HIGH ACCURACY TIME TRANSFER SYNCHRONIZATION

Paul Wheeler, Paul Koppang, David Chalmers,
Angela Davis, Anthony Kubik and William Powell
U.S. Naval Observatory
Washington, DC 20392

Abstract

In July 1994, the US Naval Observatory (USNO) Time Service System Engineering Division conducted a field test to establish a baseline accuracy for two-way satellite time transfer synchronization. Three Hewlett–Packard model 5071 high performance cesium frequency standards were transported from the USNO in Washington, DC to Los Angeles, California in the USNO's mobile earth station. Two-Way Satellite Time Transfer links between the mobile earth station and the USNO were conducted each day of the trip, using the Naval Research Laboratory(NRL) designed spread spectrum modem, built by Allen Osborne Associates(AOA). A Motorola six channel GPS receiver was used to track the location and altitude of the mobile earth station and to provide coordinates for calculating Sagnac corrections for the two-way measurements, and relativistic corrections for the cesium clocks.

This paper will discuss the trip, the measurement systems used and the results from the data collected. We will show the accuracy of using two-way satellite time transfer for synchronization and the performance of the three HP 5071 cesium clocks in an operational environment.

INTRODUCTION

The purpose of this experiment was to demonstrate our ability to accurately calibrate remote precise time laboratories and Department of Defense (DOD) installations using two–way satellite time transfer techniques [1]. Although the USNO has participated in two–way experiments for years, little work has been done in performing absolute calibrations of remote sites using this technique. When the need for high accuracy calibrations to remote DOD sites arose, the two–way satellite time transfer technique was selected because of its greater accuracy (± 1 ns) than the Global Positioning System (GPS). This accuracy of two–way has been demonstrated at the USNO and other laboratories, but two–way accuracy had not been demonstrated in the field, in particular in the east–west direction where Sagnac effects are significant.

CLOCK TRIP

For this experiment a two–member team drove the USNO's mobile earth station from the USNO in Washington, DC to Los Angeles, California and a second two–member team drove it back to the USNO (see Figure 1). Two–way measurements were made each day to provide a precise time link between the three cesium clocks in the van and the USNO. The trip was started on July 11th, 1994 and completed on July 22nd.

The USNO's mobile earth station is a Ford Econoline 350 van with a folding Ku-band 1.8 meter dish antenna on the roof, a generator, air conditioning and three equipment racks of electronics to support the antenna and two–way operations. For this trip three Hewlett–Packard 5071A high performance cesium frequency standards, a PC–based data acquisition system, and a Motorola six channel GPS receiver were added.

The data acquisition system consisted of an industrial grade PC manufactured by Texas Microsystems Inc. controlling a Stanford Research SR650 time interval counter, a Hewlett–Packard 3488 VHF switch and the GPS receiver. The GPS receiver was mounted inside the PC and connected to one of the PC serial ports. The clocks and the GPS receiver 1 pps (1 pulse per second) were intercompared every minute with the time interval counter. The GPS position information was logged every 10 minutes. While the mobile earth station was at the USNO, a 1 pps from the Master Clock was also connected to the VHF switch so that the clocks were compared against UTC USNO. This was done before and after the trip to establish the performance of the clocks while they were in the van.

In order to calibrate the two–way system, repetitive two–way measurements between our 4.5 meter base station and the mobile earth station were taken. A calibrated 1 pps and a 5 MHz reference signal, both from the USNO Master Clock, were connected to the modem in each earth station. With this setup the resulting measurement, one clock measured against itself, should be zero, if the transmit and receive delays are identical through the modem, the earth station, the satellite and back, and the cable delays from the reference clock are the same. In reality this is not the case and the resulting measurement will be the calibration factor that is applied to the measurements throughout the experiment. The calibration factor measured to be 243.3 nanoseconds. After returning from the trip this calibration procedure was repeated to verify that the delays through the two–way system had not changed.

The trip was started after a final calibration run. After arriving at a destination in the evening, the van was fueled and parked in the hotel parking lot so that there was good satellite visibility. The clocks and measurement equipment were transferred from inverter power to generator which kept the equipment and air conditioner operating throughout the night. The satellite was located and the equipment was set up in preparation for the time transfer measurement in the morning. For this experiment and most of our domestic two-way operations we use Satellite Business Systems satellite SBS-6.

