TIME TRANSFER BETWEEN THE GODDARD OPTICAL RESEARCH FACILITY AND THE U.S. NAVAL OBSERVATORY USING 100 PICOSECOND LASER PULSES*

C. O. Alley, J. D. Rayner, C. A. Steggerda, J. V. Mullendore, L. Small and S. Wagner

Department of Physics and Astronomy
University of Maryland
College Park, Maryland 20742

ABSTRACT

A horizontal two-way time comparison link in air between the University of Maryland laser ranging and time transfer equipment at the Goddard Optical Research Facility (GORF) 1.2 m telescope and the Time Services Division of the U.S. Naval Observatory (USNO) has been established. Flat mirrors of 25 cm and 30 cm diameter respectively have been placed on top of the Washington Cathedral and on a water tower at the Beltsville Agricultural Research Center since direct line of sight transmission is not possible. The bent path has a one-way distance of 26 km. Two optical corner reflectors at the USNO, identical to those placed on the Moon during the Apollo program, reflect the laser pulses back to the GORF.

Light pulses of 100 ps duration and an energy of several hundred microjoules from a neodymium-YAG laser, frequency-doubled to a wavelength of 532 nm (green) are sent at a rate of 10 pulses per second. The detection at the USNO is by means of an RCA C30902E avalanche photodiode and the timing is accomplished by an HP 5370A computing counter and an HP 1000 computer with respect to a 10 pps pulse train from the Master Clock.

The reflected light is detected back at the 1.2 m telescope at the single photoelectron level and the epoch of reception is recorded by a University of Maryland designed event timer attached to a NOVA 2/10 minicomputer. About 100 detection events are recorded for 1000 pulses transmitted. The outgoing pulses have their epoch of transmission recorded by the same event timer, which is driven by an HP cesium beam frequency standard.

* This work has been supported by the U.S. Naval Observatory and the Office of Naval Research under contract N000 14-78-C-0338. The following members of the Time Services Division of the USNO have participated actively in the experiments: G.M.R. Winkler, W. Klepczynski, K. Putkovich, A. Kubik, P. Wheeler and D. Chalmers.

The Einstein prescription is used to relate the epoch of the received event at the USNO to the midpoint between the transmitted and received events at the GORF. This procedure is independent of the delays introduced by the atmosphere. The standard deviation for 100 comparisons is typically 200 to 400 ps. The corresponding standard deviation of the mean is 20 to 40 ps. We are still working on the calibration accuracy which at present is 1 to 2 ns, established by a portable clock trip.

The link was to have been a near real time connection with the USNO during our planned participation in the LASSO experiment. The link is also serving to provide experience for the high accuracy short pulse laser time transfer part of the Space Time and Frequency Transfer (STIFT) experiment to be discussed at this PTTI meeting.

INTRODUCTION

There have been two major purposes for the experiments described in this paper.

1) To gain additional practical experience with the short laser light pulse technique of time comparison between remote clocks. The method was pioneered in atomic clock experiments with aircraft which measured the effect of gravitational potential on time.[1] It will be used in both the Laser Synchronization from Stationary Orbit (LASSO)[2] and the Space Time and Frequency Transfer (STIFT)[3] experiments, if these are carried out. The technique offers the most accurate practical means of remote time comparison.

2) To provide a link to the USNO from the GORF 1.2 meter telescope to facilitate time comparison with Western Europe during the LASSO experiment. The failure on 20 September 1982 of the third stage of the ARIANE rocket carrying the SIRIO-2 satellite with the LASSO instrumentation has prevented this experiment from being performed. The LASSO participants have been informed by P. Berlin, the project manager for the SIRIO-2 satellite, and B.

[1] C. O. Alley, "Relativity and Clocks", Proceedings of the 33rd Annual Symposium on Frequency Control, U.S. Army Electronic Research and Development Command, Fort Manmouth, NJ, pp. 4-39A (1979). Copies available from Electronic Industries Association, 2001 Eye Street, N. W. Washington, D. C. 20006.

[2] B.E.H. Serene, "Progress of the LASSO Experiment," Proceedings of the Twelfth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting; NASA Conference Publication 2175, pp 307-327, December 2-4, 1980.

[3] R. Decher, D.W. Allan, C.O. Alley, C. Baugher, B.J. Duncan, R.F.C. Vessot, and G.M.R. Winkler, "High-Accuracy Global Time and Frequency Transfer with a Space-Borne Hydrogen Maser Clock", Proceedings of the Fourteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, November 30 - December 2, 1982. To be published as a NASA Conference Publication.

Serene, the project manager for LASSO, that there is active consideration now being given within the European Space Agency to flying a new SIRIO-2B satellite with LASSO instrumentation, using existing engineering test equipment. If the decision is favorable, and another ARIANE launch can be arranged, perhaps the LASSO experiment can be performed in about two years.

THE SHORT LIGHT PULSE TIME TRANSFER TECHNIQUE

Einstein's Prescription

The idea of using short light pulses to compare the readings of separated clocks is one of the conceptual foundations of relativity contained in Einstein's original paper.[4] It is remarkable that the advent of lasers with their ability to produce very short pulses of light has allowed the method to be implemented as perhaps the most accuracte means of remote time comparison.

