EXPERIMENTAL COMPARISON OF TIME SYNCHRONIZATION TECHNIQUES BY MEANS OF LIGHT SIGNALS AND CLOCK TRANSPORT ON THE ROTATING EARTH

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Abstract

An experiment was conducted to investigate the equivalence of two methods of time transfer in a noninertial reference frame: by means of an electromagnetic signal using laser light pulses and by means of the slow ground transport of a hydrogen maser atomic clock. The experiment may also be interpreted as an investigation of whether the one–way speeds of light in the east–west and west–east directions on the rotating earth are the same. The light pulses were sent from a laser coupled to a telescope at the NASA Goddard Optical Research Facility (GORF) in Greenbelt, Maryland to the U.S. Naval Observatory (USNO) in Washington, DC. The optical path was made possible by a 30–cm flat mirror on a water tower near GORF and a 25–cm flat mirror on top of the Washington National Cathedral near USNO. The path length was 26.0 km with an east–west component of 20.7 km. The pulses were reflected back over the same path by a portable array of corner cube reflectors. The transmission and return times were measured with a stationary Sigma Tau hydrogen maser and a University of Maryland event timer at GORF, while the times of reflection were measured with a similar maser and event timer combination carefully transported to USNO. Both timekeeping systems were housed in highly insulated enclosures and were maintained at constant temperatures to within $\pm 0.1°C$ by microprocessor controllers. The portable system was also protected from shock and vibration by pneumatic supports. The difference ΔT between the directly measured time of reflection according to the portable clock and the time of reflection calculated from the light pulse signal times measured by the stationary clock was determined. For a typical trip $\Delta T < 100$ ps and the corresponding limit on an anisotropy of the one–way speed of light is $\Delta c/c < 1.5 \times 10^{-6}$. This is the only experiment to date in which two atomic clocks were calibrated at one location, one was slowly transported to the other end of a path, and the times of transmission, reflection, and return of short light pulses sent in different directions along the path were registered.

INTRODUCTION

The precision of time synchronization techniques made possible by hydrogen maser atomic clocks, event timers, and short pulse laser ranging systems implies that relativistic effects must be modelled

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in the practical realization of a spatially distributed time scale. The prescription requires the adoption of an appropriate set of conventions and a coordinate reference frame so that a self–consistent scale of coordinate time can be established [1, 2]. There are two methods for the comparison of remote clocks: the propagation of an electromagnetic signal and the transport of an intermediate portable clock.

Experiments are required to test the assumptions and interpretation of the theoretical model. These experiments also provide a means to investigate the foundations of the metric theory of space, time, and gravitation, in which the behavior of clocks and light pulses plays a central role. In particular, the equivalence of the two methods of time synchronization in the noninertial reference frame of the rotating earth was recently tested at the University of Maryland [3]. This experiment may also be interpreted as a test of the isotropy of the one–way speed of light in the east–west and west–east directions.

In the experiment, short pulses of light were sent from a laser coupled to the 1.2–meter telescope at the NASA Goddard Optical Research Facility (GORF) in Greenbelt, Maryland, to the U.S. Naval Observatory in Washington, DC. The pulses were reflected back over the same path by a portable array of corner cube reflectors. The proper time of emission τ_1 and proper time of return τ_3 of each pulse were recorded by a hydrogen maser and event timer at GORF. The proper time of reflection τ_2 was recorded by a second hydrogen maser and event timer carefully transported to USNO. The two timekeeping systems were calibrated both before and after the portable clock trip. If the corresponding coordinate times of reflection calculated from the measurements by the portable clock and the electromagnetic signals are respectively t_2^{PC} and t_2^{ES}, the quantity

$$\Delta T \equiv t_2^{\mathrm{PC}} - t_2^{\mathrm{ES}} \tag{1}$$

should be zero in any self–consistent relativistic prescription. The object of the experiment was therefore to determine ΔT.

Research in preparation for this experiment has been reported in previous PTTI papers. In 1982 measurements of light pulse time comparisons were first performed over the optical link using cesium beam clocks to support the proposed LASSO experiment [4]. With the cooperation of the Johns Hopkins University Applied Physics Laboratory, several trips were made in 1987 to test the feasibility of using a hydrogen maser as a portable clock. In one trip a time transfer between APL and USNO was completed with a time closure of less than 200 ps [5]. A pilot experiment to measure ΔT was carried out during the spring and summer of 1988 using a Sigma Tau maser borrowed through the courtesy of APL and JPL as the portable clock and an APL NR–series maser on loan from the NASA Crustal Dynamics Project that was kept at GORF. Subsequently, the present experiment was carried out over the period from September 1988 through April 1989 using two Sigma Tau masers loaned by the National Radio Astronomy Observatory VLBI program. Preliminary results were described at the 1988 PTTI meeting [6].

This is the first experiment in which two atomic clocks were calibrated at one location, one was slowly transported to the other end of a path, and the times of transmission, reflection, and return of short light pulses sent in different directions along the path were registered. In contrast to experiments of the Michelson–Morley type [7], in which light is sent around a closed path, these measurements test the isotropy of the one–way speed of light. However, unlike other recent experimental tests, such as Mössbauer gamma ray absorption experiments on a rotating disk [8, 9] and atomic beam laser
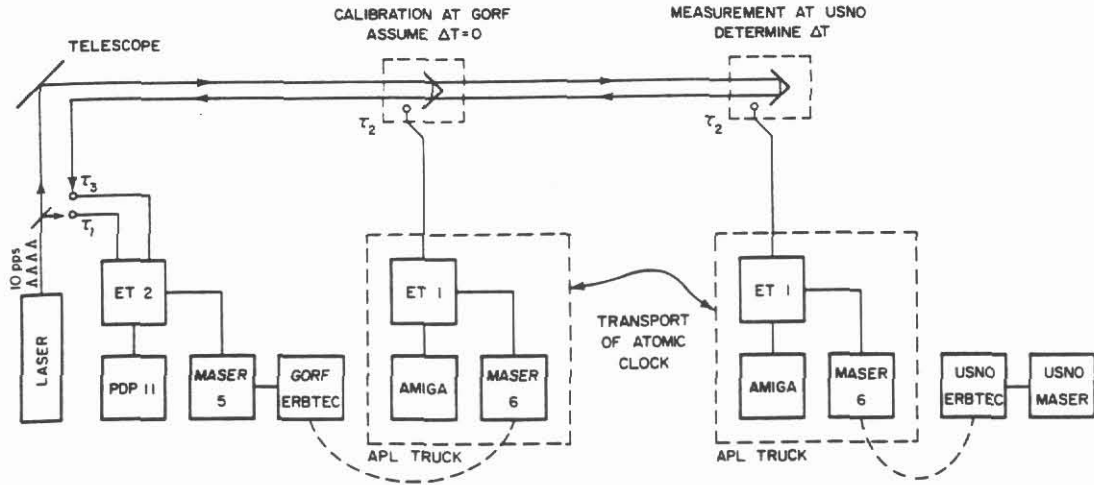
Figure 1. Schematic diagram of experiment.

spectroscopy measurements [10], this experiment uses short light pulses involving the group velocity and actual measurements of time rather than waves involving the phase velocity and measurements of phase difference or frequency. It complements two other experiments involving hydrogen masers at the opposite ends of a path: the JPL experiment of Krisher *et al.* [11, 12], in which a possible diurnal variation was monitored in a continuous laser signal sent along a fiber–optic link, and the Smithsonian Astrophysical Laboratory experiment of Vessot *et al.* [13], in which the rate of a rocket–borne hydrogen maser was measured as a function of height, speed, and direction.