In the morning the satellite was re–acquired and then, typically, three two–way measurements were obtained. Each result consisted of 300 averaged 1 pps measurements. The AOA modems used for this experiment operate in a source/target configuration. The modem in the van was operated as the source and the target was at the USNO. This gave the travelers control of the satellite link and the two–way measurements. The two–way measurement data from the target modem was transmitted back over the satellite link to the source modem, allowing the results of the measurement set to be calculated. This allowed the field members to evaluate the measurements and to look for anomalies in the data being collected.

The two–way data collected each morning were used to measure the time of the three cesium clocks in the van. The GPS receiver position data were used to calculate Sagnac corrections for the two–way measurements and to calculate relativity corrections for the clock data. The 1 pps from the GPS receiver was used as a coarse rule to compare the clocks.

RELATIVISTIC EFFECTS

The data collected throughout this experiment needed to be corrected for relativistic effects. There are many excellent references [1−5] on the derivation and theory behind these effects; therefore, they will only be touched upon briefly in this paper. Due to the rotation of the earth and the satellite, the path lengths (from one earth station to the satellite to the other earth station and back) during a satellite two–way time transfer are not symmetrical. This phenomenon is referred to as the Sagnac effect. The time difference caused by this effect is given by $2\omega A/c^2$, where c is the velocity of light, ω is the Earth's rotation rate, and A is the area defined by the projection onto the equatorial plane by the segments connecting the satellite and the Earth's center to the two earth stations [1]. Figure 2 is a plot of the Sagnac corrections needed for the two–way data taken during the trip.

There are three main components of relativistic corrections that need to be addressed for the clock trip elapsed time. These corrections are due to height (red shift), velocity (Doppler shift), and east–west motion. The equation used to calculate these corrections is:

$$\Delta t = \int_{path} ds \left[1 - g(\phi)h/c^2 + \frac{1}{2}(v/c)^2 + \frac{\omega}{c^2} a v_E \cos\phi\right] \tag{1}$$

where g(ϕ) is the acceleration of gravity, v_E is the ground velocity of the clock having an eastward component , h is the altitude above the geoid, ω is the angular velocity of rotation of the Earth, a is the Earth's equatorial radius, and ϕ is the geographical latitude [3].

The GPS receiver provided most of the information needed to solve the above equation. Every 10 minutes the position of the van (height, latitude, and longitude) and the time were gathered from the GPS receiver and stored on the PC.

The height correction:

$$g(\phi)h/c^2 \tag{2}$$

of 82.57 ns turns out to be the dominant clock trip relativistic correction term in this experiment due to the trip length of 11 days and the vast height differences encountered along the trip, for instance Washington, DC is at 55 meters while part of Colorado is over 3000 meters(see Figure 3). Since this term does not depend on velocity, but on height, it is continuing to have an effect as long as there is a height differential. Therefore, the clocks were realizing a relativistic change of rate even when the van was parked for the night at a location with a different elevation than that of Washington, DC.

The east-west correction:

$$\frac{\omega}{c^2} a v_E \cos\phi \tag{3}$$

ends up being an integration of east(west) velocity over time, which is then just the distance traveled east(west). Since this term turns out to be proportional to the distance traveled and independent of velocity, it would be the same whether a van or, for instance, an airplane was used for the clock trip. For a round trip (east–west, west–east) this term cancels out at the conclusion of the trip, but gives a necessary correction to the data during the trip.

The Doppler term is:

$$\frac{1}{2}(v/c)^2 \tag{4}$$

Even though the van traveled very slowly compared to the speed of light, the 11 day trip was long enough to give the Doppler term a non–negligible correction of 1.24 ns. Figure 4 shows the three different contributions along with the total relativistic correction for the trip.

It is interesting to compare these clock trip data to what we would have seen on a airplane trip from Washington, DC to Los Angeles and back. We will assume an average air speed of 550 miles per hour and an average altitude of 25,000 feet. The height correction for the round trip calculates to be -28.2 ns, while the velocity correction would be 11.4 ns. Therefore the total correction to the clock data would be -16.8 ns as compared to the -82.6 ns of the van trip.

