DIFFERENTIAL COMPARISON OF THE ONE-WAY SPEED OF LIGHT IN THE EAST-WEST AND WEST-EAST DIRECTIONS ON THE ROTATING EARTH

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ABSTRACT

A status report is presented for a time transfer experiment which compares the times of flight in the east-west and west-east directions of short pulses of light sent from a laser coupled to the 48-inch telescope at the NASA Goddard Optical Research Facility to the U.S. Naval Observatory and reflected back over the same path. The times t_1 and t_3 when each light pulse leaves GORF and returns are measured with an event timer referenced to a hydrogen maser. The time t_2 when the pulse is reflected at USNO is measured with a portable event timer and maser combination carried in a heated and air-conditioned truck. Each maser is maintained in a temperature-controlled environment. The portable maser enclosure is supported by pneumatic shock and vibration suppression mounts. The quantity

$$\Delta T \equiv t_2 - \frac{1}{2}(t_1 + t_3) = \frac{1}{2}[(t_2 - t_1) - (t_3 - t_2)]$$

is determined. The apparatus is calibrated by performing corresponding measurements with the portable detector at GORF in the same equipment configuration used at USNO while also monitoring the phase difference between the masers.

The central question to be answered by the experiment is whether the Einstein prescription for the synchronization of clocks with light pulses occurs automatically ($\Delta T = 0$) or must be imposed by convention in the context of a theory ($\Delta T \neq 0$). The necessary precision of ≤ 50 ps has not yet been achieved for the complete measurement although it has been accomplished for clock trips and laser pulse detection on separate occasions.

INTRODUCTION

A fully successful theory of space, time, and gravity must be founded upon actual experience with the behavior of clocks and the propagation of light pulses in gravitational fields and in accelerated frames of reference. The remarkable stability of current atomic clocks and the precision of short pulse laser ranging and time transfer systems now allow new types of experiments to be undertaken. These will allow the necessary experience to be gained. Indeed, the originally astonishing predictions of special and general relativity about the behavior of clocks in relative motion and experiencing different gravitational potentials have become part of engineering practice, as the PTTI community knows well.[1] With these refined techniques the foundations of curved spacetime theories of gravity can be probed and crucial tests of alternative theories performed. Our comprehension and understanding of the theories will surely benefit from actually doing such experiments.

The central role of clocks in the description of gravity as curved spacetime -- Einstein's grand concept -- is most appropriately expressed, in the words of John Leighton Synge,[2] as "Riemannian Spacetime *Chronometry*," rather than *geometry*. The spacetime interval with metric $g_{\mu\nu}$ is given by

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu = g_{00}\,(dx^0)^2 + 2\, g_{0j}\, dx^0\, dt + g_{ij}\, dx^i\, dx^j \qquad (1)$$

where a repeated Greek index is summed 0 to 3, a repeated Latin index is summed 1 to 3, and $x^0 \equiv c\ t$. For a clock $ds^2 = c^2\ d\tau^2$, where $d\tau$ is the increment of "proper time" read by the clock between neighboring events which occur at the position of the clock. In contrast, dt is the increment of "coordinate time" between the same two neighboring events inferred by an observer who could be in relative motion, or in a different location, with respect to the clock. Another convention is that the "coordinate speed" of light is to be given by setting $ds^2 = 0$.

In a 1982 PTTI paper[3] describing time transfer experiments between the NASA Goddard Optical Research Facility and the U.S. Naval Observatory using short pulses of laser light, it was noted that on the rotating earth the metric usually ascribed to general relativity[4-6] seems to predict an asymmetry in the one-way speed of light between the east-west and west-east directions, the fractional difference being $\pm\ v/c$, where v is the surface speed of the earth due to its rotation. For the latitude of Washington, DC, $v \approx 361$ m/s and $v/c \approx 1.2 \times 10^{-6}$, leading to a difference in propagation times of 165 ps. It was suggested that this difference might be detected in future experiments.

The importance and significance of actually performing such experiments were recognized as a result of many clarifying discussions with Professor Hüseyin Yilmaz about his new theory of space, time, and gravitation.[7] This is a fully developed curved spacetime alternative theory to that of Einstein. (The differences between the new theory and general relativity are briefly sketched at the end of this paper.) In the new theory of Yilmaz, if the Einstein prescription for synchronization with light pulses is automatic, then the theory predicts that the local speed of light is isotropic, even in an accelerated frame of reference such as the surface of the rotating earth. If the speed of light is not isotropic, it can be made so by an imposed Einstein synchronization (for example, by physically resetting the distant clock), in which case, however, the constancy of the velocity of light is more like a convention than a law. In other words, this experiment may resolve the old unresolved controversy (Poincaré *vs.* Einstein) as to whether the constancy of the speed of light is a convention or a law.

Several features of the experiment should be emphasized. We believe that it is the first comparison of the one way speeds of light in different directions along a path in which the time of arrival of the light pulse is actually registered on a clock which has been slowly transported from one end to the other of the path. Also, in contrast to the optical experiments of the Michelson-Morley type[8], the Mössbauer gamma ray absorption experiments on a rotating disk,[9] and recent comparisons of two separated atomic clocks using a continuous wave laser signal modulated at 100 MHz and propagated over a fiber optics cable,[10] we work with short pulses involving the group velocity and actual measurements of time rather than with waves involving the phase velocity and measurements of phase difference or frequency. Note also that we do not physically adjust the transported clock in any way.

DESIGN OF EXPERIMENT

Test of the Einstein prescription.

According to the Einstein prescription in special relativity for the synchronization of two clocks using light pulses, if a pulse is sent out at time t_1, reflected from a distant point at time t_2, and received back at time t_3, then t_2 is to be identified with the midpoint in time between t_1 and t_3,

$$t_2 = \frac{1}{2}(t_1 + t_3) . \tag{2}$$

It is usually assumed that this relation is appropriate for all inertial observers. Define the time difference

$$\Delta T \equiv t_2 - \frac{1}{2}(t_1 + t_3) = \frac{1}{2}[(t_2 - t_1) - (t_3 - t_2)]. \tag{3}$$

The Einstein prescription implies that for all inertial observers $\Delta T = 0$. It follows that the times of light propagation between the two clocks are equal. The object of the experiment is to determine whether the Einstein prescription is also valid for accelerated observers on the rotating earth by measuring the difference in times of light propagation in the east-west and west-east directions from the readings of a stationary clock and a clock transported from the stationary clock to a distant place.

Another way of viewing the experiment is as the comparison of two different methods for the synchronization of two remote clocks: by the transmission and reception of light signals and by the slow transport of an atomic clock. Does the Einstein prescription from special relativity, which assumes the speed of light is c both ways, occur automatically for local measurements on the rotating earth ($\Delta T = 0$) or must it be imposed by convention in the context of a theory ($\Delta T \neq 0$)?