EXPERIMENT DESIGN

A schematic diagram of the experiment is illustrated in *Figure 1*. The phase difference between the portable and stationary masers was monitored continously at GORF, interrupted only by the portable clock trips. Before and after a trip, a series of optical measurements with the laser pulses was also performed at GORF to calibrate the time measurement systems assuming $\Delta T = 0$ locally. Then the portable system was transported to USNO and the optical measurements were repeated to determine the value of ΔT at the other end of the path. The portable clock was compared with one of the USNO masers to verify its stability while at the remote site.

Assume that coordinate time is established by synchronization with the clock at GORF. Then the coordinate time of reflection of each light pulse according to the method of clock transport is

$$t_2^{\text{PC}} = \tau_2 + \Delta t_{\text{rel}}^{\text{PC}} \tag{2}$$

where $\Delta t_{\text{rel}}^{\text{PC}}$ is a relativistic correction for clock transport. Similarly, the coordinate time of reflection obtained by using electromagnetic signals is

$$t_2^{\text{ES}} = \tau_1 + \frac{1}{2}(\tau_3 - \tau_1) + \Delta t_{\text{rel}}^{\text{ES}} = \frac{1}{2}(\tau_1 + \tau_3) + \Delta t_{\text{rel}}^{\text{ES}} \tag{3}$$

where $\Delta t_{\text{rel}}^{\text{ES}}$ is a relativistic correction for electromagnetic signals. The value of ΔT is therefore

$$\Delta T = \left(\tau_2 + \Delta t_{\text{rel}}^{\text{PC}}\right) - \left[\frac{1}{2}(\tau_1 + \tau_3) + \Delta t_{\text{rel}}^{\text{ES}}\right] = \left[\tau_2 - \frac{1}{2}(\tau_1 + \tau_3)\right] + \Delta t_{\text{rel}} \tag{4}$$

89

where $\Delta t_{\text{rel}} \equiv \Delta t_{\text{rel}}^{\text{PC}} - \Delta t_{\text{rel}}^{\text{ES}}$. The individual relativity corrections $\Delta t_{\text{rel}}^{\text{PC}}$ and $\Delta t_{\text{rel}}^{\text{ES}}$ depend on the coordinate system but in any self–consistent relativistic prescription their difference Δt_{rel} is independent of the coordinate system. Physically, this is because the apparatus with which the measurements are performed cannot be affected by the choice of coordinate system in which the data are analyzed. For example, in a locally inertial system, $\Delta t_{\text{rel}}^{\text{PC}} = \int_{\text{path}} (v^2/2c^2 - gh/c^2)\, d\tau$ and $\Delta t_{\text{rel}}^{\text{ES}} = 0$, where v is the portable clock velocity, g is the acceleration of gravity, and h is the height above the geoid. Alternatively, in an earth–centered rotating coordinate system, $\Delta t_{\text{rel}}^{\text{PC}} = \int_{\text{path}} (v^2/2c^2 - gh/c^2)\, d\tau + 2\omega A/c^2$ and $\Delta t_{\text{rel}}^{\text{ES}} = 2\omega A'/c^2$, where ω is the angular rate of rotation of the earth and A or A' is the equatorial projection of the area bounded by the path and the earth's radii at each end of the path. Therefore, if the portable clock path coincides with the light path, so that $A = A'$, in either case

$$\Delta t_{\text{rel}} = \frac{1}{c^2} \int_{\text{path}} \left(\frac{1}{2} v^2 - gh \right) d\tau . \tag{5}$$

The portable clock correction has been tested experimentally in the neighborhood of the earth [14]. The isotropy of the one–way speed of light investigated by the present experiment requires that this difference in corrections should be frame–invariant.

The actual measurements are the clock "registration times" τ_1^*, τ_2^*, and τ_3^*. The corresponding proper times associated with the stationary clock are

$$\tau_1 = \tau_1^* - \Delta\tau_{\text{S}} \tag{6a}$$

and

$$\tau_3 = \tau_3^* - \Delta\tau_{\text{S}} \tag{6b}$$

while the proper time associated with the portable clock is

$$\tau_2 = \tau_2^* - \Delta\tau_{\text{P}} - \Delta\tau_{\text{PS}} \tag{7}$$

where $\Delta\tau_{\text{S}}$ and $\Delta\tau_{\text{P}}$ are the total systematic offsets due to cable delays and response times in the stationary and portable systems, respectively, and $\Delta\tau_{\text{PS}}$ is the proper time offset due to the phase difference between the two systems. The net systematic delay is

$$\Delta\tau_{\text{del}} \equiv \Delta\tau_{\text{P}} - \Delta\tau_{\text{S}} . \tag{8}$$

Due to inefficiencies in optical detection, only about 50 out of 1000 pulses yield measurements of all three times. Therefore, the measurements of τ_1^*, τ_2^*, and τ_3^* are merged on a computer for all of the laser pulses to identify the corresponding sets of values. The matching program produces distributions for the differences

$$\Delta T_{21}^* \equiv \tau_2^* - \tau_1^* \tag{9a}$$

and

$$\Delta T_{31}^* \equiv \tau_3^* - \tau_1^* . \tag{9b}$$

Therefore, we can express Eq. (4) in the form

$$\Delta T = \Delta T_{21}^* - \frac{1}{2} \Delta T_{31}^* - \Delta\tau_{\text{del}} - \Delta\tau_{\text{PS}} + \Delta t_{\text{rel}} \tag{10}$$