The method is illustrated in the spacetime diagram of Figure 1. In an inertial system in the absence of an atmosphere, the speed of light is

$$c \approx 2.9979 \times 10^{8} \text{ m/s} \approx 30 \text{ cm/ns}, \qquad (1)$$

so that for the units shown, the light lines have a slope of 45° for an outgoing pulse and -45° for an incoming pulse, representing the same velocity in each direction.* If a pulse is sent out at time t_1, reflected from a distant point at time t, and received back at time t_3, then t_2, the midpoint in time between t_1 and t_3, is to be identified with t, according to Einstein:

$$t_2 = t_1 + (t_3 - t_1)/2 = (t_1 + t_3)/2 = t. \qquad (2)$$

Also, the distance x is given by the radar equation from the difference between measured epochs t_1 and t_3:

$$x = (t_3 - t_1)\ c/2. \qquad (3)$$

The effect of the atmosphere is to reduce the speed of light from c to c/n, where n is the index of refraction. (The detailed physics leading to this result is rather complex and not widely known, but will not be discussed here.) The value of n depends on the frequency of the light, the atmospheric pressure, the temperature, and the composition of the atmosphere, including

[4] A. Einstein, "Zur Elektrodynamik Bewegter Körper," Annalen der Physik, 17, 1905. A translation into English is available: "On the Electrodynamics of Moving Bodies," in The Principle of Relativity, a Collection of Original Papers on the Special and General Theory of Relativity, translated by W. Perrett and G. B. Jefferey, Dover Publications, Inc., New York, 1952.

* In a coordinate system attached to the surface of our rotating Earth, which is not an inertial system, the speed in the East-West direction differs from that in the West-East direction by about 3×10^{-6} at the equator. In the present experiment, the effect might be barely detectable as the calibration is refined.

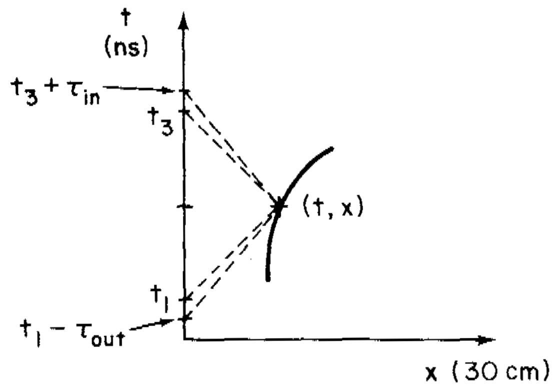

Fig. 1. The Einstein Prescription.

the partial pressure of water vapor. (The dependence on water vapor is far smaller for optical frequencies than for microwave and radio frequencies.) The atmosphere thus produces an additional time delay for the light pulse on the way out, τ_{out}, and a corresponding delay on the way in, τ_{in}, as shown in Figure 1. The Einstein prescriptions for determining the coordinates (t, x) of the reflection event as expressed in equations (2) and (3) now become

$$t = \left[(t_1 - \tau_{out}) + (t_3 + \tau_{in})\right]/2 = (t_1 + t_3)/2 + \underbrace{(\tau_{in} - \tau_{out})/2}_{\text{nearly cancel}} \tag{4}$$

$$x = \left[\underbrace{(t_3 + \tau_{in}) - (t_1 - \tau_{out})}_{\text{measured round trip time}} - \underbrace{(\tau_{in} + \tau_{out})}_{\text{additive}}\right] c/2 \tag{5}$$

Note that for the time determination in equation (4), the atmospheric delays, τ_{out} and τ_{in}, occur as a difference. They are essentially the same and will nearly cancel. <u>The Einstein prescription for determining the time of a distant event by the midpoint in time between the emitted and the received (reflected) pulse is essentially unaffected by the atmosphere</u>.

This is to be contrasted with the effect of the atmosphere on the distance determination, equation (5), in which the sum of the delays τ_{out} and τ_{in} must be subtracted. <u>An accurate distance measurement requires that the atmospheric delays be known</u>.

An added advantage of the light pulse method of determining the time of a distant clock with respect to a local clock is that the motion of the distant clock does not have to be considered in the comparison between the local midpoint event and the distant reflection event. There are no Doppler effect complications.

However, if the distance between the clocks is not changing, one can use the radar delay to determine the one-way time difference. This is helpful when the returned light pulse is so weak that single photo-electron detection

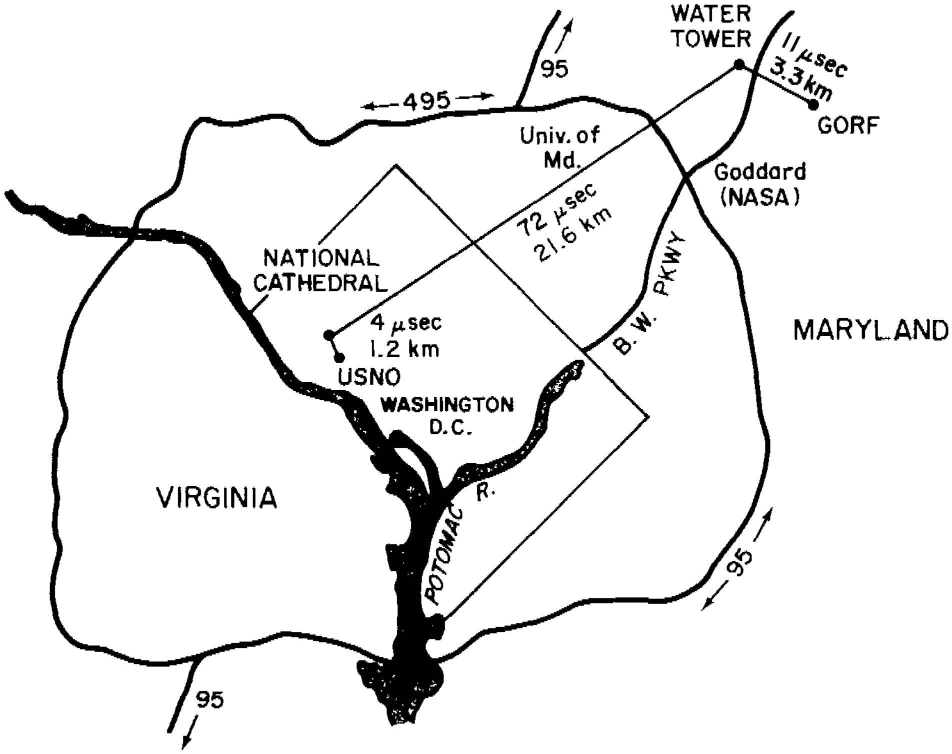

Fig. 2. The path of the laser beam across Washington.

is required. Under these circumstances the reflected pulse at t_3 will not be recorded for each shot, but only with a certain probability, perhaps one in ten. This will be discussed in the later section on the analysis of typical data.