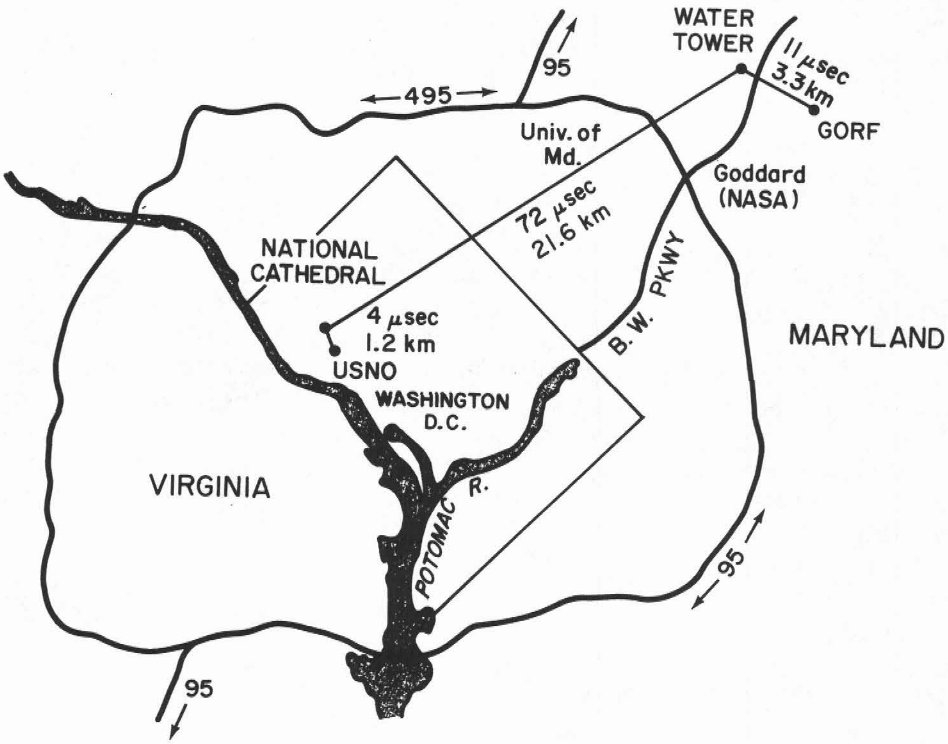


Fig. 1. Optical path across Washington.

Optical path.

In our experiment we send short pulses of green light from a laser coupled to the 48-inch telescope at the NASA Goddard Optical Research Facility in Greenbelt, MD (longitude 76° 49.'7, latitude 39° 01.'3, elevation 42 m) to a portable detector set up on the grounds of the U.S. Naval Observatory in Washington, DC (longitude 77° 04.'0, latitude 38° 55.'3, elevation 78 m). Although there is no direct line of sight, the optical path is 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.[3] The cathedral can be seen on the horizon from the water tower. There are three corner cubes mounted on a support ring surrounding the detector. The corner cubes are of the type used in the American Laser Ranging Retro-Reflectors left on the moon by the Apollo 11, Apollo 14, and Apollo 15 astronauts.[11,12] Usually only one of these is left uncovered and reflects the light pulses back over the same path. The light travel time is 87.1 μs over a distance of 26.1 km, as illustrated in Fig. 1. The east-west component is 20.6 km.

Measurements are made of the time t_1 when a laser pulse leaves the telescope and the time t_3 when it returns using an event timer whose frequency standard is a hydrogen maser kept in the telescope building at GORF. The time t_2 when it is reflected at USNO is measured with a second, portable event timer and hydrogen maser combination carried in a field laboratory truck owned

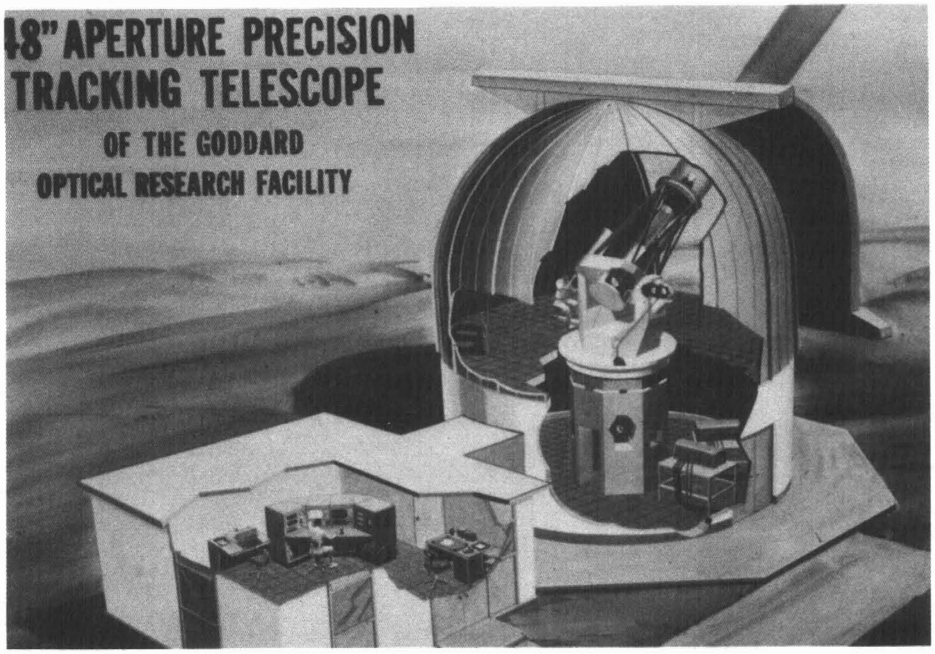


Fig. 2. The 48-inch telescope at the NASA Goddard Optical Research Facility.

by the Applied Physics Laboratory. Both masers and their environments are maintained at controlled temperatures. The portable maser is protected from shock and vibration by pneumatic support mounts. The t_1 and t_3 detectors are located on the laser table below the telescope. The t_2 detector is set up on a tripod next to the truck. A diagram illustrating the geometry of the telescope and laser is shown in Fig. 2.

Mirror alignment.

The mirrors used for the across-Washington optical link were installed in 1982 for use in earlier laser time transfer tests and are illustrated in Ref. [3]. For this experiment a third mirror was installed on a tower about 100 meters from the GORF telescope for routine tests and local calibration. It is shown in Figures 3 and 4.

The water tower and cathedral mirrors must be aligned very precisely. A small Edmund Scientific Company telescope modified with a retroreflector that partially obscures the aperture is used to sight in the forward and backward directions simultaneously.[3] When the water tower mirror is properly aligned, the image of the cathedral appears inverted and superposed on top of the image of the Goddard 48-inch telescope. Similarly, the cathedral mirror is aligned to superpose the image of the location of the USNO t_2 detector on top of the image of the water tower. During a night when measurements are taken, people must be dispatched to the water tower and cathedral in order to make minor mirror adjustments caused by initial alignment errors, changing

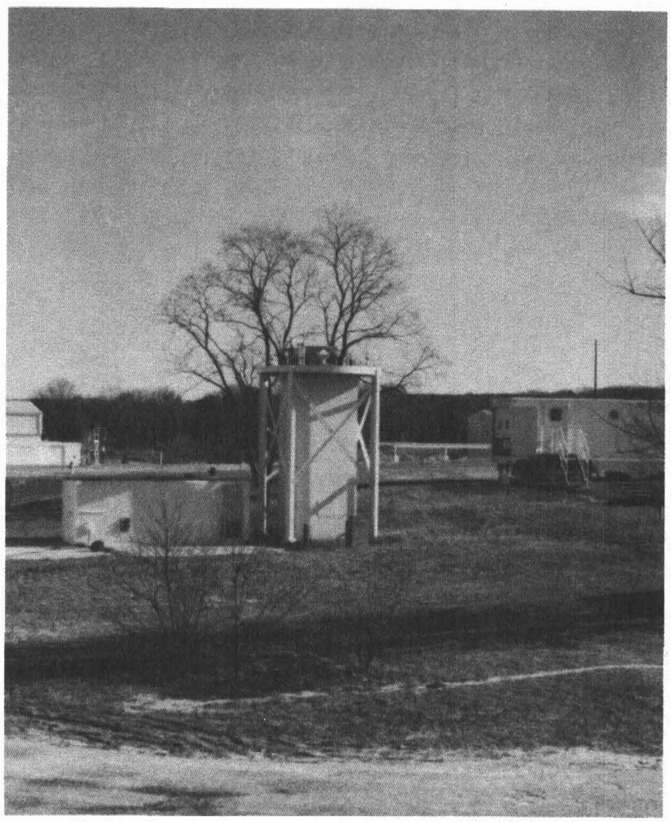


Fig. 3. Local calibration mirror on top of tower near telescope.