DATA

The two–way time transfer method was used to compare cesium clock serial #254 vs. the Master Clock at 12 different sites during the round trip. The phase data being logged between clocks #254, #416, and #227 locally in the van (see Fig. 5) along with the two–way data was used to calculate the differences between the Master Clock and the clocks #416 and #227 during the trip. The relativistic corrections due to the clock trip were then made to the cesium clock – Master Clock data after Sagnac effect corrections to the two–way data had been taken into account. Figures 6–8 show the raw data and the data corrected for both the two–way Sagnac and relativistic clock trip effects. In Figures 6–8 the data that are bunched together at the beginning and the end of the plots were taken at USNO with the Master Clock directly connected to the measurement system, while the individual points were obtained via the two–way time transfer method.

The cesium clocks performed very well considering the less than ideal environmental conditions inside the van during the trip. The clocks experienced approximately 40 degree temperature swings and considerable vibration. The Allan deviations of the cesium clocks as measured in the van during the trip were:

hr	#227-#416	#254-#227	#254-#416	#points
1	1.14e-13	1.18e-13	1.18e-13	415
2	8.21e-14	8.06e-14	8.44e-14	207
4	5.93e-14	5.85e-14	6.38e-14	103
8	4.52e-14	3.81e-14	4.47e-14	51
16	3.18e-14	2.80e-14	3.59e-14	25
32	2.32e-14	2.46e-14	3.24e-14	12
64	1.83e-14	1.39e-14	2.38e-14	6
128	1.50e-14	7.38e-15	1.82e-14	3

Clock pairs 227–416 and 254–227 had stabilities that were below the specifications given by the manufacturer for clocks under environmental control(see Figure 9).

CONCLUSION

This experiment has shown that the two–way time transfer method can be used to accurately calibrate remote precise time laboratories and DOD installations using the necessary Sagnac corrections to the data. Also, it is necessary to take into account the effects of relativity when using a portable clock to do remote synchronization no matter what the mode of transportation of the clock. The three HP 5071 clocks performed very well in less than ideal conditions.

REFERENCES

[1] D.W. Hanson, *"Fundamentals of two–way time transfers by satellite"*, Proceedings of the 43rd Annual Symposium on Frequency and Control, 31 May – 3 June 1989, Denver, Colorado, pp. 174-178.

[2] G.M.R. Winkler, *"Synchronization and Relativity"*, Proceedings of the IEEE, Vol. 79, No. 6, June 1991. (This paper gives references to many excellent papers on relativity.)

[3] N. Ashby and D.W. Allan, *"Practical implications of relativity for a global coordinate time scale"*, Radio Science, Vol. 14, 1979, pp. 649–669.

[4] J.C. Hafele and R.E. Keating, *"Around the world atomic clocks"*, Science, Vol. 177, pp. 166–170, July 1972.

[5] N. Ashby, *"RELATIVITY and GPS"*, GPS World, Nov. 1993. pp. 42–47.