Path Across Washington and Atmospheric Effects

The actual path of the light pulses from the 1.2 m telescope at the Goddard Optical Research Facility to the dome on the roof of the Time Services Building at the U.S. Naval Observatory where two lunar type corner reflectors and a detector are located is shown in Figure 2. A direct line of sight is not possible because of the topography of the Washington area, but a 30 cm flat mirror on a water tower at the Beltsville Agricultural Research Center and a 25 cm flat mirror on the top of the National Cathedral (the highest point in the Washington area) allow a connection. The approximate light travel times and distances for the several legs are given on the map. The total one-way light travel time is 87 microseconds corresponding to a total one-way distance of 26 km. The value of the atmospheric index of refraction[5] for green light of 532 nm wavelength from the frequency-doubled neodymium YAG

[5] C.W. Allen, Astrophysical Quantities, the University of London Athlone Press, London, Second Edition, 1955, pp 119f. This reference contains many useful tables and formulas for the optical index of refraction.

laser, for a pressure of 760 mm of Hg, for a temperature of 15° C, and for water vapor pressure of 4 mm of Hg is given by

$$n - 1 = 0.000277 \tag{6}$$

and produces a one-way atmospheric delay of 24 nanoseconds. This does not matter for the Einstein prescription, as discussed above. Other atmospheric effects do cause experimental troubles, however.

If the "visibility" as quoted for the Washington National Airport is less than five or six miles, we cannot detect reflected light over the 52 km round-trip path even at the single photo-electron detection sensitivity for our several hundred microjoule pulses of green light.

Instabilities in the atmosphere associated with a changing vertical temperature gradient, which often occur a cloudless cold night after a warm day, require frequent adjustment of the pointing of the 1.2 m telescope to keep the narrow laser beam on the water tower mirror. This bending of the light is similar to mirage effects. The laser beam is about 2 cm in diameter as it leaves the telescope, expanding to about 45 cm over the 3.3 km path to the water tower. At the cathedral the beam is 200 to 300 cm wide and scintillations are observed - a changing mottled pattern - caused by the non-uniformity of the atmosphere in the transverse dimension of the beam during the 21.6 km path to the cathedral. Changing vertical temperature gradients also require occasional angular adjustment of the water tower mirror to keep the beam on the cathedral mirror. At the USNO the laser beam has a horizontal extent of about 15 cm and a vertical extent of about 25 cm, the projected dimensions of the cathedral mirror as it intercepts the beam.

Methods of Aligning the Mirrors

It has proven necessary during a time transfer to have people at the various locations to make the initial mirror alignments and to maintain them: one person at the USNO, one person at the cathedral, and two persons at the water tower. Three persons are needed at the telescope to operate it, the laser, and the computer, and to coordinate all the activities. A telephone has been installed at each location and a conference call is arranged during each time transfer exercise to allow the necessary communications.

The most difficult adjustment is the initial alignment of the water tower and cathedral mirrors. A very elegant and fast method of accomplishing this was finally devised by D. G. Currie, J. V. Mullendore, C. A. Steggerda, and C. O. Alley, at the University of Maryland. The idea derives from methods used to direct narrow laser beams to a specific location on the Moon.[6] The method uses a high quality 38 mm diameter circular corner reflector identical to

[6] C.O. Alley, "Laser Ranging to Retro-Reflectors on the Moon as a Test of Theories of Gravity," in _Quantum Optics, Experimental Gravitation, and Measurement Theory_, edited by P. Meystre and M.O. Scully, Plenum Publishing Corporation, New York (1983).

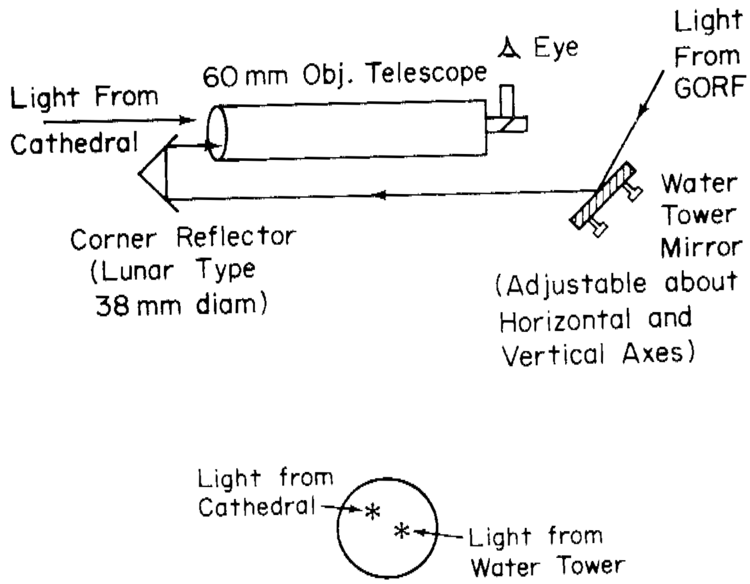

Fig. 3. Optical arrangement for the telescope which looks forward and backward at the same time.