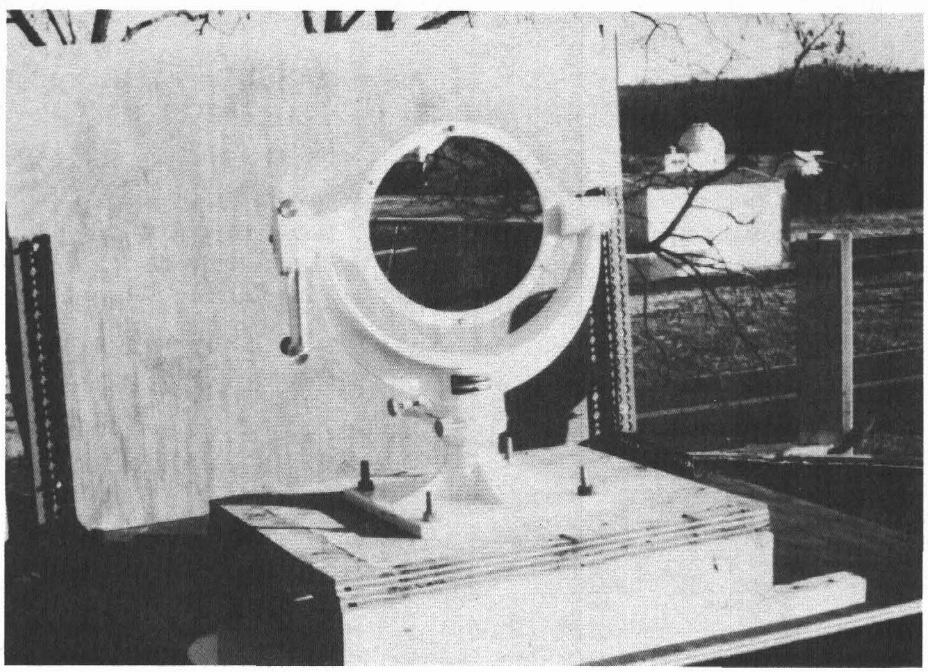


Fig. 4. Closeup view of local mirror.

atmospheric conditions, and movement of the water tower. The activities at the various locations are coordinated by means of a telephone conference call. On a clear night the laser signal arriving at USNO is bright enough to project its image on a screen and cast shadows of the detector package against the side of the truck. Our experience has been that bright signals can be seen easily when the visibility is 15 to 20 miles according to reports for National, Dulles, and BWI airports. During much of the summer it was not possible to establish the optical link because the visibility was only about 5 miles due to haze.

Effect of the atmosphere.

The Einstein prescription is essentially unaffected by the atmosphere. Assume that the atmosphere introduces a delay Δt_1 for the emitted pulse and a delay Δt_3 for the received pulse. The Einstein prescription becomes

$$t_2 = \frac{1}{2}[(t_1 - \Delta t_1) + (t_3 + \Delta t_3)]$$

$$= \frac{1}{2}(t_1 + t_3) + \frac{1}{2}(\Delta t_3 - \Delta t_1) . \qquad (4)$$

The atmospheric delays in the second term are each about 26 ns but they nearly cancel since the paths are nearly the same. (Of course, atmospheric delays do affect measurements of range, where they are additive.) Since we are measuring differences in the times of propagation, each set of pulse times is independent. It is known that fluctuations in the atmosphere occur over intervals on the order of 1 ms or more, whereas the round trip time for a single pulse is about 174 μs.

Clock registration times.

The times t_1, t_2, and t_3 are ideal times that do not account for detector rise times, cable delays, event timer processing times, and other systematic errors. We must also account for the changing relative phase between the masers. In the experiment our actual measurements are the "registration times" t_1^*, t_2^*, and t_3^* recorded by the electronic timing equipment and atomic clocks instead of the ideal times. The ideal time of each event is related to the registration time by

$$t = t^* - \Delta t_{DEL} - \Delta t_{PHASE} \qquad (5)$$

where Δt_{DEL} is the total delay time comprising the rise times, cable delays, and processing times, Δt_{PHASE} is the clock phase difference including clock drifts, synchronization errors, and relativistic effects due to clock transport. Substituting the relation given by Eq. (5) for times represented in Eq. (3) we obtain

$$\Delta T = \Delta T^{*} - [\Delta t_{DEL2} - \frac{1}{2}(\Delta t_{DEL1} + \Delta t_{DEL3})] - \Delta t_{PHASE2} \tag{6}$$

where we assume the reference clock for relative phase comparisons is the stationary clock and

$$\Delta T^{*} \equiv t_2^{*} - \frac{1}{2}(t_1^{*} + t_3^{*}) . \tag{7}$$

The quantity ΔT^{*} is the quantity we measure in the experiment.

A critical feature in the design of the experiment is that the entire timekeeping apparatus for the t_2 measurement is a portable, self-contained system. This permits us to perform local calibration measurements at GORF in exactly the same configuration of equipment as the measurements made at USNO. The instrumental delay times are unknowable. However, assuming that environmental factors do not cause significant shifts, they remain constant and can be eliminated by the local calibration measurements. The phase difference is determined independently during the optical calibration.

Measurement procedure and analysis.

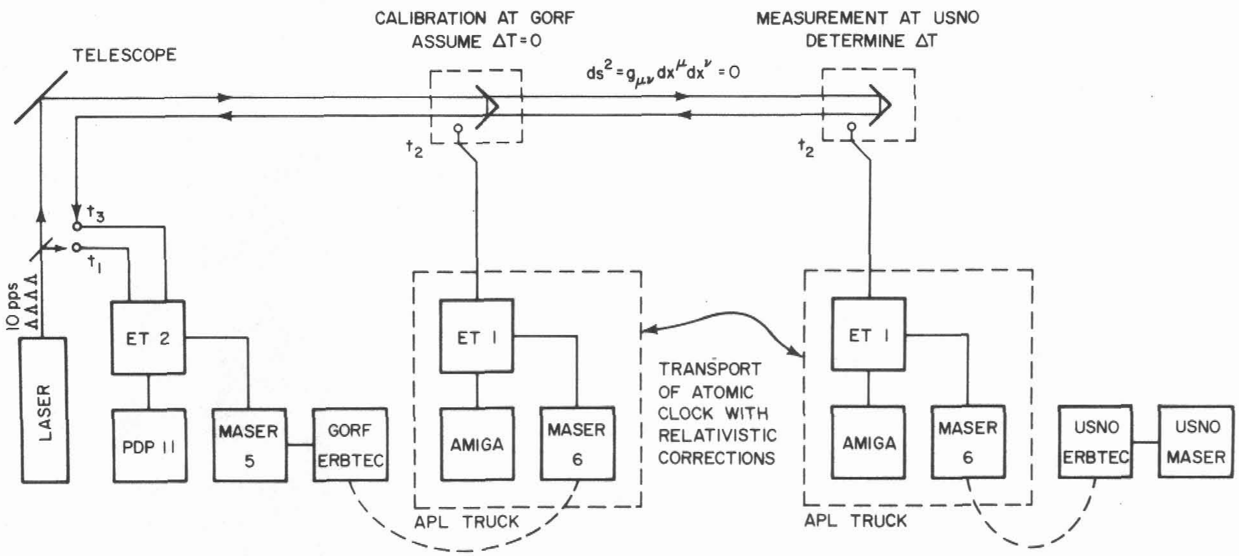
In each experiment exercise we first perform a series of optical calibration measurements of t_1, t_2, and t_3 at GORF using the local mirror while the phase difference between the masers is monitored. Next the t_2 event timer, maser, and detector are transported to USNO and the measurements are repeated using the across-Washington optical link. While at USNO the phase of the portable maser is compared against the USNO maser master reference. Finally, the equipment is brought back to GORF and the local calibration measurements are repeated. The procedure is summarized in a schematic diagram in Fig. 5. Figure 6 shows the truck and detector at GORF and Fig. 7 shows the position in front of Building 1 at USNO.