where Δt_{rel} is given by Eq. (5). This is the primary working equation for the experiment. The delay $\Delta\tau_{\text{del}}$ is eliminated by the calibration measurement at GORF, while the proper time offset $\Delta\tau_{\text{PS}}$ between the portable and stationary masers at the time of the remote measurement is determined by interpolation.
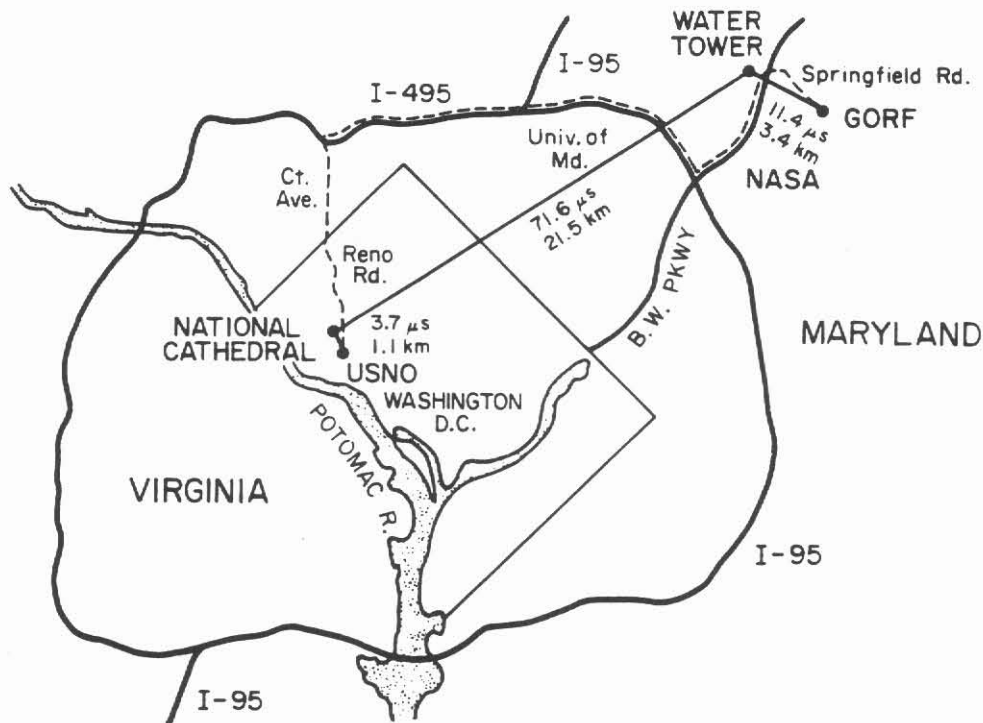
Figure 2. Optical path across Washington and portable clock route.

OPTICAL PATH AND CLOCK ROUTE

The optical path from GORF to USNO is illustrated in *Figure 2*. A truck equipped with an electrical power generator was provided by APL and was used to carry the portable maser. The 1.2–meter telescope at GORF is at longitude 76° 49.7′, latitude 39° 1.4′, and elevation 43 m. The site is shown in *Figure 3*. The retroreflector array was set up in front of Building 1 at USNO at longitude 77° 4.0′, latitude 38° 55.3′, and elevation 79 m. The truck is shown parked at this location in *Figure 4*. Due to local topography, there is no direct line of sight. However, the optical path was made possible by a 30–cm flat mirror on a water tower near GORF and a 25–cm flat mirror on top of the Washington National Cathedral near USNO. The path length was 26.0 km with an east–west component of 20.7 km. The 37.4 km route taken by the portable clock in the truck is indicated by a broken line.

During a calibration measurement, light pulses from the telescope were reflected off a small mirror mounted on the tower labeled "laser beacon system" in *Figure 3*. This system previously had been disassembled and the dome removed. The telescope is shown in the calibration position in *Figure 5*. The truck containing the portable maser can be seen (partially obscured by a trailer office) with the portable detector behind it. A closeup view of the detector package is illustrated in *Figure 6*.

A telephone was installed at each location. On the night of a measurement, the activities were coordinated by means of a telephone conference call. A minimum team consisted of three people at GORF to operate the laser and event timer and to coordinate activities; one person at the water tower and one person at the cathedral to adjust the mirrors; and three people at USNO to drive the truck, adjust the detector, and run the portable event timer. *Figure 7* shows the beam as seen from the cathedral. The green laser flashes from the water tower were brighter than all other lights visible and the signal arriving at USNO projected shadows of the detector against the side of the truck.

Figure 3. Overhead view of the NASA Goddard Optical Research Facility (GORF).

Figure 4. Truck parked in front of Building 1 at USNO where optical measurements are taken.

Figure 5. 1.2–meter telescope. The laser is in the structure beneath the telescope. The building at left contains the telescope tracking computer. The building in rear contains the stationary maser and event timer and electronic equipment. The water tower is visible on the horizon.

Figure 6. Portable corner cube reflectors and detector.

Figure 7. Laser beam from water tower as seen from the cathedral. The illuminated structure at left is a 215-m high television broadcast antenna.

MASERS AND EVENT TIMERS

The masers used in this experiment were Sigma Tau masers 5 and 6 that were loaned by the National Radio Astronomy Observatory near Soccoro, NM. Maser 5 was kept at GORF and maser 6 was kept in the truck. These masers were part of a group of ten that were constructed for NRAO by Harry Peters and his associates at the Sigma Tau Standards Corporation for use in the Very Long Baseline Interferometry program [15].

The two event timers used in this experiment were developed by the University of Maryland Quantum Electronics Group, as described in Reference [6]. Each event timer has two channels and can measure the epoch of an event to a precision of 20 ps. Data at GORF were recorded by a PDP–11 computer and data for the portable system were recorded by an Amiga PC carried in a van that accompanied the truck.

The portable maser and event timer were contained in a specially constructed, highly insultated enclosure mounted on pneumatic supports. The temperature of the interior of the enclosure was maintained constant to within ±0.1°C by a Shimaden SR–22 PID microprocessor. The truck interior was also temperature controlled. The configuration of the portable maser and event timer is shown in *Figure 8*. Similarly, the stationary maser and event timer at GORF were maintained within temperature controlled enclosures with the same level of stability. All maser cabling used a temperature–stabilized foam–dielectric cable manufactured by Cablewave Systems (FLC 12-50J) with type "N" connectors. The temperature sensitivity of this cable is about 10 ppm/°C.

The phase difference between the portable and stationary masers was monitored at GORF continuously except during the portable clock trips with an Erbtec system [16]. This system utilizes a
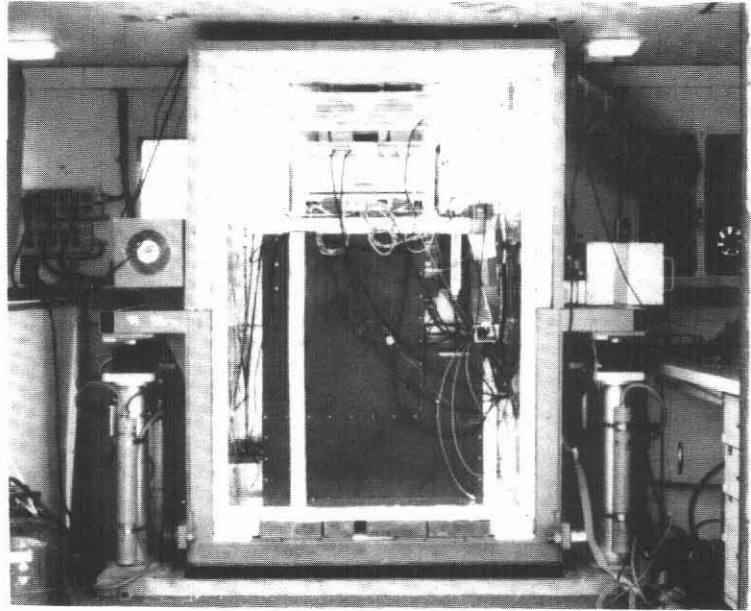
Figure 8. Portable maser and event timer within enclosure.

principle of mixing the 5–MHz frequency of each maser with a synthesized frequency of 4.999 990 MHz to generate two 10–Hz beat signals. The phase difference between these beat signals can be measured by standard methods and is equal to the phase difference between the 5–MHz signals themselves. The resolution is 0.2 ps with an ambiguity of 200 ns.