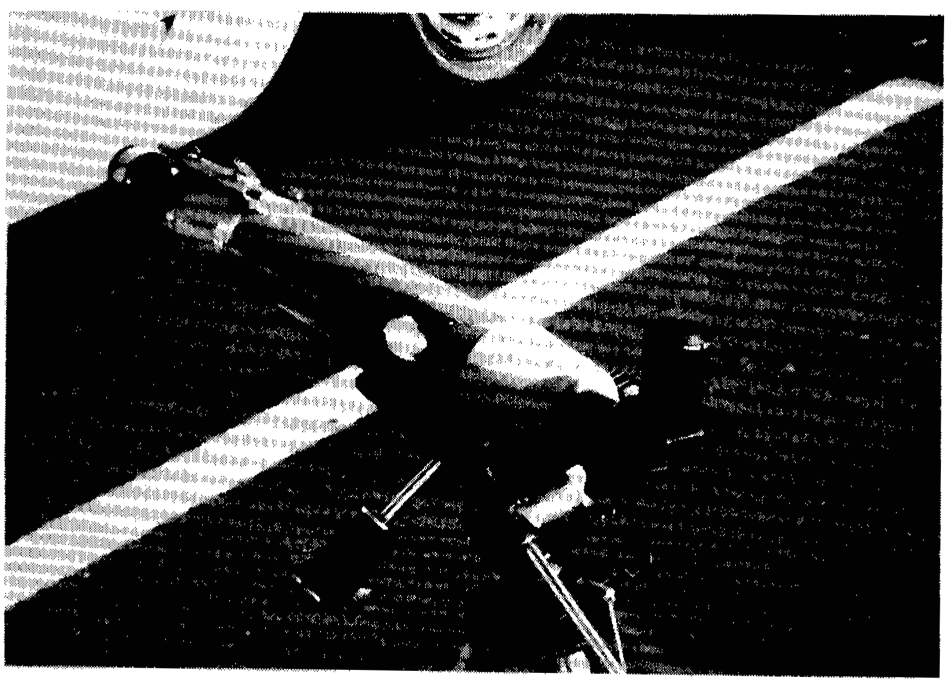

Fig. 4. Picture of the forward and backward looking telescope.

those placed on the Moon, together with an Edmund Scientific Company Celestial/Terrestrial 60 mm objective refracting telescope. Figure 3 shows the arrangement. It allows one to look forward and backward at the same time. A corner reflector has the property that an entering ray of light is reflected three times at three orthogonal mirrors, emerging at a diametrically opposed point with a reversed propagation vector. When the reflector is mounted as shown, halfway across the entrance pupil of the telescope, the view from behind is superposed on the normal field of view of the telescope. Coarse adjustment of the mirror is achieved by viewing the cathedral and the GORF telescope dome during daylight, bringing the telescope dome into coincidence with the corner of the cathedral spire. Fine adjustment is done at night by superposing the image of the attenuated laser beam on the image of an incandescent light placed at the cathedral mirror. Once this is done, the laser beam is guaranteed to hit the cathedral mirror. An even finer angular adjustment can now be accomplished by temporarily placing a corner reflector at the cathedral mirror and observing the reflection from it in the 60 mm telescope (after rotating its corner reflector out of the way) adjusting the water tower mirror to maximize the intensity. A picture of the forward and backward looking telescope is shown as Figure 4.

For the water tower mirror, this procedure with the two-way telescope and lights must be done before each time transfer exercise since the alignment does not stay constant. We believe that both the changing water level in the tank and the temperature changes in the structure cause the angular changes in the mirror. Carrying the equipment to the top of the tower, setting it up, and making the adjustments usually requires about a half-hour. For the cathedral mirror, the two-way telescope is used only rarely since the mounting of the mirror is very stable, and the optical "lever arm" to the USNO is only 1.2 km. Usually, an adjustment of only 30 to 60 cm in translation is needed. This is accomplished by observing the position of the green light from the laser on the back of the dome, and adjusting the cathedral mirror until the detector/reflector combination casts a shadow in the middle of the green spot. The propagation vector reversal of the corner reflectors adjacent to the detector at the USNO causes the reflected light to retrace the path back to the telescope at the GORF.

DESCRIPTION OF THE EQUIPMENT

Laser and Timing Instrumentation at the GORF

At the 1.2 m telescope a frequency doubled neodymium YAG laser produces 100 picosecond duration pulses of green light at 532 nm, each with an energy of about 0.5 millijoule. For the time transfer experiments the repetition rate is set at 10 pps to match the 10 pps master clock pulse train at the USNO, although the laser is capable of operating at 30 pps. This laser is described in detail in a recent paper[7] and is the same one that was used in

[7] C. O. Alley, "Proper Time Experiments in Gravitational Fields with Atomic Clocks, Aircraft, and Laser Light Pulses." in Quantum Optics, Experimental Gravitation, and Measurement Theory, edited by P. Meystre and M. O. Scully, Plenum Publishing Corporation, New York (1983).

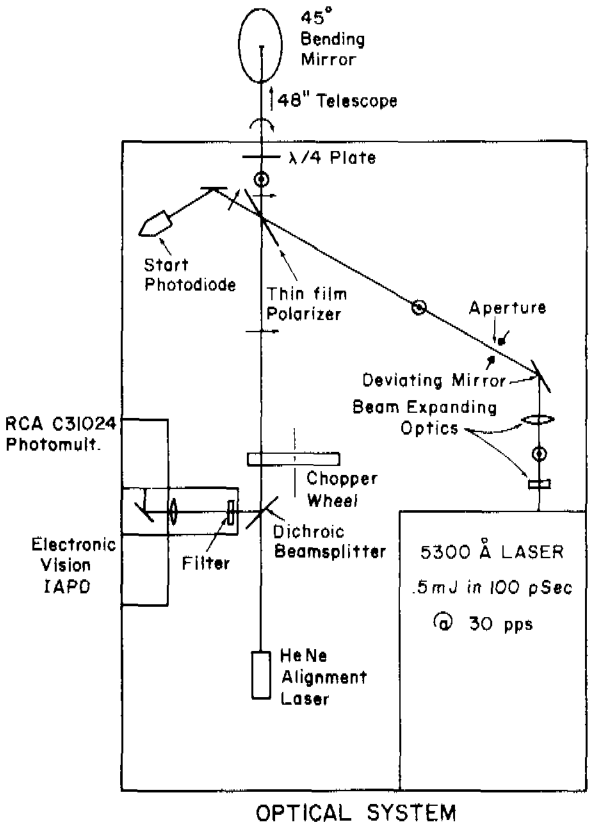

Fig. 5. Coupling of laser and detector to the telescope.