The optical measurements of t_1, t_2, and t_3 are merged on a computer for all laser pulses for which a complete set is obtained. The matching program produces distributions for the differences $t_{31}^{*} \equiv t_3^{*} - t_1^{*}$ and $t_{21}^{*} \equiv t_2^{*} - t_1^{*}$. Then we calculate

$$\Delta T^{*} = t_{21}^{*} - \frac{1}{2} t_{31}^{*}. \tag{8}$$

We can rearrange Eq. (6) in the form

$$\Delta T^{*} = \Delta T + [\Delta t_{DEL2} - \frac{1}{2}(\Delta t_{DEL1} + \Delta t_{DEL3})] + \Delta t_{PHASE2} . \tag{9}$$



$$\Delta T \equiv t_2 - \frac{1}{2}(t_1 + t_3)$$

Fig. 5. Schematic diagram of experiment.

For the local measurements at GORF we assume $\Delta T^* = 0$. The second term is constant for all measurements. The variation in ΔT^* measured optically should thus track the variation in Δt_{PHASE2} measured by the maser phase comparison.

Relativistic corrections must be applied to the t_2^* measurements due to the velocity and change in elevation of the truck. During a trip the velocity of the truck is measured continuously on a strip chart recorder and annotations of location are made at various points along the route. The maximum truck speed is 65 km/h (40 mph). The elevation of USNO is 36 m higher than GORF. Each trip requires about one hour to drive from GORF to USNO, two or three hours of dwell time, and one hour to return. The relativistic corrections for the entire trip are on the order of - 10 ps for velocity and + 14 ps per hour of dwell time for elevation. There may also be a relativistic correction due to the earth's rotation. Part of this investigation entails clarification of the nature of this correction.

If the Einstein prescription is valid on the rotating earth, optical measurements of ΔT^* made at USNO should agree with values obtained by interpolation of the calibration measurements after appropriate relativistic corrections are applied to t_2^* to account for the transportation of the atomic clock. Since the configuration of equipment remains the same, a discrepancy between the measured and interpolated values of ΔT^* would imply a nonzero value for the quantity ΔT of Eq. (2). For an asymmetry in the coordinate speed of light, as discussed in the INTRODUCTION, the difference in propagation coordinate times is $2\ v\ d/c^2 \approx 165$ ps where d is the east-west distance between the ends of the light path at GORF and USNO and v is the surface velocity, according to a possible interpretation of general relativity. This is developed explicitly in Eq. (19) below.

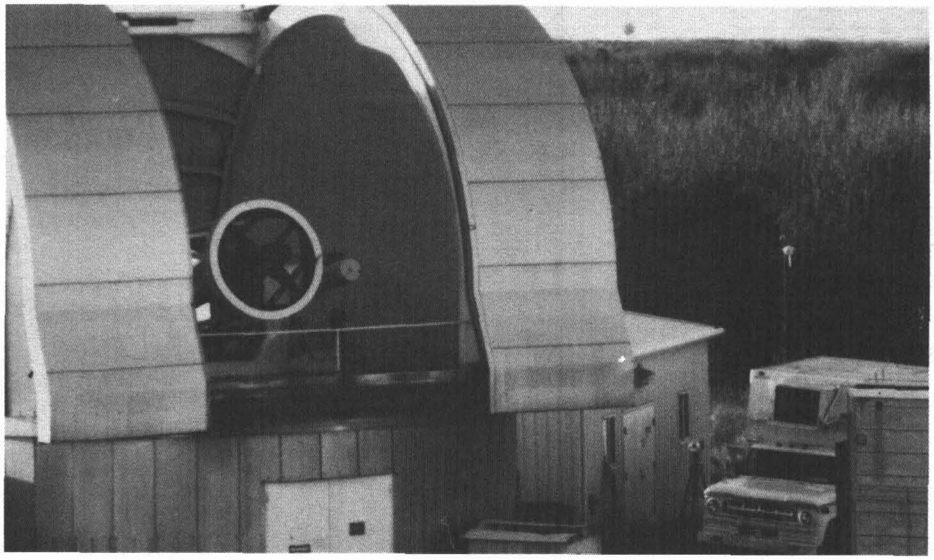


Fig. 6. Truck and detector at GORF with water tower visible on the horizon as seen from the calibration mirror tower.

Fig. 7. Truck parked at USNO during a maser comparison test.

DESCRIPTION OF EQUIPMENT

Laser and detectors.

The light pulses are generated by a Q-switched, mode-locked, neodymium YAG laser with two amplifiers. The fundamental infrared wavelength 1064 nm is converted to be green at 532 nm by frequency doubling. The pulse width is 70 ± 10 ps. The output energy in the green is 15 ± 2 mJ per pulse and the repetition rate is 10 Hz. The t_1 detector is a PIN diode sensitive to infrared wavelengths with 50 ps rise time. The diode is placed after the oscillator but before the amplifiers and frequency doubler. The t_3 detector is a Hamamatsu R2809U microchannel plate photomultiplier tube with a rise time of 150 ps and a transit time spread of 55 ps. The output of the microchannel plate tube is attenuated by 7 dB and then amplified by two Mini Circuits ZFL-2000 2-GHz amplifiers for a net gain of 36 dB. The t_1 and t_3 signals are fed into two channels of a Tennelec 455 constant fraction discriminator modified to discriminate on the fast rise times and are recorded by two channels of the event timer, respectively. The measurements are stored on a PDP-11/73 computer. The t_2 detector is an RCA C30902E avalanche photodiode operating in the avalanche mode with a rise time of less than 500 ps. The diode is cooled to - 65 °C with dry ice and produces an output of 150 mV by itself. The signal is fed directly into a Tennelec 453 constant fraction discriminator and measured by one channel of the portable event timer carried in the APL truck. The data are stored on an Amiga personal computer.

Masers.

The masers that we are using in this experiment are Sigma Tau masers 5 and 6 on loan to us from the National Radio Astronomy Observatory near Socorro, NM. Maser 5 is used as the stationary maser at GORF and maser 6 is used as the portable maser in the APL truck. These masers are part of a group of ten, model VLBA-112, being constructed for NRAO by Harry Peters and his associates[13] at the Sigma Tau Standards Corporation and are shown in Fig. 8. We have measured their relative phase to have a root Allan variance of about 2×10^{-15} at 3 hours. The performance of these two masers is consistent with characteristics reported by T.K. Tucker in his evaluation of masers 2 and 3.[14] Masers 5 and 6, however, have the additional feature of a servo loop that compensates for changes in the z-component of the magnetic field of the environment.