LASER AND DETECTORS

The laser is a Q–switched, mode–locked, cavity dumped neodymium–YAG (Nd: YAG) stable resonator with two amplifiers. The fundamental infrared wavelength of 1064 nm is converted to green at 532 nm by frequency doubling with a nonlinear crystal. The conversion efficiency is more than 40%. The output energy in the green is 10 mJ with a stability of 10%. The average pulse width was 70 ps and the repetition rate was 10 Hz.

A passive polarization switch coupled the laser to the telescope. The light was reflected by a thin film polarizer and entered the telescope through a zero–order quarter–wave plate, which changed the polarization from linear in the vertical direction to circular. The beam emerging from the telescope was about 30 cm in diameter and passed to one side of the secondary mirror. The returning pulses suffered some depolarization but were mostly circularly polarized in the opposite sense. The quarter–wave plate changed the polarization from circular back to linear in the horizontal direction. The light then passed through the thin film polarizer and was reflected by a dichroic mirror to the return pulse detector.

The τ_1–detector for the outgoing pulse was a Lasermetrics model 3117PD high–speed silicon PIN diode with a risetime of less than 150 ps and a jitter of less than 10 ps. The τ_3–detector was a Hamamatsu microchannel plate photomultiplier tube with a risetime of 150 ps and a time jitter on the order of 30 ps. The τ_2–detector in the portable timing electronics was an RCA C30902E avalanche photodiode
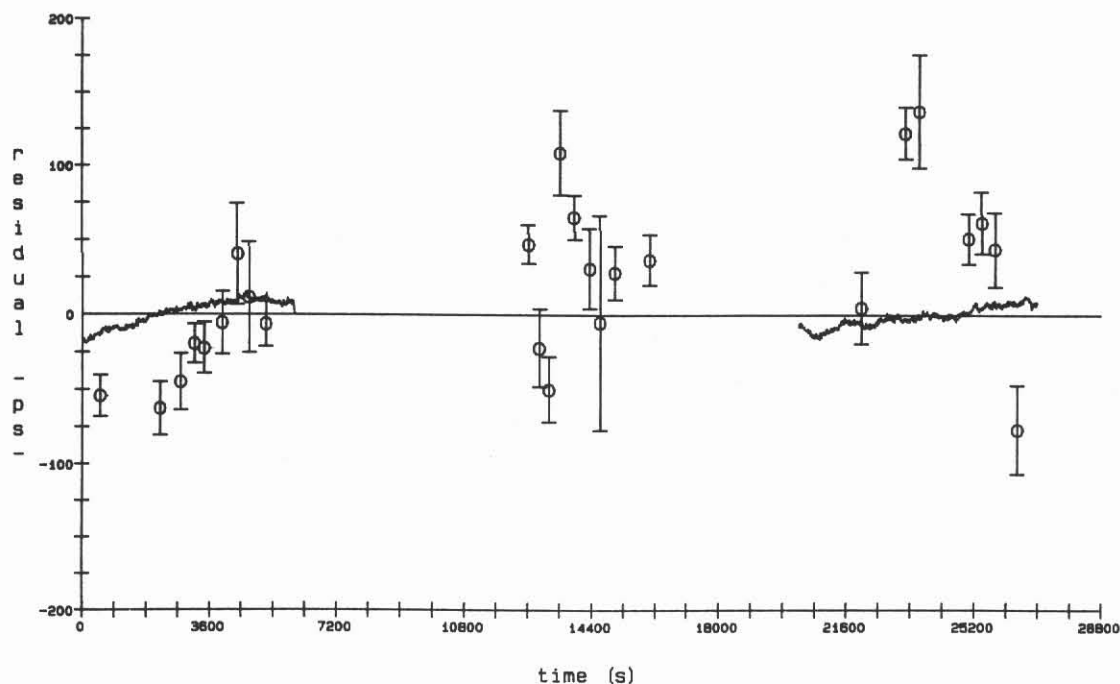
95

Figure 9. Measurement residuals for the trip of March 22, 1989. Data at left and right are calibration measurements performed at GORF. Data in center are ΔT measurements performed at USNO. Solid lines represent maser phase comparisons. Circles represent optical measurements, where error bars indicate standard deviations of the mean.

cooled with dry ice and operated in the avalanche mode. The risetime was approximately 500 ps with a jitter on the order of 150 ps. The measured energy sensitivity was approximately 10 ps/mV. The output level was held constant to within about 10% of 150 mV by adjusting the incident light with an iris on the detector package, as illustrated in *Figure 6*.

RESULTS

A parabola was fitted to the maser relative phase measurements obtained before and after each trip by the method of least squares. The pretrip and posttrip optical measurements were next fitted to this parabola to remove the constant systematic delays associated with the cables and electronics. The relative difference between the optical measurements performed at USNO and the interpolated maser phase measurements then determined ΔT. Measurement residuals for a typical trip are illustrated in *Figure 9*. The values for all nine trips in which a complete set of measurements were obtained are summarized in *Table 1*. Plots of measurement residuals for these trips and a composite plot of optical residuals are given in the Appendix.

For a typical trip $\Delta T < 100$ ps and the corresponding limit on the anisotropy of the one–way speed of light is $\Delta c/c < 1.5 \times 10^{-6}$. By comparison, if there had been a Galilean effect associated with the earth's motion around the sun at a velocity of 30 km/s, the result would have been $\Delta T = -6.9$ ns. However, the data are not sensitive to a hypothetical Galilean effect of 83.1 ps associated with the earth's rotational velocity of 360 m/s at latitude 39°.

The relativity correction Δt_{rel} of Eq. (5) was integrated numerically using Simpson's rule. The truck velocity was monitored with a Stewart–Warner "sender" unit attached to the speedometer cable. The

96

Table 1

Measured values of ΔT according to Eq. (10)

Trip	ΔT		Maser rate change
	mean	sd	posttrip − pretrip
	(ps)	(ps)	($\times 10^{-14}$)
March 10	65.2	27.1	+3.7
March 16	69.9	89.7	−2.7
March 21	82.6	48.0	−1.8
March 22	35.6	68.9	+0.6
March 25	−6.6	38.1	−1.9
March 28	123.2	73.4	−2.0
April 9	−14.4	36.6	+0.2
April 11	35.4	52.8	+1.4
April 13	−29.4	22.1	+0.3

sender generates a squarewave whose frequency is proportional to the velocity. A frequency–to–voltage converter circuit was used to record the velocity as a function of time on a strip chart recorder. The truck was driven at a maximum velocity of 50 km/h to minimize vibration. Elevations were determined from topographic maps. The resulting velocity correction is +2.6 ps and the elevation correction is −12.6 ps, yielding a net correction of − 10.0 ps. There is an additional correction of −14.3 ps per hour of dwell time at USNO due to higher elevation. A typical trip required about one hour to drive each way and two hours to perform the optical measurements. The total correction upon return to GORF was thus about −50 ps. The Sagnac correction $2\omega A/c^2$ due to the earth's rotation is 83.1 ps in an earth–centered coordinate system, but this correction was not included in the data reduction since it should apply equally to light propagation and clock transport for coincident paths.