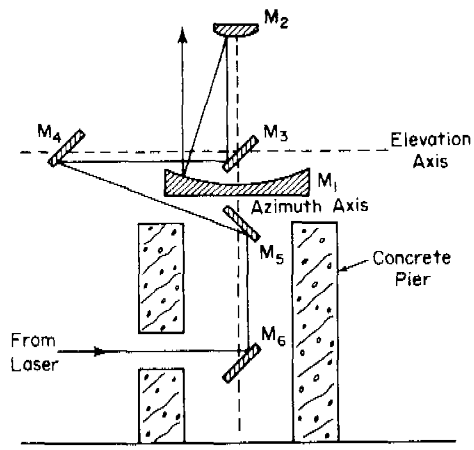

Fig. 6. Path of the laser beam through the telescope.

the aircraft atomic clock relativity experiments (reference 1). The optical system for coupling the laser to the telescope and for detecting the reflected light is shown in Figure 5. The pulse from the laser is linearly polarized with the electric vector vertical. It therefore reflects from the multi-layer thin film polarizer and passes through a quarter-wave plate which converts the linear polarization to circular polarization. The pulse is reflected off-center from a 45° bending mirror (M6 in Figure 6), allowing it to proceed through the telescope optics as shown in Figure 6, emerging with a diameter of about 2 cm from the annular region between the edge of the primary mirror M1 and the edge of the secondary mirror M2.

The returning light has suffered some depolarization, but is still mainly circularly polarized in the opposite sense. On passing through the quarter-wave plate the light becomes linearly polarized in the horizontal plane and therefore passes through the thin film polarizer. A rotating chopper wheel carries a vane which blocks the light which has been scattered back from the telescope optics and nearby atmosphere. The chopper wheel is phased to be open when the return light appears after the 174 micro-second round trip time. The light is reflected from a dichroic beam splitter through a 10 Å spectral filter and through neutral density filters (variable from zero attenuation up to N.D. 12). The return light is then focussed to a small spot on the photocathode of an RCA 31024 photomultiplier tube. The neutral density filters allow the simulation of the single photo-electron detection which will be needed in the LASSO experiment (the satellite will be in synchronous orbit). They also allow the equipment to be checked at the single photoelectron level by ranging to a corner reflector located on the water tower. An excellent review article by S. K. Poultney gives many details on the techniques of accurate time measurements with single photoelectrons.[8]

The electronic timing equipment is shown in the block diagram of Figure 7. The start pulse is obtained from a fast photodiode responding to leakage light from the multilayer thin film polarizer. A standard NIM pulse is formed by an Ortec discriminator and passes through an 'or' circuit and a clean up discriminator to an event timer/computer combination which records the epoch of the outgoing pulse with a resolution of 50 ps. The single photoelectron pulse from the photomultipler is amplified by two Hewlett-Packard wide band amplifiers and goes to an Ortec 473 constant fraction discriminator which minimizes the "walk" in time associated with amplitude fluctuations. A range gate is provided by an adjustable width pulse activated by an "alarm clock pulse" from the event timer/computer combination. The E G & G fast trigger is open only when activiated by the adjustable width pulse. The return pulse then passes through the same 'or' circuit as the start pulse and on to the event timer where its epoch is recorded in the NOVA 2/10 computer. The equipment above the dashed line is located in the telescope dome and that below the dashed line is in a trailer adjacent to the dome.

The event timer is basically a clock which can be read with a resolution of 50 ps without stopping it. It can handle up to 100 pulses per second, a limit currently imposed by the associated computer. The operation of the event timer is illustrated schematically in Figure 8. A 5 MHz external reference frequency (currently an HP 5061 cesium standard; for the LASSO experiment a hydrogen maser was to have been used) is doubled to 10 MHz inside the event timer and operates a synchronous counter. An incoming NIM pulse latches the synchronous counter to provide the epoch to 100 ns. The 0.05 ns resolution is achieved by a dual slope integrator in which the pulse also starts a capacitor charging until it is stopped by an appropriate pulse in the 10 MHz train. The capacitor is then discharged in a time 250 times longer than the charging time, and the discharge time is measured with an 80 MHz oscillator to the nearest cycle. Details of the basic circuits are given in a University of Maryland Technical Report.[9] (A new type of event timer is being developed at the University of Maryland by C.A. Steggerda with a resolution of 10 to 20 ps.)

[8] S. K. Poultney, "Single Photon Detection and Timing: Experiments and Techniques," in Advances in Electronics and Electron Physics, vol. 31, edited by L. Marton. Academic Press, New York and London (1972).

[9] C.A. Steggerda, "A Precision Event Timer for Lunar Ranging," University of Maryland Technical Report 74-038, November, 1973.