In earlier measurements during the summer of 1988 we used Peters maser *ST*1 provided by the Applied Physics Laboratory through the courtesy of JPL and an APL-designed NR-series maser on loan from the NASA Crustal Dynamics Project and the Bendix Field Engineering Corporation. The JPL Peters maser was also used last year in the APL truck for time transfer experiments between the USNO and APL to test the feasibility of making precision time comparisons using a carefully packaged hydrogen maser as a portable clock.[15]

The relative phase of the 5-MHz outputs of masers 5 and 6 is measured at GORF using an Erbtec Engineering Co. double mixing system and an HP 9826 computer lent to us by the Naval Research Laboratory and the U.S. Naval Observatory. Maser 6 is compared with the USNO maser standard during an optical measurement with another Erbtec system when at USNO.

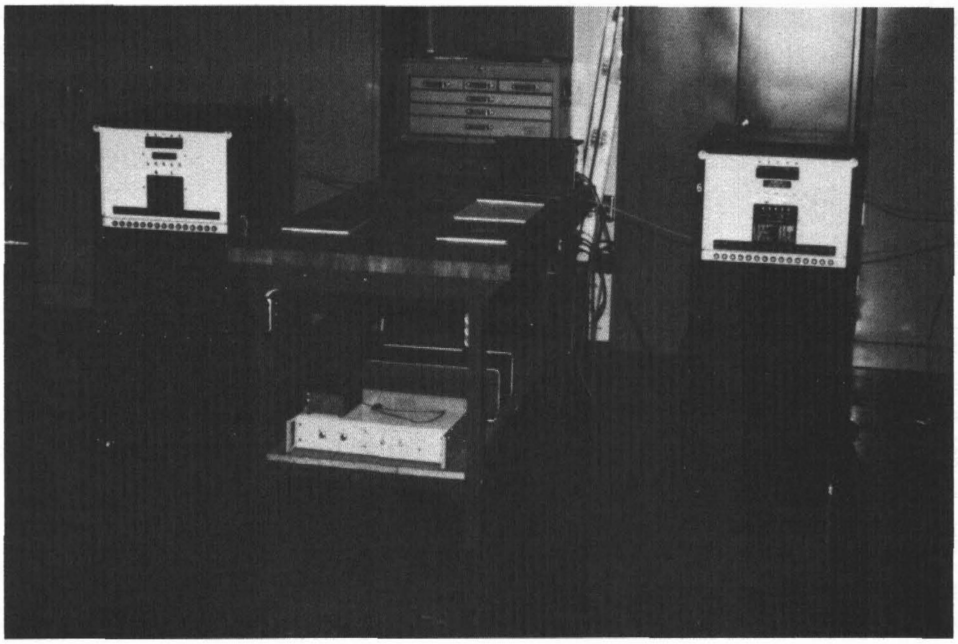


Fig. 8. Masers 5 and 6 at Sigma Tau Standards Corporation.

Event timers.

The two event timers used in this experiment are dual frequency, dual channel event timers designed and constructed in the Quantum Electronics Group of the University of Maryland Department of Physics.[16] Each event timer can measure the epoch of events to a precision of 20 ps on two different channels. With its Z-80 microprocessor system, the event timer serves as a time of day clock and as a range gate system operated under external computer control. The event timer contains a Z-80 microprocessor system with 60 K of ROM and 2 K of RAM memory and may operate with other computers via an RS-232 serial port or IEEE 488 parallel bus (GPIB).

The event timer uses dual frequency verniers developed by Hewlett Packard for their HP5370 time interval meter. Figure 9 illustrates the principle of operation. One of the dual frequencies, $F1$, is produced by a 200-MHz tunable crystal oscillator which is synchronized to a 5- or 10-MHz output of a hydrogen maser. The $F1$ oscillator runs continuously to drive a 26 bit synchronous counter which is the time generator. The time generator has exactly 50 000 000 states so it repeats every quarter second. The second of the dual frequencies, $F2$, is produced by a restartable delay line oscillator which is adjusted by other circuits to operate at 199.221 7899 MHz (abbreviated 199* MHz) and is derived from $F1$ by the equation $F1 - F2 = F2/256$. Thus for every 256 cycles of $F2$ there are exactly 257 cycles of $F1$.

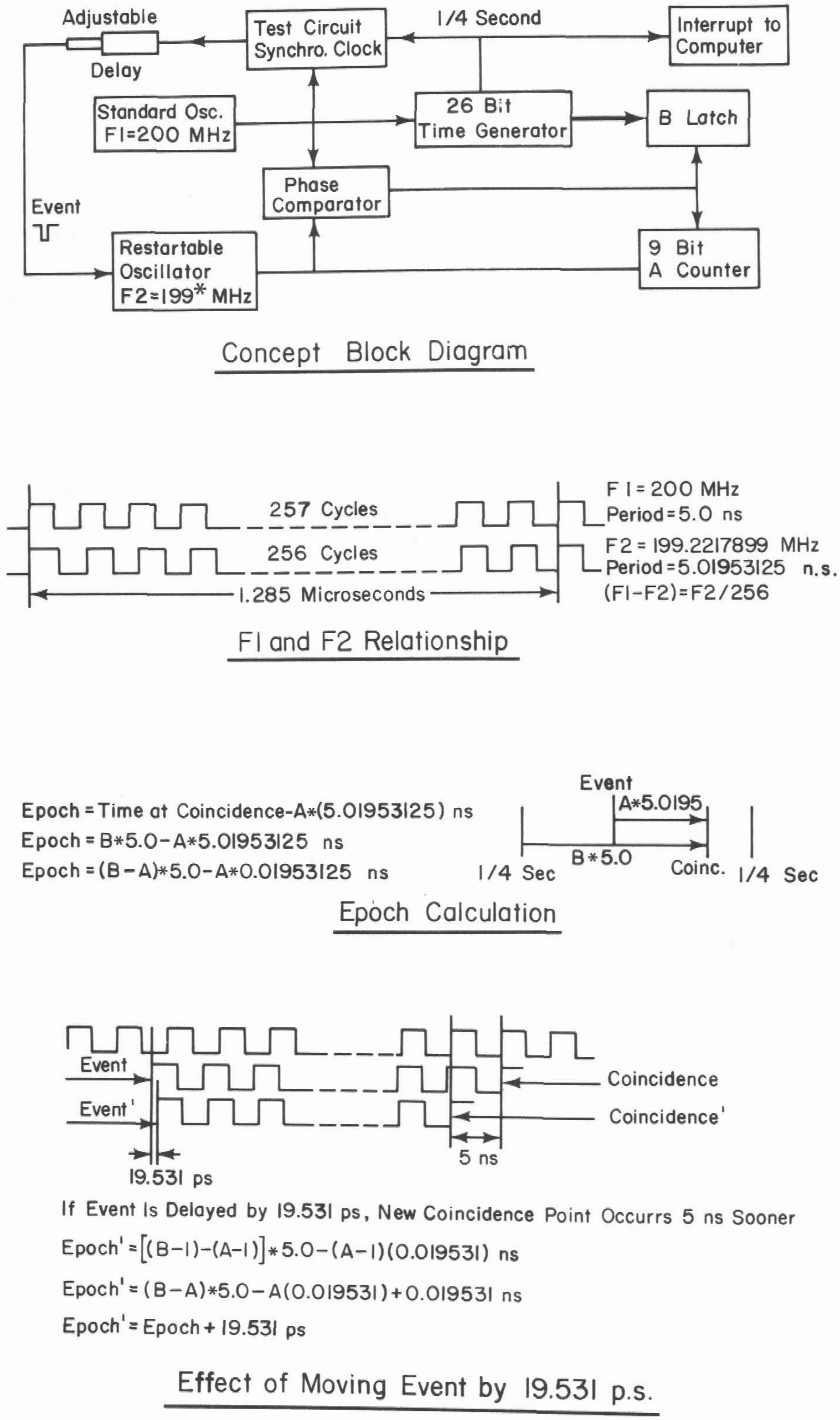


Fig. 9. Dual frequency event timer concepts.

