly one-third of second time intervals. Some of them were as high as minus 70 dBc. So I think there's some contributions back there close in that are due to the SONET data that didn't totally get filtered out. I'm not sure, Sam might want to address that question.

SAM STEIN (TIMING SOLUTIONS CORP.): I'm not exactly sure, Mike, of the interpretation of this plot, but the link noise is white phase noise. So that if you measure Allan deviation between the master and the slave with them sitting next to each other, the noise averages out as $1/\tau$.

MARC WEISS (NIST): The delay changes by 2 nanoseconds with temperature. And if it's simply due to the change in fiber length, I would have thought, with the two-way mode, that that would still cancel below the 2-nanosecond level. I'm wondering if you had some idea what the cause of the 2-nanosecond change was.

MALCOLM CALHOUN: It should cancel below the 2-nanosecond level. There is a possibility that there was an error in the measurement of the links of our two fibers. There could have been as much as a 4-meter difference in the links of the two cables; that would be roughly 4 nanoseconds.

Now, we did reverse the position of the two cables, and we still measured the 2 nanoseconds delay variation. We're going to do some more testing.

Yes, I agree with you. It should have been smaller than 2 nanoseconds.