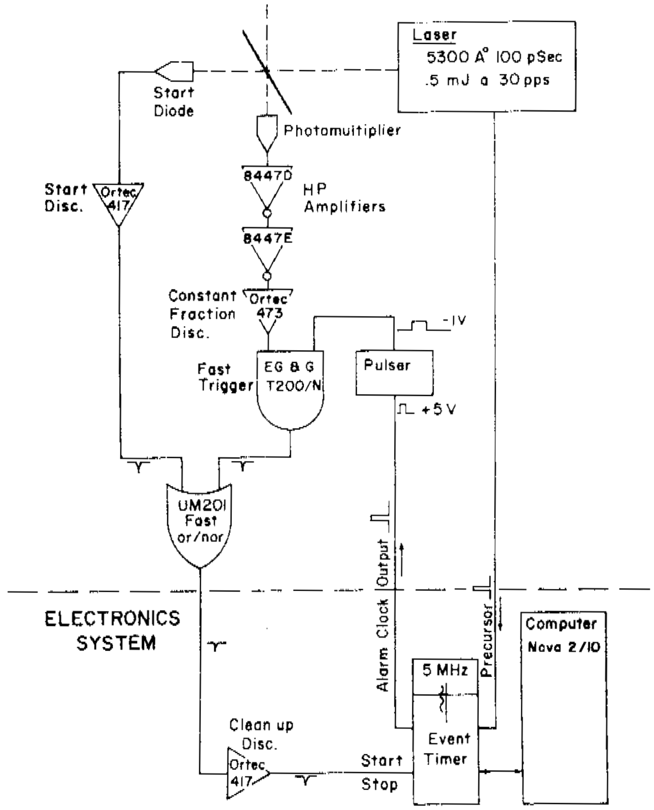

Fig. 7. Electronic timing equipment at the 1.2 m telescope.

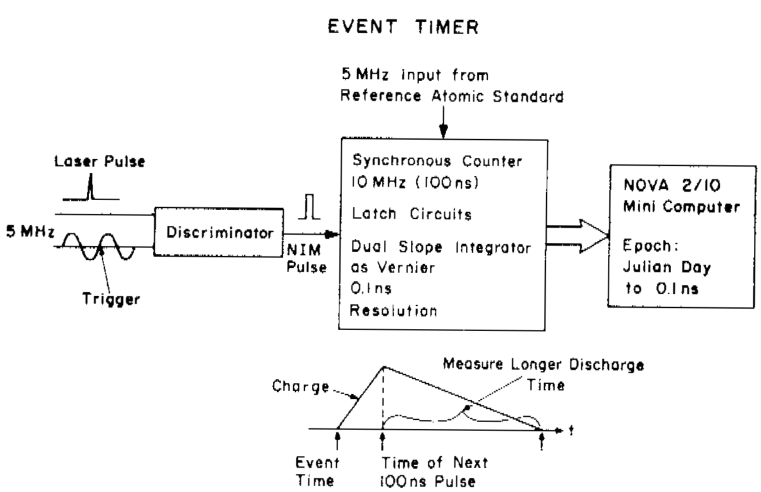

Fig. 8. Operation of the event timer.

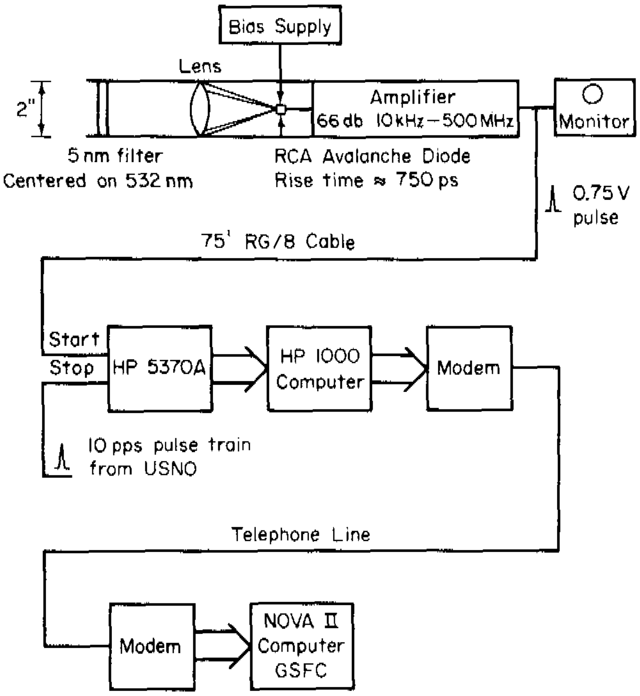

Fig. 9. Instrumentation at the USNO.

Instrumentation at the USNO

Figure 9 is a block diagram of the equipment installed at the Time Services Division of the USNO. The detector is an RCA C30902E silicon avalanche photodiode of the same type used in the LASSO instrumentation (reference 2). It has a rise time of 500 ps. We chose it rather than a faster detector in order to gain experience with the expected performance of the LASSO equipment. A 5 nm band pass spectral filter precedes a 2-inch diameter lens which focusses light on the diode. Provision is made for adding neutral density filters. The fluctuations in amplitude of the laser pulses reaching the detector are quite large due to scintillation effects in the 26 km air path across Washington. (It is interesting to note that in transmitting to space, the vertical scale height of the atmosphere is only 7 km). The wide band amplifier, similar to that in the LASSO equipment, produces a rise time of about 750 ps, and drives a typical 0.75 v pulse down 75 feet of low loss RG/8 cable to start a HP 5370A computing counter. The stop pulse for the counter comes from the 10 pps train of the USNO Master Clock. The measured arrival time of each laser produced pulse at the counter with respect to the Master Clock can be stored in an HP 1000 computer. This computer can be accessed by telephone connection from the NOVA computer at the GORF site and instructed to create a data file which is then transferred from the USNO. These are the times "t" to be compared with the times "t_1" and "t_3" defined above in the description of the Einstein Prescription. This analysis is done by the computer at the GORF site.