The event to be timed stops, then restarts the $F2$ oscillation, which is counted by a 9-bit A counter from the point of restart. Constantly monitoring the two frequencies is a D type flip flop phase comparator which looks for a special point of closest coincidence of the rising edges of the two voltage waveforms. When this coincidence point is found the A counter is stopped and a B latch system freezes and then stores the state of the synchronous counter time generator. From the contents of the A and B registers the epoch of the event can be computed to within a quarter second interval.

Vernier action occurs because the period of $F1$ and $F2$ differ by 19.53125 ps. Theoretically, any coincidence point can be used to compute the epoch. For the Nth coincidence point,

$$\begin{aligned} \begin{matrix} event \\ epoch \end{matrix} &= (B + 257\,N) \times 5 \text{ ns} \; - \; (A + 256\,N) \times [(257/256) \times 5 \text{ ns}] \\ &= (B - A) \times 5 \text{ ns} \; - \; A \times (5/256) \text{ ns} \\ &= (B - A) \times 5 \text{ ns} \; - \; A \times 19.53125 \text{ ps} \,. \qquad (10) \end{aligned}$$

The resolution of the event timer for a single event is thus approximately 20 ps.

Portable maser vehicle.

The APL truck is equipped with heating and air conditioning and has a gasoline-powered generator capable of supplying 10 kW of power for mobile operation. Between trips the truck is parked next to the telescope building and is connected to the building electrical power. The power to the portable maser and event timer is supplied via uninterruptible power supplies which provide continuous power during switchover from house to generator power and remove all vehicle electrical transients, spikes, and frequency variations.

The portable maser is housed within a highly insulated enclosure which is supported by pneumatic shock and vibration isolation mounts. Air is drawn in through a duct and is maintained at a controlled temperature. The enclosure is loaded onto a set of rails using a forklift and rolled into the truck, as shown in Fig. 10. When the enclosure is in place the supports are pressurized and the rails are removed. Once loaded, the maser is kept in the truck at all times. The arrangement of the maser within the insulated enclosure is shown in Fig. 11.

The truck speed is measured with a Stewart-Warner "sender" unit attached to the speedometer cable that produces a square wave signal whose frequency is proportional to the vehicle speed. This frequency is converted to a dc voltage and is measured by a strip chart recorder. This system has replaced a mechanically driven generator attached to the drive shaft used in earlier measurements.

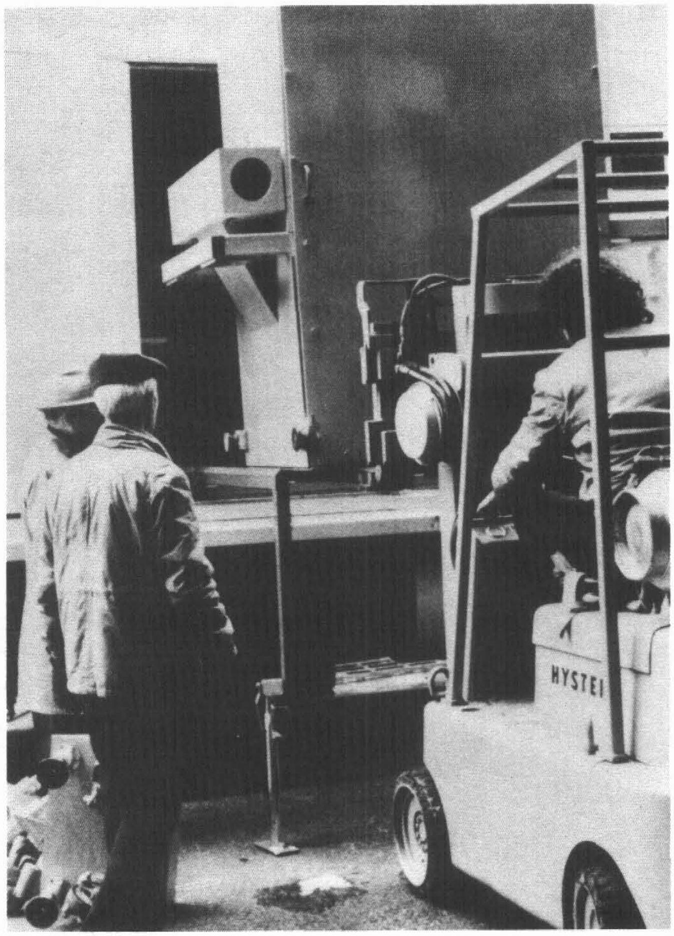


Fig. 10. Maser enclosure being loaded into APL truck.

Temperature control.

The temperature of the air entering each maser enclosure is maintained by a resistive heater controlled by a proportional, integral, derivative (PID) microprocessor that measures the temperature with a 100-ohm RTD sensor and provides a 4 - 20 mA control current to a zero-crossing power regulator. The temperatures are monitored by arrays of thermistors whose resistances are measured by an HP 3421A Data Acquisition/Control Unit run with an HP 71 calculator. Similarly, the truck interior and maser room of the telescope building are also temperature controlled. During periods of limited access, the truck and room temperatures are maintained at 23 °C within a few tenths of a degree and the maser enclosures are maintained at 24 °C within about one tenth of a degree. Four controllers and power regulators are thus in operation to regulate the temperatures of the two masers and their environments. We have found that the Shimaden SR-22 controller performs very well for this purpose. These controllers have an auto-tune feature that automatically performs a temperature cycle and selects the appropriate parameters for the system.

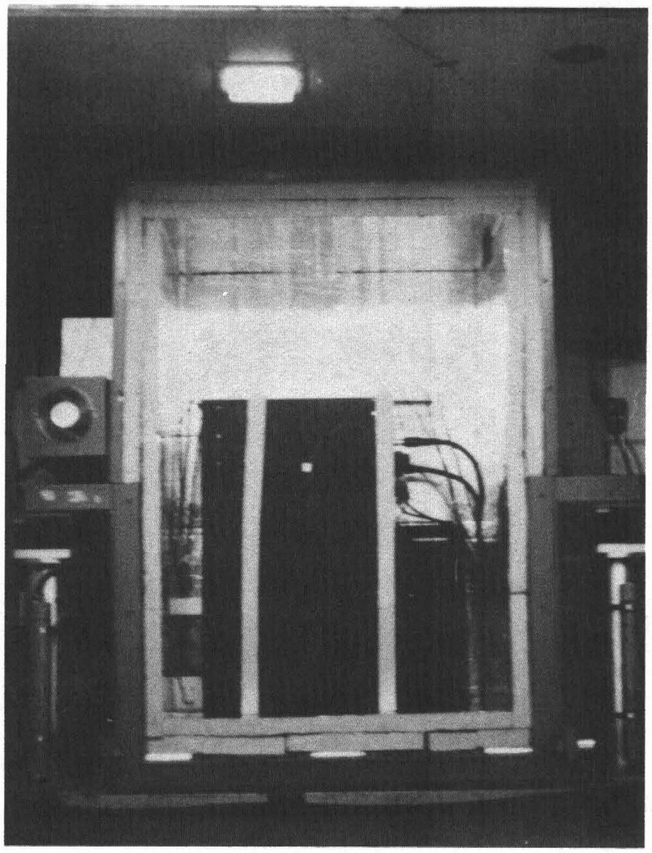


Fig. 11. Maser 6 inside temperature-controlled enclosure.