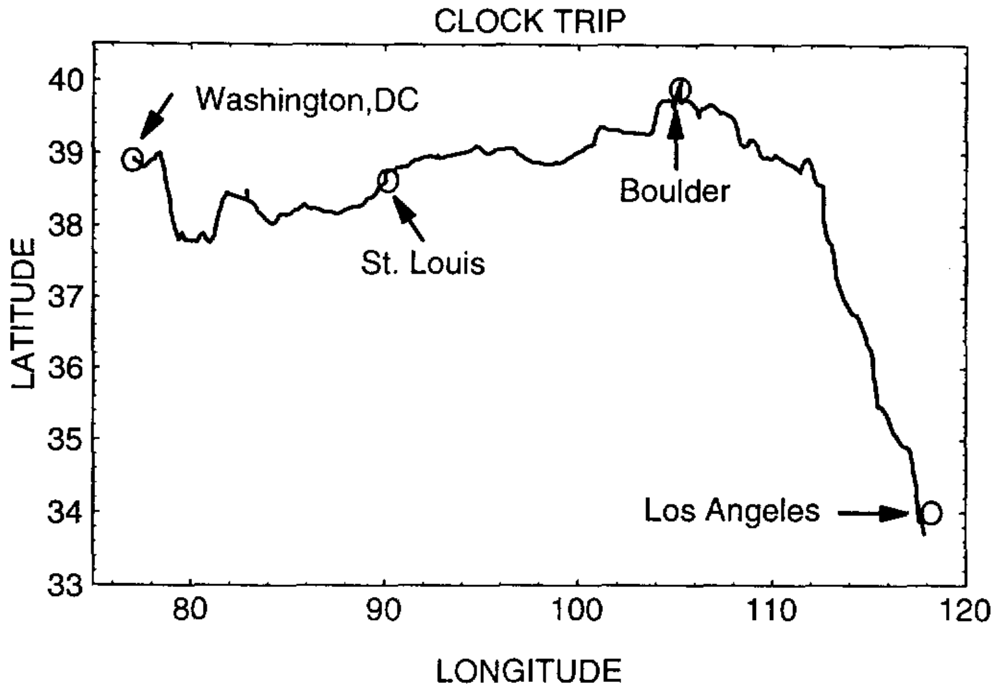

Figure 1. Clock trip as measured by the GPS receiver.

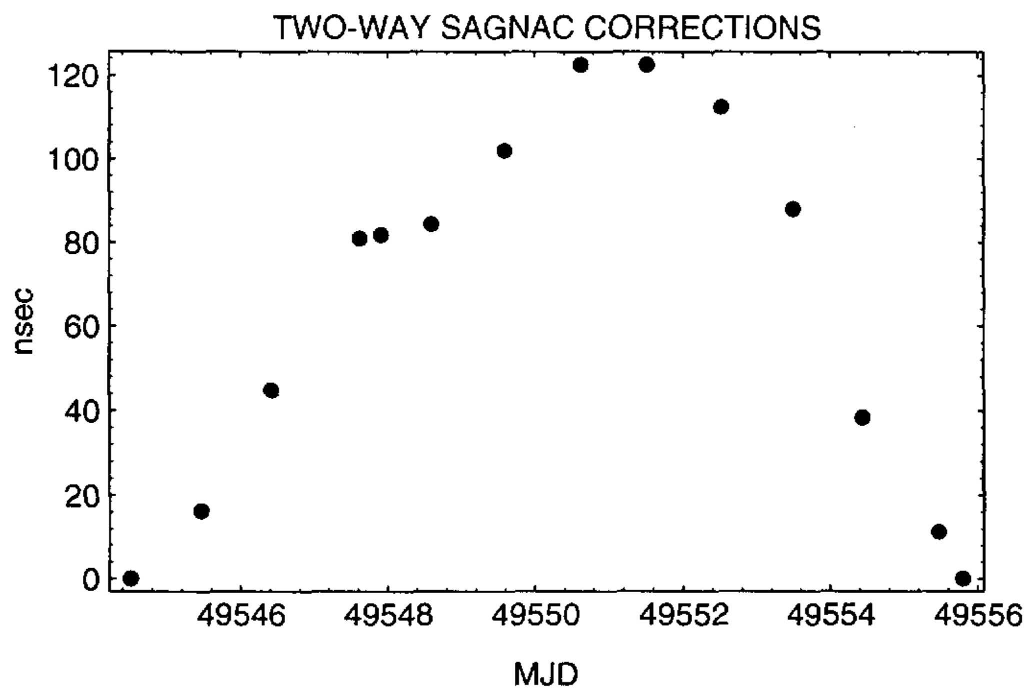

Figure 2. Sagnac corrections calculated for the two-way data.