ANALYSIS OF TYPICAL DATA

The expected return from the LASSO retro-reflectors on the SIRIO-2 satellite in synchronous orbit was at the single photo-electron level. That is, not every firing of the laser would produce a detected return event, and one must treat the returns in a statistical way, there being only a probability of detection for each shot. To simulate this condition we are able to add neutral density filters in front of the photo-multiplier. This is necessary only when the visibility is very good -- on the order of 15 to 20 miles. For poorer visibility the single photoelectron detection must be used with zero attenuation. We try to simulate the LASSO return with a probability of about one detection in ten shots.

Under these conditions it is convenient to take advantage of the constant distance for the horizontal timing link. (The distance to a synchronous satellite is also approximately constant for short times; for longer times one could fit a smoooth curve to the measured range). We measure first the two-way time delay (range) in a statistical way. Then one half of this value is taken as the one-way time delay and used to identify "matches" between the epoch t_1 of the sending event and the epoch t of the pulse arrival at the USNO. This allows a determination of the time difference between the clock at the GORF and the Master Clock at the USNO. A typical time transfer is carried out with 1000 transmitted pulses, requiring 100 seconds at the 10 pps firing rate. Midway into the run, the HP1000 computer is instructed to record epochs of arrival of pulses at the USNO for the next 100 transmitted pulses and to transmit these back to the NOVA computer, creating a data file. (Because of scintillations at the USNO detector, a few of the pulses are not detected.)

Some analyzed results from time transfers carried out 14 minutes apart during the evening of 2 July 1982 are shown in Figures 10 and 11 (draftsman's copies of the display on the Tektronix graphics terminal attached to the NOVA 2/10 computer). The top histogram in each figure shows the distribution of the round trip time measurements. In our earlier notation, the measured quantity is

$$(t_3 + \tau_{in}) - (t_1 - \tau_{out}).$$

The bottom histogram in each figure shows the distribution of the measured time difference between the USNO and the GORF. In our earlier notation, the measured quantity is

$$t - \left[(t_1 - \tau_{out}) + \langle (t_3 + \tau_{in}) - (t_1 - \tau_{out}) \rangle_{AV}\right].$$

For each of the time transfers, an attenuation of the returned signal by N.D. 3.5 (approximately 3×10^3) was imposed to obtain single photoelectron detection.

For the earlier time comparison of Figure 10, 55 returns were recorded out of 1000 shots yielding a measured round trip time of 174.3291 μs with a standard deviation of 690 ps. The spread in the distribution is caused primarily by the jitter in the transit time in the photomultiplier detector

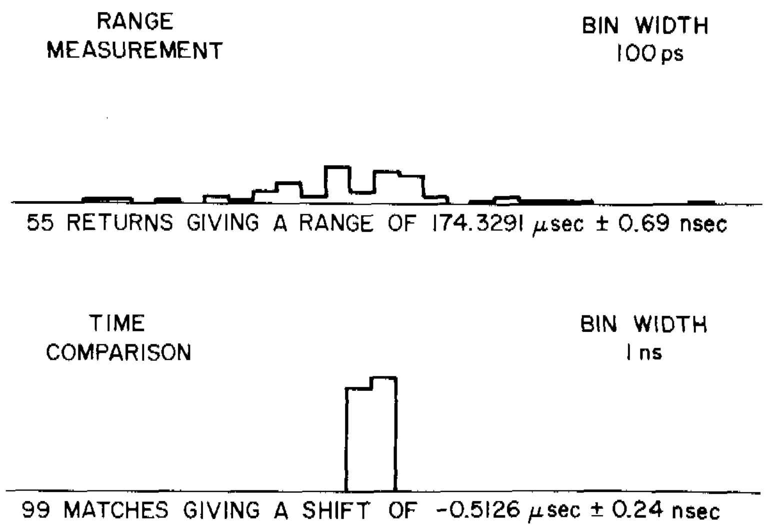

Fig. 10. Time Transfer on 2 July 1982 at 04:32 UTC.

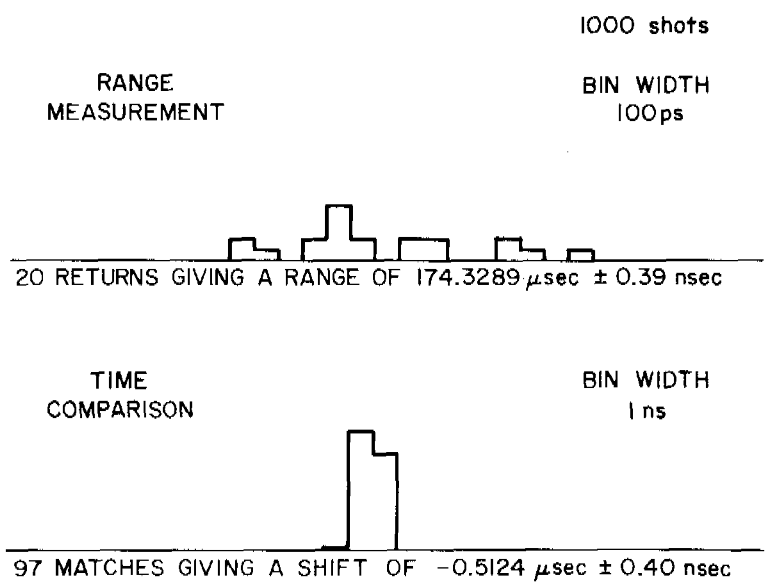

Fig. 11. Time Transfer on 2 July 1982 at 04:46 UTC.

operating at the single photoelectron level. The spread in the distribution of time comparisons is somewhat tighter since no single photoelectron detection is involved. For 99 matches, the standard deviation is 240 ps about a mean time difference of -512.6 ns.