We have taken care to select coaxial cables with low temperature sensitivity and to minimize their lengths so as to eliminate the effect of environmental temperature fluctuations on the measurements. We have replaced our original RG223 cables, with a sensitivity on the order of 200 ppm/ °C, with expansion-compensated cables having copper conductor and foam dielectric, Cablewave Systems FLC 12-50J, which have a temperature coefficient of about 10 ppm/ °C. Also, we have minimized the lengths of the cables. During the summer we performed the t_2 measurements from the dome on top of the Time Services Building at USNO where the original optical link was established. This location required running cables over the roof to the truck below. In order to account for possible fluctuations in delay caused by changes in temperature, we made measurements on two channels with cables of different length and determined their difference. In order to eliminate, rather than correct for, the problem we have redirected the cathedral mirror to a point in front of USNO Building 1 where the cathedral bell tower can be seen from ground level. We are now able to set up the t_2 detector next to the parked truck with cables short enough to ignore the temperature change.

Remote comparison of masers.

Besides the Erbtec double mixing systems used to compare maser 6 with maser 5 at GORF and maser 6 with the USNO master maser, we have set up a double mixing system to compare maser 5 directly with the USNO maser by means of a TV signal link. The technique is similar to that originally used by Claude Audouin and his colleagues in Paris[17] The carrier signal of station WTTG, Channel 5, in Washington uses a cesium clock as a reference. This standard was set up several years ago by USNO engineers in cooperation with WTTG in order to use the technique to compare masers between USNO and the Naval Research Laboratory. The 77.240 MHz carrier is mixed with a 77.242 250 MHz signal synthesized at the USNO with their maser. The resulting 2.250 kHz beat note is sent to GORF over a dedicated telephone line. At GORF another 77.242 250 MHz signal is synthesized from the 5 MHz of maser 5. The phase between the GORF-derived 2.250 kHz signal is measured with respect to the USNO-derived 2.250 kHz signal using a linear phase-comparator. The resolution is equivalent to between 50 and 100 ps between masers. The output voltage is recorded on a strip chart and stored by the HP 3421A Data Acquisition/Control Unit for future study. By combining the frequency offset of maser 6 with respect to the USNO maser during an across-Washington optical measurement with the frequency offset of maser 5 with respect to the USNO maser obtained via the TV link, we can draw an inference about the relative phases of masers 5 and 6 even while they are separated. These data are used to estimate the effects of transportation on the frequency of maser 6 and to interpolate the phase data acquired with the Erbtec system during calibration measurements at GORF.

PRELIMINARY RESULTS

We have been able to obtain clock closures for a round trip of under 50 ps after allowing for the measured rate difference between masers 5 and 6 before and after the trip and applying relativity corrections for speed and elevation difference. The optical measurements during calibration follow the clock phase difference determined by the independent phase comparison. The precision of timing of the 70 ps pulses of laser light has been observed to be as low as 30 ps (standard deviation of the mean).

We need to achieve these performances for both clocks and optical detection simultaneously for a number of clock trips so that we can measure ΔT to within less than 50 ps in order to test for a possible asymmetry in the speed of light with respect to the rotating earth. Many improvements are being made as this investigation continues.

DISCUSSION OF THEORY

Only the briefest impressions will be given here.

As mentioned in the INTRODUCTION, for a clock the metric coefficients $g_{\mu\nu}$ of Eq. (1) are intended to relate the increment $d\tau$ of the clock's own time -- usually called its proper time -- between two neighboring events on the clock's path and the spacetime coordinate increments dx^{μ} (equal, for example, to $c\ dt$, dx, dy, and dz) between the same two events as inferred by some observer according to his space and time coordinate system. In general, the metric coefficients are functions of the four spacetime coordinates x^{μ}. There are ten independent components because of the symmetry $g_{\mu\nu} = g_{\nu\mu}$. In this discussion we adopt a sign convention with signature (+ - - -).

It should be the task of the field equations of a curved spacetime theory of gravitation to provide solutions for the appropriate $g_{\mu\nu}$ which describe a given physical situation. Einstein has written,

> My equation is like a house with two wings. The left hand side is made of fine marble but the right hand side is of perishable wood.

His field equation is

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8 \pi G}{c^4} T_{\mu\nu} \tag{11}$$

where $R_{\mu\nu}$ is the Ricci tensor constructed from a nonlinear combination of the $g_{\mu\nu}$ and their first and second derivatives, R is the scalar curvature, $T_{\mu\nu}$ is the stress energy tensor for matter, and G is the Newtonian gravitational constant. Equation (11) represents ten equations (for μ, ν = 0,1,2,3 with symmetry) to be solved for the $g_{\mu\nu}$ in terms of the x^μ.

In the new theory of Yilmaz[7] the left hand side of the field equation is kept the same but the right hand side is changed to include the stress-energy tensor $t_{\mu\nu}$ of the gravitational field,

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8 \pi G}{c^4} (T_{\mu\nu} + t_{\mu\nu}) . \tag{12}$$

The field equations apparently become more complicated but their solution becomes easier. The general solution is of the form of an exponential,

$$g_{\mu\nu} = \{\eta \exp[2(\phi - 2 \hat{\phi})]\}_{\mu\nu} \tag{13}$$

where $\hat{\phi} \equiv \phi_\mu{}^\nu$, a generalized gravitational field satisfying a wave equation with matter sources, and $\phi = \phi_\mu{}^\mu$. In the low velocity limit for the motion of the sources, when the retardation effects of field propagation can be ignored, the $g_{\mu\nu}$ become exponential functions of the familiar Newtonian potential ϕ. The symbol η represents the Minkowski metric coefficients.