The atmosphere affects the determination of range but not the transfer of time [4]. In the case of a range measurement by the radar technique, the delays caused by the atmosphere are additive. In contrast, in an optical time transfer the atmospheric delays are subtracted. The standard deviations of ΔT_{21}^* and ΔT_{31}^* were of the order of 100 ps and 200 ps, respectively, for a trial of about 1000 pulses over 100 seconds. The variation was approximately the same for calibration measurements at GORF (1 μs round trip time) and for optical time transfer measurements at USNO (174 μs round trip time). Thus the data support the assumption that atmospheric fluctuations over the round trip time of flight were neglible.

The principal limiting factor of the experiment was the poorly understood response of the detectors. For an improvement in the result, the time jitter due to light intensity fluctuations of the τ_2–detector, in particular, must be reduced. A second source of ambiguity was the change in rate of the portable maser, which was typically about 1 part in 10^{14} between the pretrip and posttrip calibration measurements. In several tests, it was found that rate changes were not induced during an uninterrupted trip; rather they took place during a pause in the trip. Changes in maser orientation also caused a rate change. Improvement in the enclosure suspension and use of one of a new generation of Sigma Tau masers having a varactor instead of a thermal mechanism in the autotune circuit would likely reduce these changes and permit a linear (rather than parabolic) fit of the maser phase difference.

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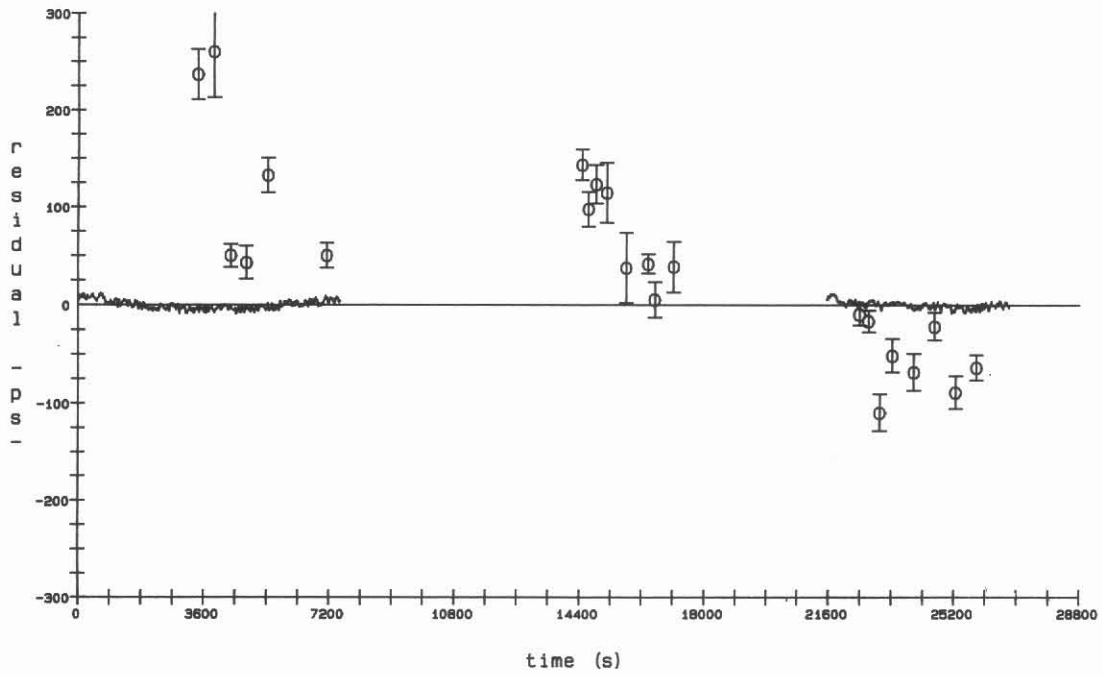
APPENDIX