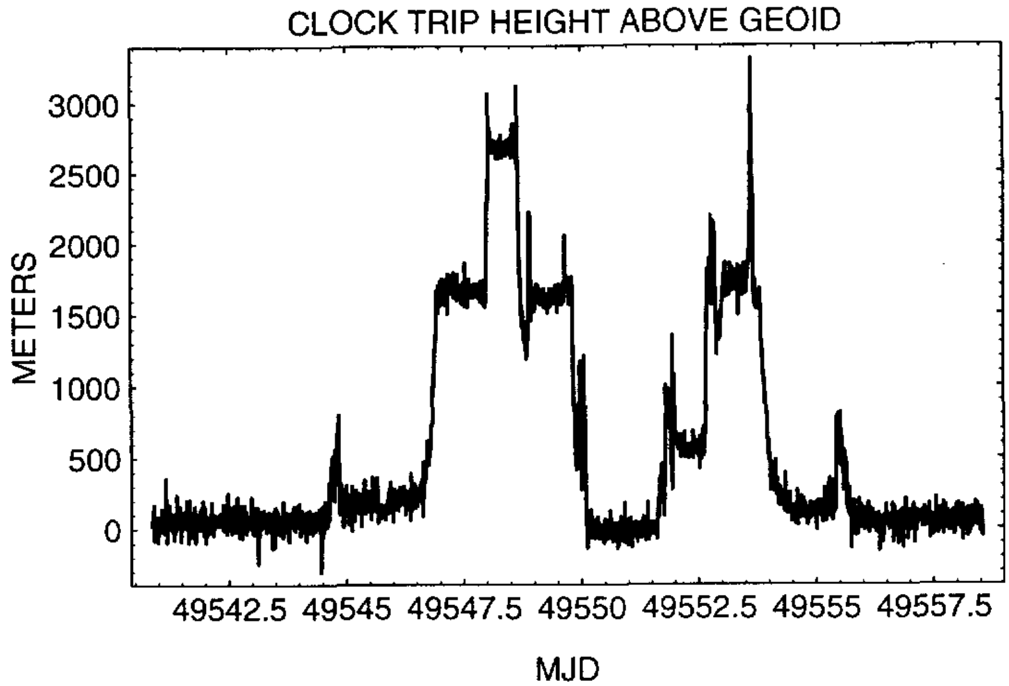

Figure 3. The height of the van above the geoid during the trip as measured by the GPS receiver.

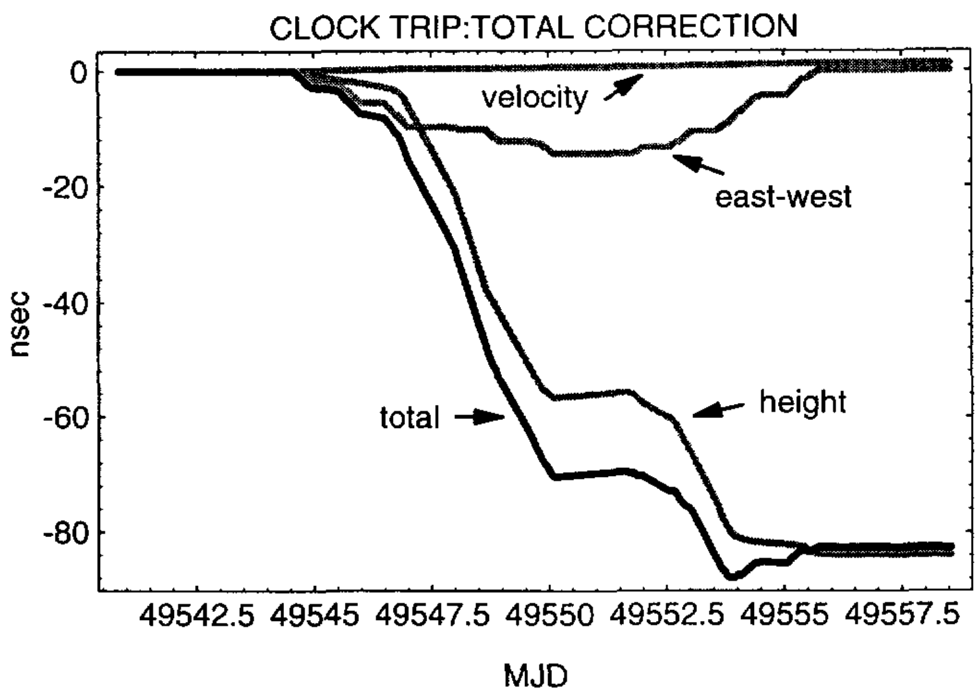

Figure 4. The total relativistic clock trip corrections along with the individual components.