The new theory successfully treats all of the classical tests of general relativity at the first order of accuracy but differs from general relativity in its second order predictions. The new theory handles many important problems extremely effectively, in part because of the simple exponential dependence of the metric coefficients on the Newtonian N-body potential in the limit discussed above. These include the problem of N interacting masses (our solar system, for example) and the calculation of gravitational radiation. For these reasons the theory of Yilmaz has been called "Deputy General Relativity" by Professor John Wheeler.[18]

There seem to be kinematic differences in the metrics for rotating systems given by the two theories. For a disk rotating with angular velocity ω the metric of general relativity usually given,[4-6] combined with a term "added by hand" representing the gravitational potential, is

$$\begin{aligned} g_{00} &= 1 - (\vec{\omega} \times \vec{r})^2/c^2 + 2\,\phi/c^2 \\ g_{0j} &= -\frac{1}{c}\,(\vec{\omega} \times \vec{r})_j \\ g_{ij} &= -\,\delta_{ij} \end{aligned} \tag{14}$$

so that for a coordinate system whose z-axis coincides with the axis of rotation,

$$ds^2 = (1 - \omega^2\, r^2/c^2 + 2\,\phi/c^2)\; c^2\, dt^2 - 2\,\omega\, r^2\, d\theta\, dt - r^2\, d\theta^2 - dr^2 \tag{15}$$

where r and θ are the polar coordinates with respect to the center of the disk. These metric components without the addition of the gravitational potential arise from the metric of flat spacetime with the transformation $r \to r$, $\theta \to \theta - \omega\, t$, $t \to t$, thereby preserving the flat spacetime. It can be shown, however, that this combined form of the metric follows from an iterative solution of the Einstein field equations for a rotating frame of reference.[19]

If Eq. (15) is applied to light propagation on the rotating earth by setting $ds^2 = 0$, one obtains a quadratic equation for dt. Assuming $dr = 0$ and neglecting ϕ/c^2, the solution is

$$dt = \frac{r\, d\theta}{-\,\omega\, r \pm c}\ . \tag{16}$$

For the outgoing (east to west) pulse $d\theta$ is negative and $d\theta = -|d\theta|$. To obtain a positive time we choose the minus sign and obtain

$$\Delta t_{EW} = \frac{r\,|\Delta\theta|}{c + \omega\, r} = \frac{d}{c + v} \tag{17}$$

where d is the east-west distance and v is the speed of the earth's surface. For the reflected (west to east) pulse $d\theta$ is positive so we choose the positive sign and obtain

$$\Delta t_{WE} = \frac{r\,|\Delta\theta|}{c - \omega\, r} = \frac{d}{c - v}\ . \tag{18}$$

From this point of view, the coordinate time difference is

$$\Delta t_{EW} - \Delta t_{WE} = -\,\frac{2\,\omega\, r^2|\Delta\theta|}{c^2 - \omega^2\, r^2} \approx -\,\frac{2\, v\, d}{c^{\,2}}\ . \tag{19}$$

The apparent coordinate speed of light is $c + v$ going west and $c - v$ going east. It is not clear whether we should actually observe this difference, however, since the metric of Eq. (15) seems to assume that the observer is located at the center of rotation.

The solution for the metric on a rotating disk in the limit discussed above of the Yilmaz theory is

$$ds^2 = [1 - \omega^2 (r^2 - r_0^2)/c^2 + 2 (\phi - \phi_0)/c^2]\ c^2\ dt^2$$

$$- 2\ \omega\ |\vec{r} - \vec{r}_0|^2\ d\theta\ dt - r^2\ d\theta^2 - dr^2\ . \tag{20}$$

In this expression $\vec{r}_0$ denotes the position of the observer on the disk with respect to the center and ϕ_0 is the gravitational potential at the observer. For a local measurement $\vec{r} \approx \vec{r}_0$ and $\phi \approx \phi_0$ and the solution for the light propagation equation $ds^2 = 0$ is

$$r\ \frac{d\theta}{dt} = \pm\ c \tag{21}$$

This metric has a nonzero spacetime curvature, even without the gravitational potential term $\phi - \phi_0$. This can be traced to the very strong principle of equivalence among inertial mass, passive gravitational mass, and active gravitational mass in the new theory.[7]

Another approach to the study of the appropriate metric for a rotating system is based on a generalization of the Lorentz transformation for an accelerated, rotating frame of reference. This approach has been pursued by the second author and yields the following metric for an observer at any point on the rotating disk:

$$g_{00} = (1 + \vec{W}\cdot\vec{\rho}/c^2)^2 - (\vec{\omega} \times \vec{\rho})^2/c^2 + 2\ \phi/c^2$$

$$g_{0j} = -\frac{1}{c}\ (\vec{\omega} \times \vec{\rho})_j \tag{22}$$

$$g_{ij} = -\ \delta_{ij}$$

where $\vec{\rho}$ is measured from the origin of coordinates on the earth's surface and $\vec{W}$ is the acceleration of the origin due to its circular motion. With this metric the relativistic effects on light propagation and the atomic clock transport due to the earth's rotation are negligible because of the small value of $\vec{\rho}$. However, the atomic clock must still be corrected for speed and elevation effects.

The purely inertial part of this metric is exact and is obtained by applying to the flat spacetime Minkowski metric a coordinate transformation that represents a generalization of the Lorentz transformation for an accelerated, rotating observer.[20] In general, $\vec{W}$ may represent any linear acceleration of the origin as measured in the observer's own rest frame. It may be shown that the combined metric with inertial terms and gravitational term above, together with higher order gravitational and mixed gravitational-inertial terms neglected here, may be derived from an iterative solution of Einstein's field equation using the method of Ref. [19].

We realize that our discussion of the theory is inadequate, given the importance of the subject. We hope that our experimental measurements will help to clarify the conceptual foundations by giving further operational significance to the distinction between coordinate and proper times. We intend to discuss the completed measurements more thoroughly in this context in a later publication.

ACKNOWLEDGMENTS

We wish to express our great appreciation to Professor Hüseyin Yilmaz for the generous investment of his time in patiently explaining his theory and the fundamental questions addressed by this experiment through many personal discussions, letters, and lectures.

We are highly indebted to the many organizations and individuals whose generous support in diverse ways is making this experiment possible:

U.S. Naval Observatory *Financial support* *(Contract* N00014-87-K-0811*)* *Technical assistance* *Loan of equipment*	Gernot Winkler, Gart Westerhout, Paul Wheeler
U.S. Air Force, Global Positioning System Program *Financial support* *(supplement to USNO Contract)*	Warner Miller, Henry Fliegel
Naval Research Laboratory *Technical assistance* *Loan of equipment*	Ron Beard, Joe White, Al Gifford
Applied Physics Laboratory *Technical assistance* *Loan of APL truck* *Loan of ST1 maser*	Al Bates, Lee Stillman, Steve Deines, Mary Chiu
Jet Propulsion Laboratory *Loan of ST1 maser*	Lute Maleki
Bendix Field Engineering Corporation *Technical support* *Loan of NR10 maser*	Peter Dachel, Bob Price, Larry Johnson

National Radio Astronomy Observatory *Loan of Sigma Tau masers 5 and 6*	Peter Napier, Larry Beno, Sam Honeywell
Sigma Tau Standards Corporation *Technical advice*	Harry Peters
Hamamatsu Photonics *Loan of MCP-PMT*	Teruo Hiruma, David Fatlowitz, Y. Shinoda
NASA Goddard Space Flight Center *Use of 48-inch telescope* *Laboratory space* *Loan of NR10 maser*	Robert Coates, John Degnan, Tom Zagwodski, Jim Abshire, Arnie Abbott, Jan McGarry
Department of Physics and Astronomy University of Maryland *Technical Support*	Frank Desrosier, Karl Harzer, Frank San Sebastian, Ed Gorsky, Ernie Grossenbacher, Jack Touart, John Mullendore, Ben Scesa, Rob Giraldi, Camille Vogts

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2. A second-in-command or assistant who usually takes charge when his commander is absent.

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QUESTIONS AND ANSWERS

DR. GERNOT WINKLER, USNO: Actually, I have a comment. I would like to emphasize your remark that there is a dispute about the interpretation of the Sagnac Effect on the basis of General Relativity. It is not uniformly understood. I think that the least that one can expect from an experiment like this is that is to settle that kind of a dispute.

DR. ALLEY: I am not sure that these disputes will get settled, but I think that it may help to clarify the situation.