Plots of Measurement Residuals

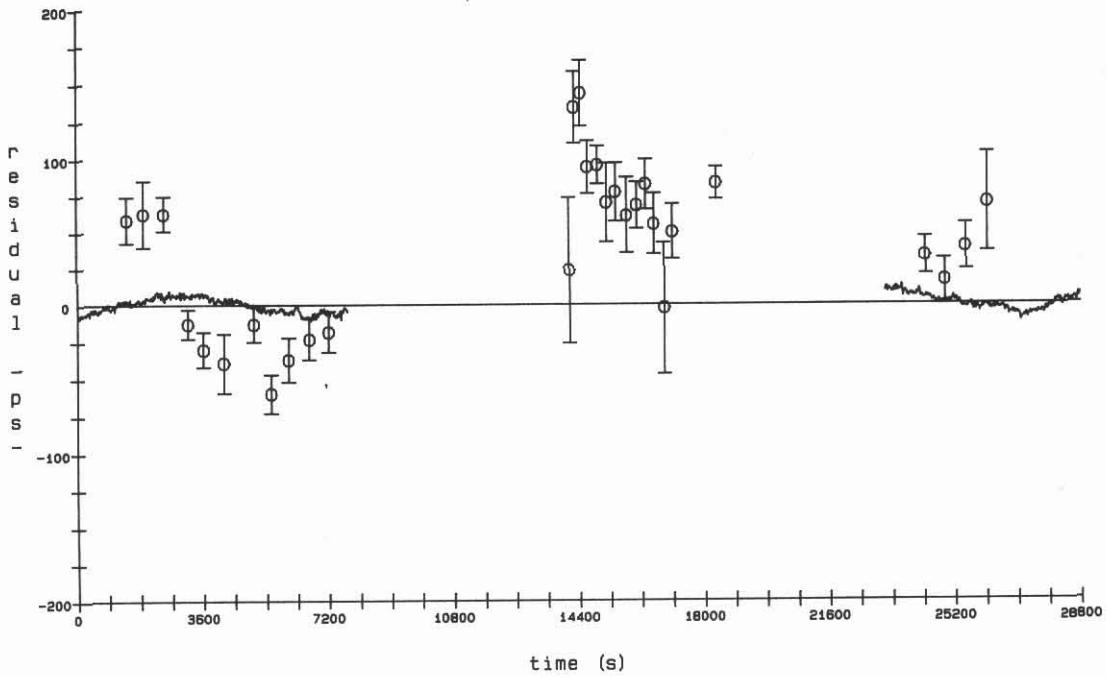Maser 6 (Truck) — Maser 5 (GORF);   t2 — (t1 + t3)/2
Trip of March 10, 1989
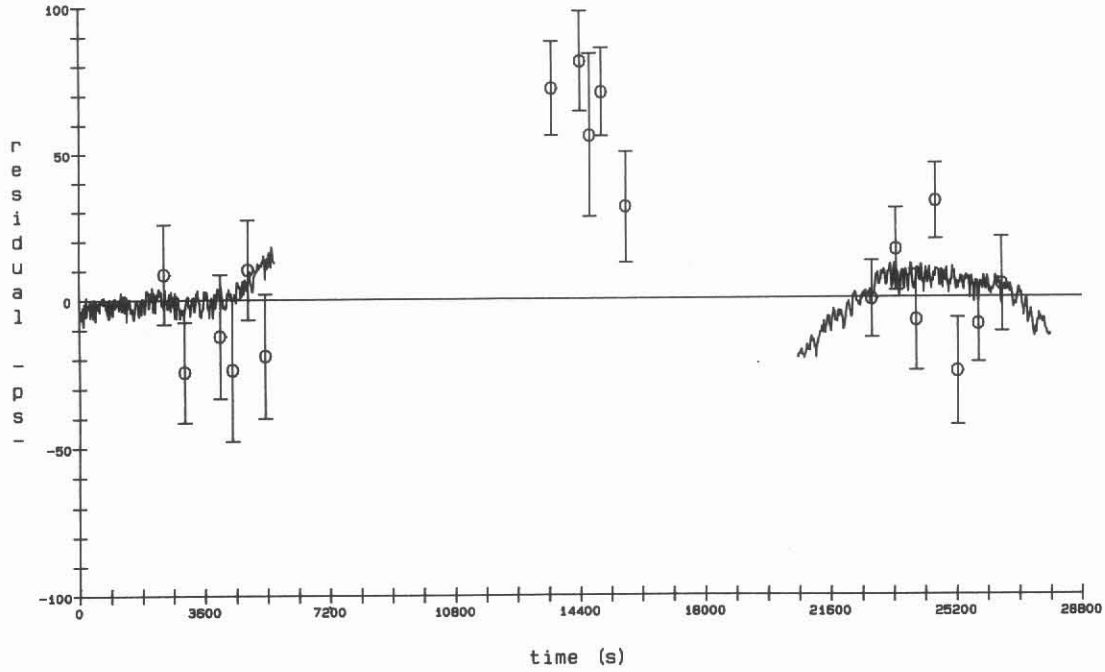
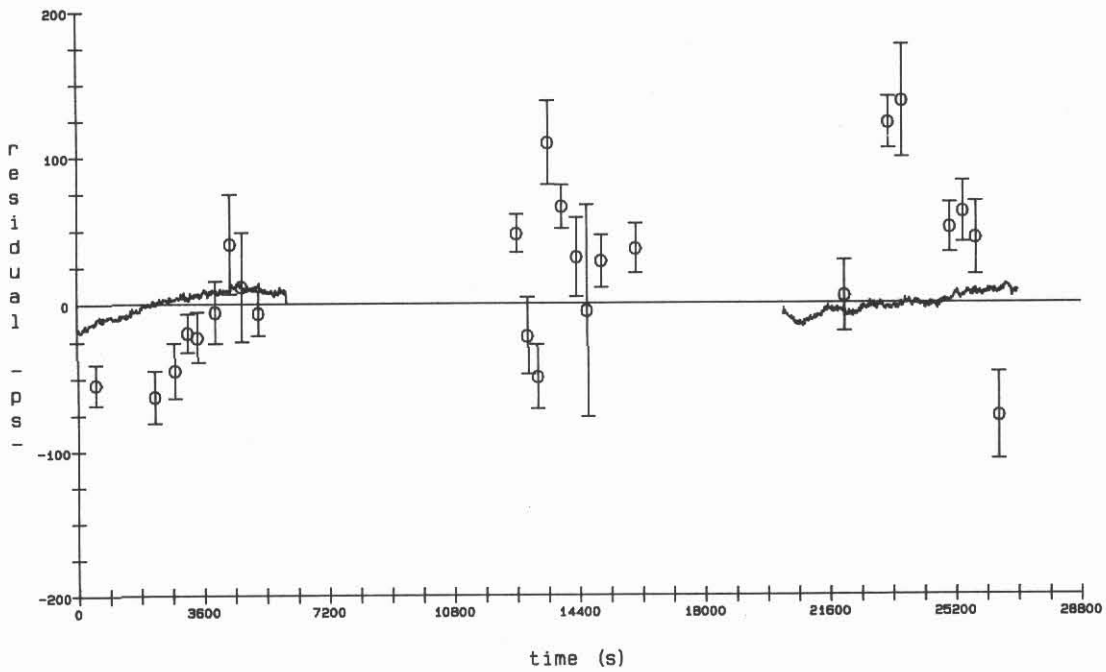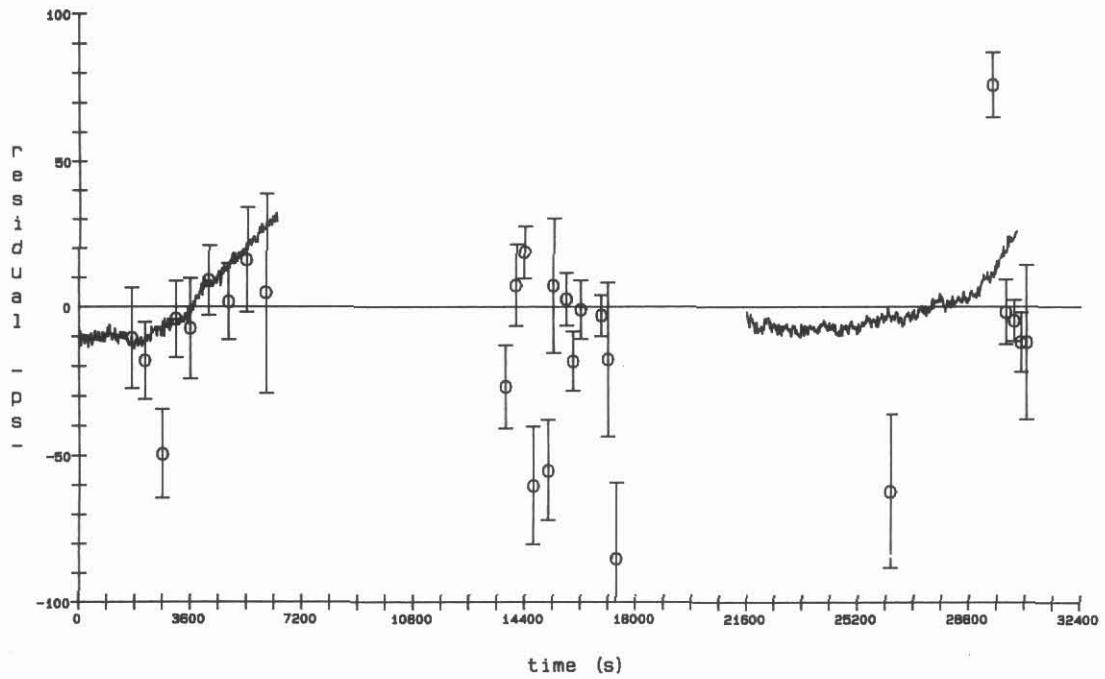Maser 6 (Truck) — Maser 5 (GORF);   t2 — (t1 + t3)/2
Trip of March 16, 1989