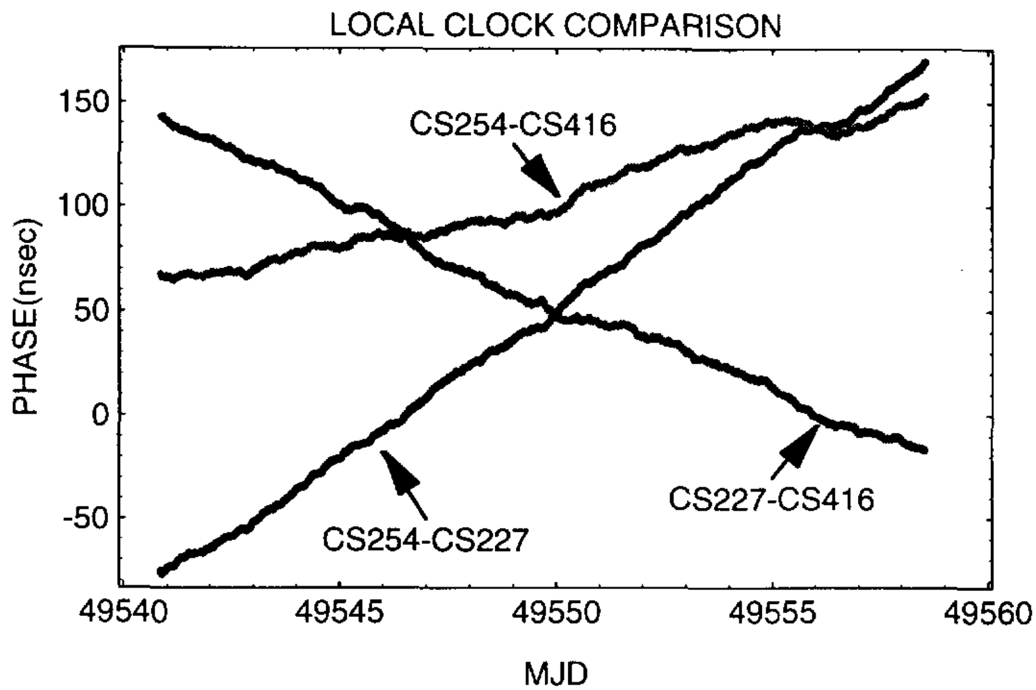

Figure 5. The cesium clocks inter-compared as measured locally in the van.

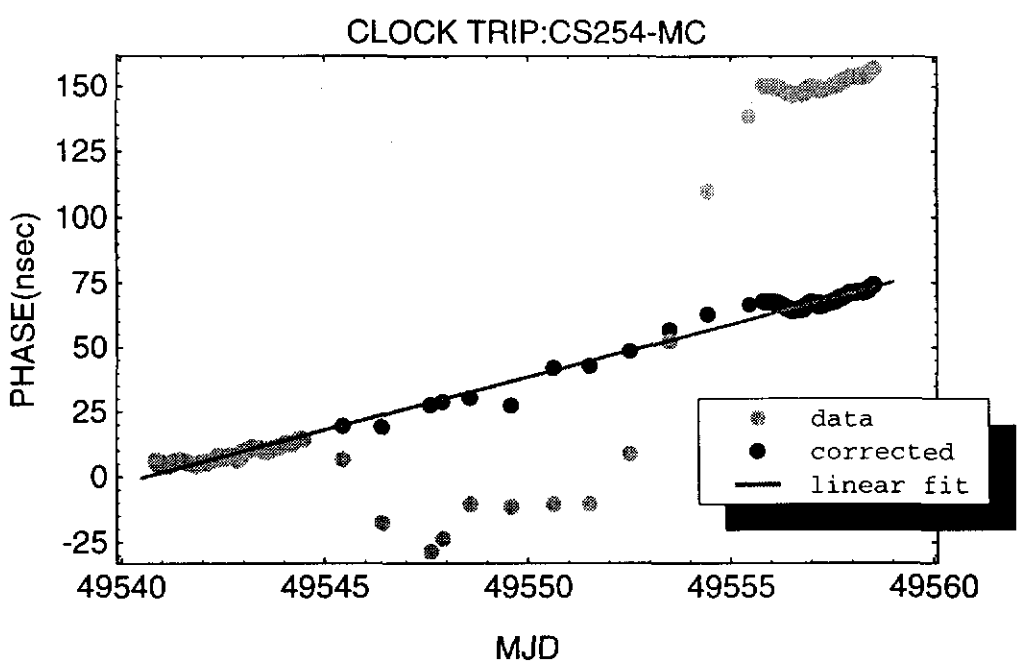

Figure 6. Shows the original cesium #254-Master Clock data along with the data corrected for two-way Sagnac and the clock trip relativistic effects.

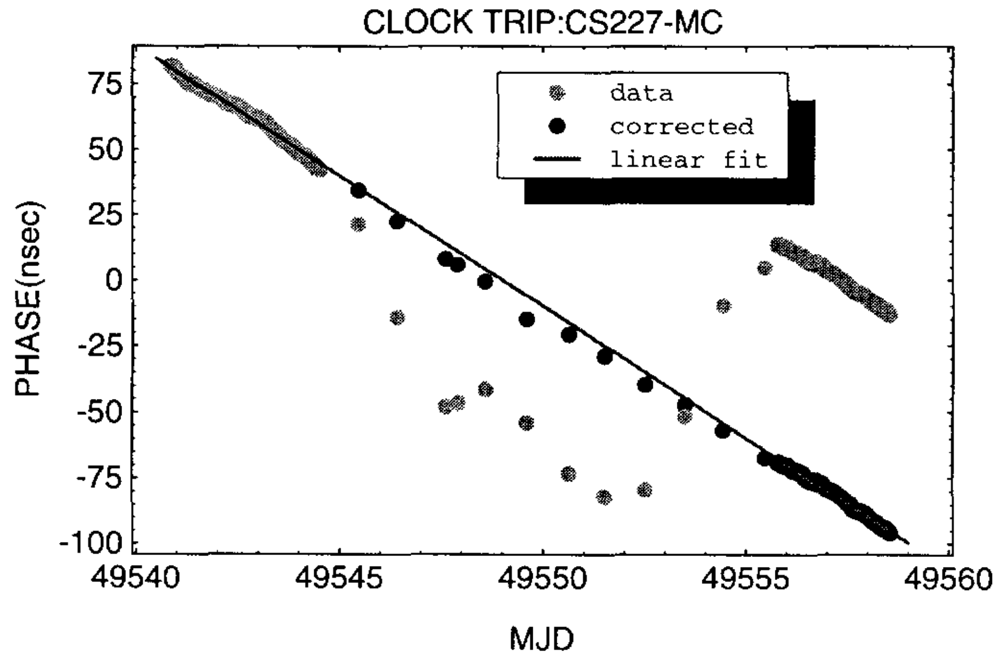

Figure 7. Shows the original cesium #227-Master Clock data along with the data corrected for two-way Sagnac and the clock trip relativistic effects.