Maser 6 (Truck) – Maser 5 (GORF);   t2 – (t1 + t3)/2
Trip of March 21, 1989

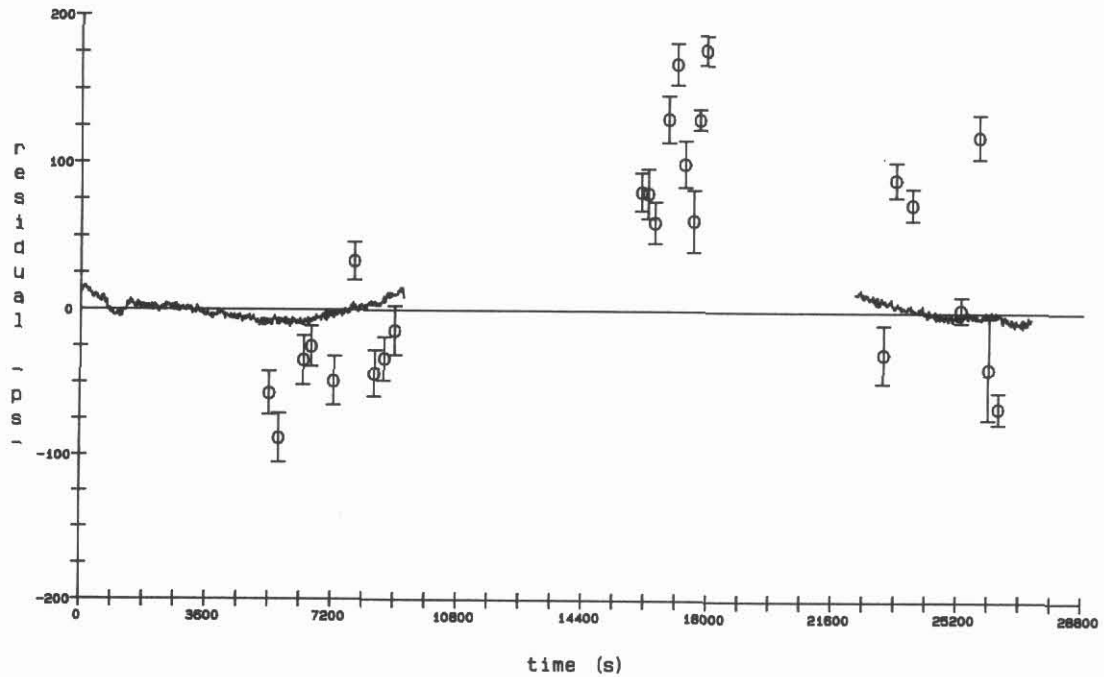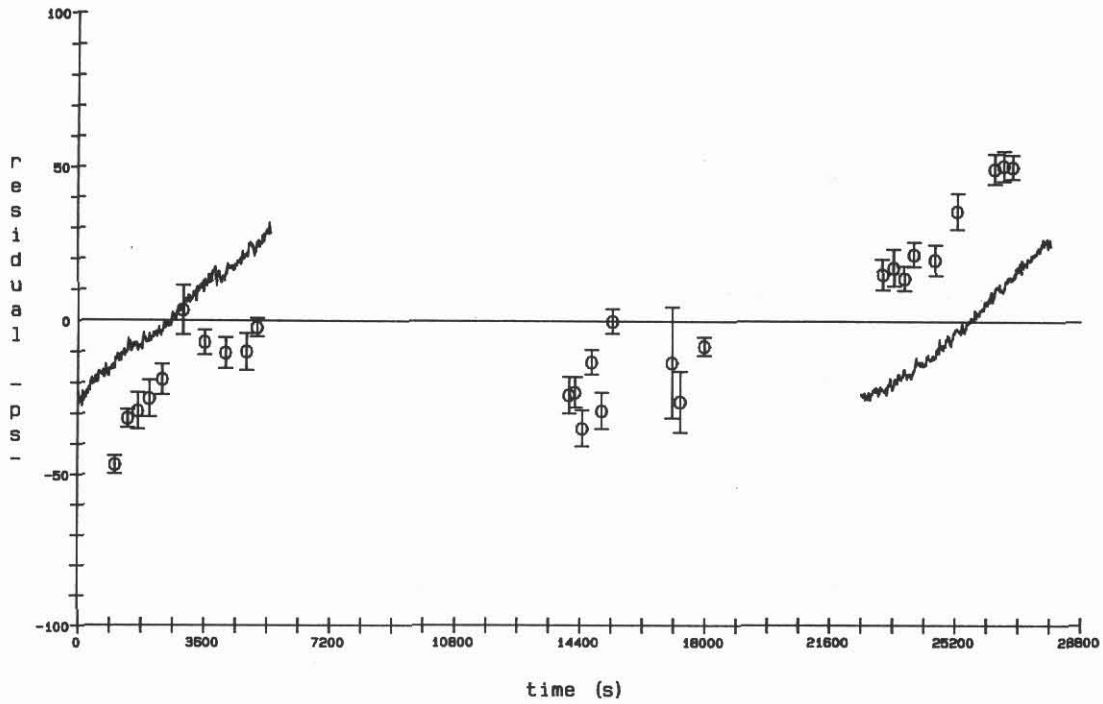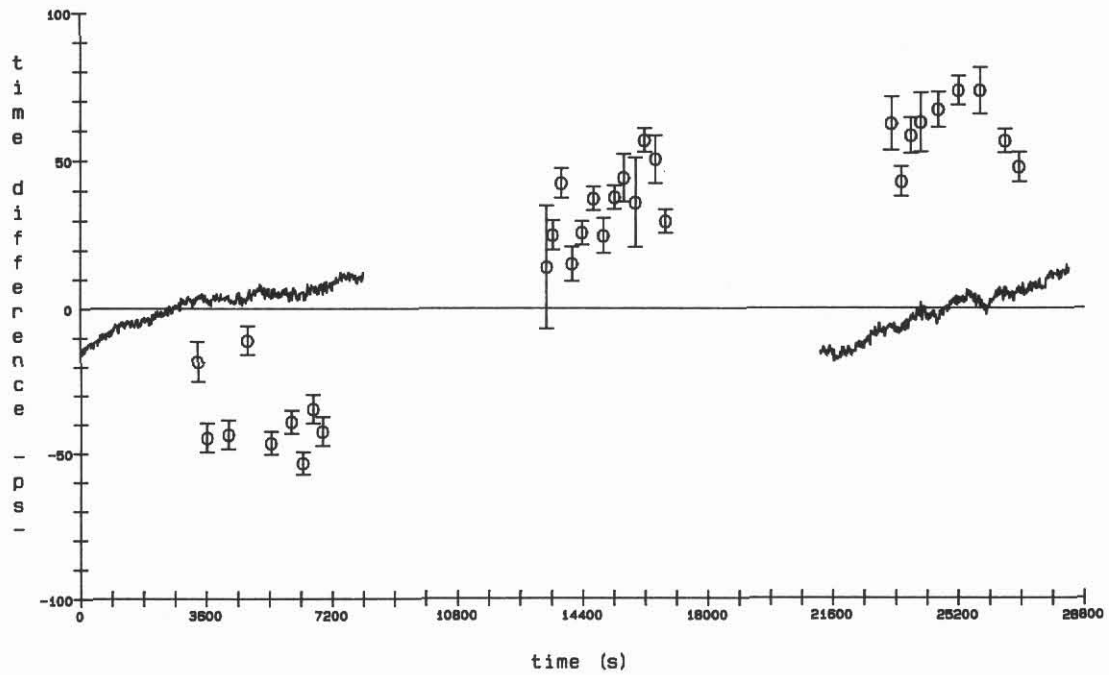time (s)