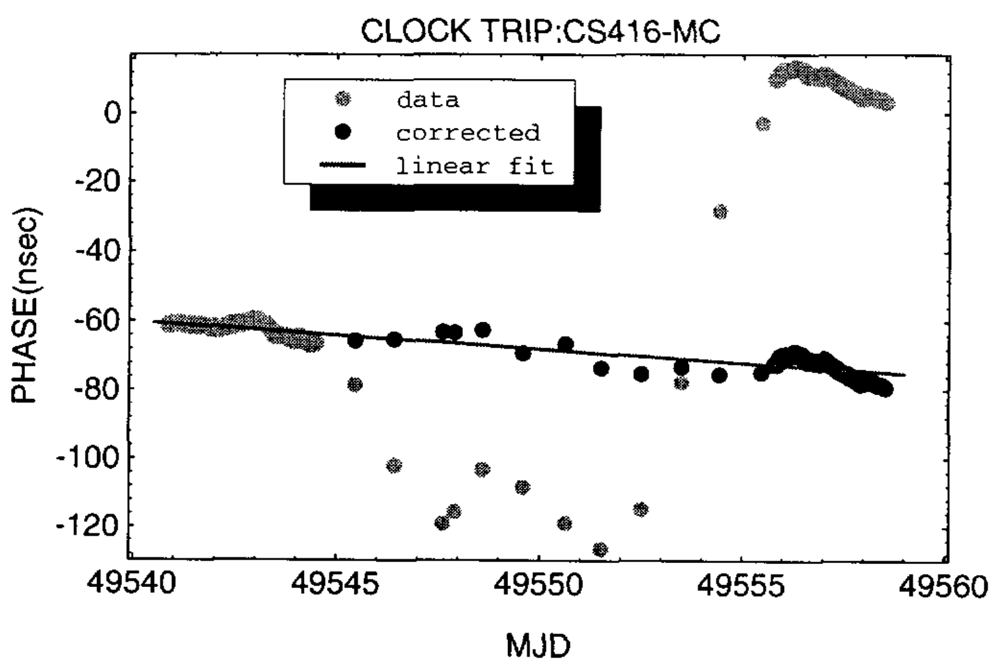

Figure 8. Shows the original cesium #416-Master Clock data along with the data corrected for two-way Sagnac and the clock trip relativistic effects.

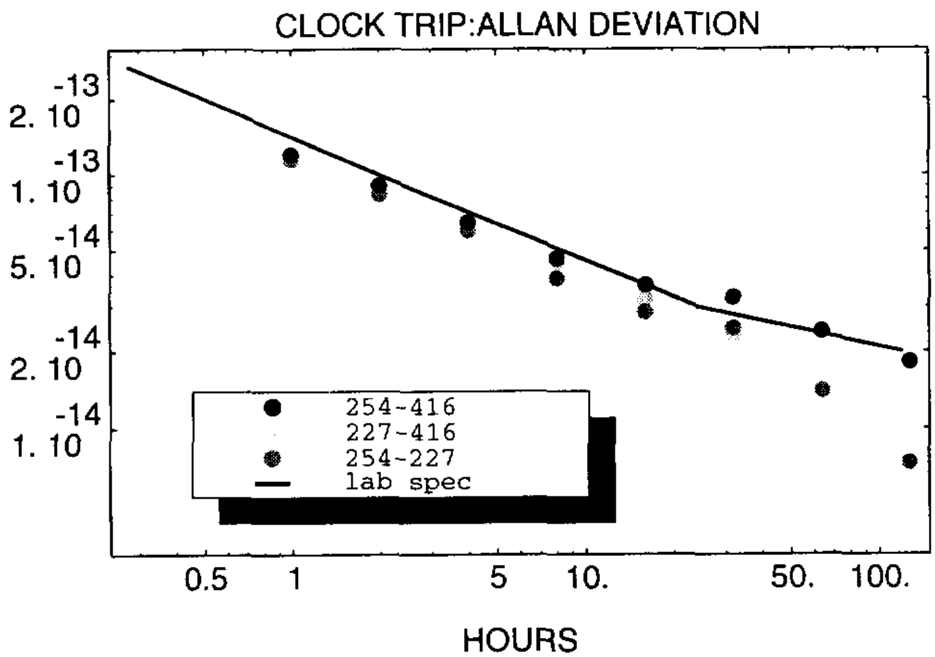

Figure 9. Stability of the cesium clocks as measured in the van during the trip.

QUESTIONS AND ANSWERS

DAVID ALLAN (ALLAN'S TIME): A question regarding the regression that you did to determine the frequency during the trip from the data. As near as I can tell, it looks like you did a linear regression to all of the phase points. Is that correct?

PAUL WHEELER (USNO): Yes.

DAVID ALLAN (ALLAN'S TIME): Given your sigma tau plot that the noise is white noise frequency modulation, which is random walk of phase, the optimum interpolater for the frequency while you were on the trip would be the end–point from the beginning and the beginning point of the end, to give you a better estimate of frequency than the linear regression. Thank you.

SIGFRIDO M. LESCHIUTTA (IEN): Could you please elaborate to me concerning the two calibration processes? One was done before and after the trip. What was done really?

The second, have you made any calibration before and after each session, calibration of the orbital treatment?

PAUL WHEELER (USNO): The calibration –– we do it a couple different ways. For this experiment, since the clocks in the van, we wanted to measure the clocks that were taken with us the same way at the Observatory as we did in the field. So we did two–way time transfer between the two stations right there at USNO, our base station being measured against the USNO Master Clock. The mobile air station being measured against one of the clocks in the van. Right after that session, we then measured that clock with a cable, to our acquisition system, against the Master Clock and determined the difference between the two ways.

The second question, the answer is no. It was strictly before we left and when we returned, and nothing in–between.