Maser 6 (Truck) – Maser 5 (GORF);   t2 – (t1 + t3)/2
Trip of March 22, 1989

time (s)

100

Maser 6 (Truck) – Maser 5 (GORF);   t2 – (t1 + t3)/2
Trip of March 25, 1989

time (s)

Maser 6 (Truck) – Maser 5 (GORF);   t2 – (t1 + t3)/2
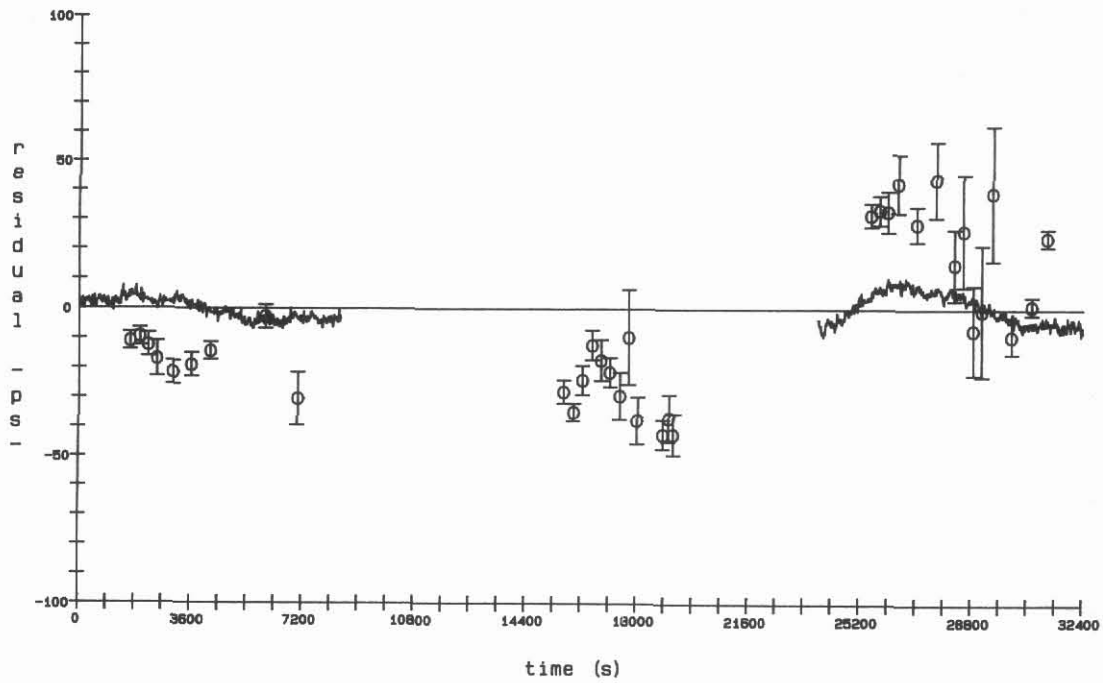Trip of March 28, 1989

time (s)

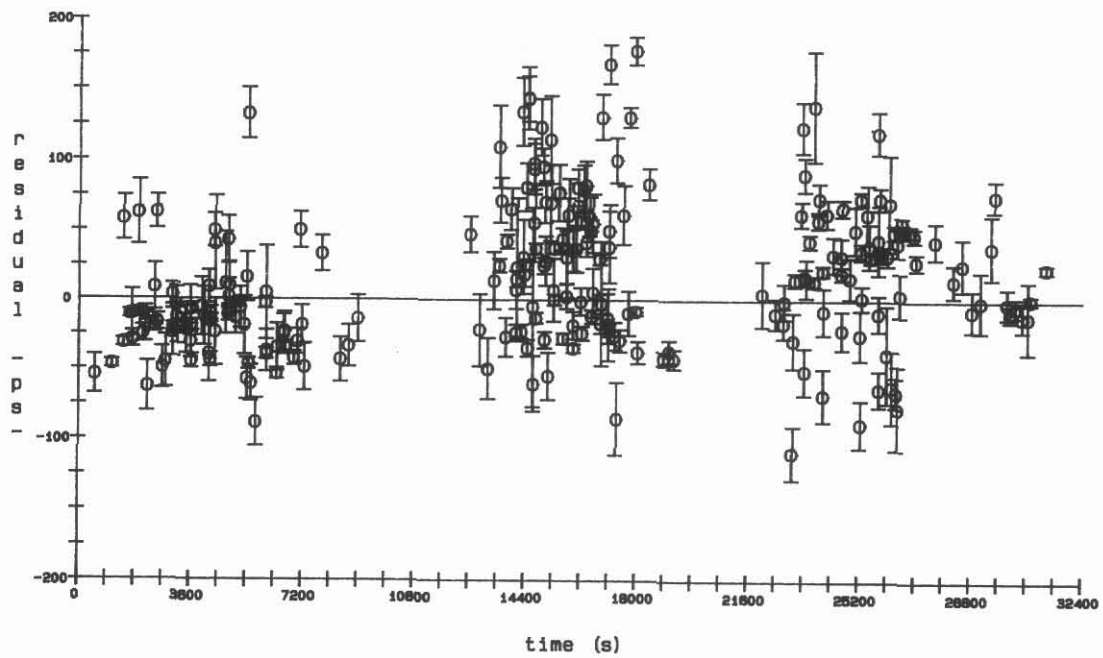Maser 6 (Truck) — Maser 5 (GORF);   t2 — (t1 + t3)/2
Trip of April 9, 1989

time (s)

Maser 6 (Truck) — Maser 5 (GORF);   t2 — (t1 + t3)/2
Trip of April 11, 1989

time (s)

102

Maser 6 (Truck) — Maser 5 (GORF);   t2 — (t1 + t3)/2
Trip of April 13, 1989

time (s)

Maser 6 (Truck) — Maser 5 (GORF);   t2 — (t1 + t3)/2
All Trips

time (s)

QUESTIONS AND ANSWERS

E. Mattison, SAO: To what do you ascribe the scatter in the measurements by light beams? What is the major contributor to the noise there? Also it seems as if the post trip calibration data had more scatter than the pretrip calibration. Was that always the case and to what to you ascribe that?

R. Nelson, University of Maryland: I am glad you asked the question because I wanted to point out what we consider to be our major source of error. Our major source of error, in our judgment, was the response of the T2 detector. Time jitter was approximately 150 picoseconds and it was primarily due to the sensitivity of the detector to the fluctuations in light intensity. It was energy sensitive. I do not think it is fair to say that the post trip calibration were anymore scattered that the pretrip. I chose one particular example but it was only considered to be representative and not definitive.