For the later time transfer, shown in Figure 11, atmospheric conditions had deteriorated somewhat and only 20 returns were detected out of 1000 shots. The measured round trip time was 174.3289 μs with a standard deviation of 390 ps. There were 97 time comparisons, giving a mean time difference of -512.4 ns with a standard deviation of 400 ps. The two measurements are consistent.

The standard deviations of the mean for the two time comparisons are 24 ps and 41 ps respectively. Most of the spread in the distributions is thought to be caused by the detector electronics at the USNO as influenced by the scintillation induced intensity fluctuations in the light pulses. We intend to install a faster detector and circuits whose delay is less sensitive to amplitude changes. Also in the future, we intend to replace the photomultiplier detector with another photomultiplier having faster response, less jitter, and higher quantum efficiency.

If the Einstein prescription for time comparison were used directly with the above data, only 55 comparisons in the first run and 20 in the second run would be possible. This would not matter if the measured distributions had very small dispersions, but with the present detectors the incorporation of the measured round trip time is desirable. In addition, use of the Einstein prescription would have required that the arrival times at the USNO be recorded for each of the 1000 transmitted pulses and sent back to the GORF instead of recording and sending back the 100 pulses in the middle of the sequence.

Calibration of the laser timing link has been accomplished so far only by a clock trip of about 30 minutes duration between the USNO and the GORF. The portable clock was compared directly with the USNO Master Clock at the HP5370A computing counter and by means of the event timer at the GORF with the HP cesium beam clock at that site. These are the basic reference points for the time comparison. The stability of the clock during the trip, estimated at 1 to 2 ns, gives the level of calibration. We plan to make measurements of the actual delays between the optical detectors and the basic reference points. It is hoped that these delays can be determined to 0.1 ns. The laser pulse link alone could then establish synchronization at this level which would require allowance for the East-West asymmetry in the speed of light mentioned earlier as a footnote to the discussion of the Einstein prescription for time comparison.

PHOTOGRAPHS OF THE EQUIPMENT

The details of experimental equipment are often best shown by actual photographs, which also convey impressions not achievable with words and drawings. The following series of pictures traces the path of a photon participating in the light pulse time time transfer as the photon itself might see it.

Figure 12 is a cutaway artist's drawing of the 48-inch (1.2 m) precision tracking telescope at the GORF.* The optical path through the telescope shown in Figure 6 can be better understood by comparing it with Figure 12. The computer controls for directing the telescope are in the room to the left. Our event timer and related equipment are located in a trailer parked adjacent to the dome on the right.

Figure 13 shows the Newport Research optical table on which the equipment of Figure 5 is located. The electronic equipment of Figure 7 is in the rack under the table. The enclosure on top of the table contains filtered air to protect the optics.

Figure 14 shows the water tower on the horizon 3.3 km from the telescope as seen through the dome opening.

Figure 15 is a picture of the water tower. The 30 cm mirror mount can been seen on the left inside the catwalk. The ladder for climbing the tower is hidden by the trees.

Figure 16 is a view of the water tower mirror mount with the front removed from the aluminum box which protects the mirror from the weather. The finely adjustable mirror mount was made by Aerotech. The micrometers for rotating about the horizontal and vertical axes can be seen at the bottom of the mount.

Figure 17 is a picture of the National Cathedral as seen on the horizon from the water tower. Because the cathedral is on a hill, the top of its tower is slightly higher than the Washington Monument.

Figure 18 is a picture of the cathedral tower taken from the ground showing the parapets between which the laser pulses enter and leave. The mirror mount cannot be seen from the ground.

Figure 19 shows the mirror mount on top of the brick stairwell enclosure. This is a very solid structure containing a spiral staircase. The adjustable mount for the mirror is identical to the one on the water tower but houses a 25 cm (10 inch) flat mirror. The reason for the difference in sizes is that these mirrors were available from the beam directing optics used in the aircraft relativity experiments with atomic clocks performed in 1975 and 1976, described in references 1 and 7, and also at the last PTTI meeting.[10]

* We are very grateful to Michael Fitzmaurice, John Degnan, and others of the Optical Instrumentation Branch of the Goddard Space Flight Center for kindly allowing us to use this excellent facility.

[10] C.O. Alley, "Introduction to Some Fundamental Concepts of General Relativity and to Their Required Use in Some Modern Timekeeping Systems," Proceedings of the Thirteenth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting; NASA Conference Publication 2220, pp. 687 - 724, December 1 - 3, 1981.

Figure 20 shows the domes of the USNO framed between parapets with the Kennedy Center and Potomac River in the background. The small dome in the center is on top of the Time Services Building and contains the detector and corner reflectors. Spectacular views of Washington are seen from the top of the cathedral.

Figure 21 shows the dome on the roof of the Time Serves building. The detector/reflector combination is mounted on an unused telescope mount in the center, as seen in Figure 22. The detector/amplifier assembly shown in Figure 9 is in the cylinder at the top left. The two corner reflectors are at the top right. They are the same ones used in the aircraft time transfer experiments described in references 1, 7 and 9 and are mounted in the housings constructed for the outside of the aircraft. The lower panel of reflectors was lent by the Marshall Space Flight Center as part of the studies for the STIFT experiment. It is not presently used.

Figure 23 shows the top of the cathedral above the trees as seen from the roof of the Time Services Building. The green laser flashes come from between two smaller parapets at the right.

Figure 24 looks toward the water tower from the top of the cathedral. Since the water tower does not project above the horizon it is not distinguishable at its distance of 21.6 km in this daytime photograph. However at night, when the laser beam is correctly pointed, the green flashes are by far the brightest light in the whole Washington area.

The final picture in the series, Figure 25, is a reflection in the water tower mirror of the many domes at the Goddard Optical Research Facility. The large dome on the right, just to the left of the dome on a tower, contains the telescope where the trip began, which is also the final destination for the photon.

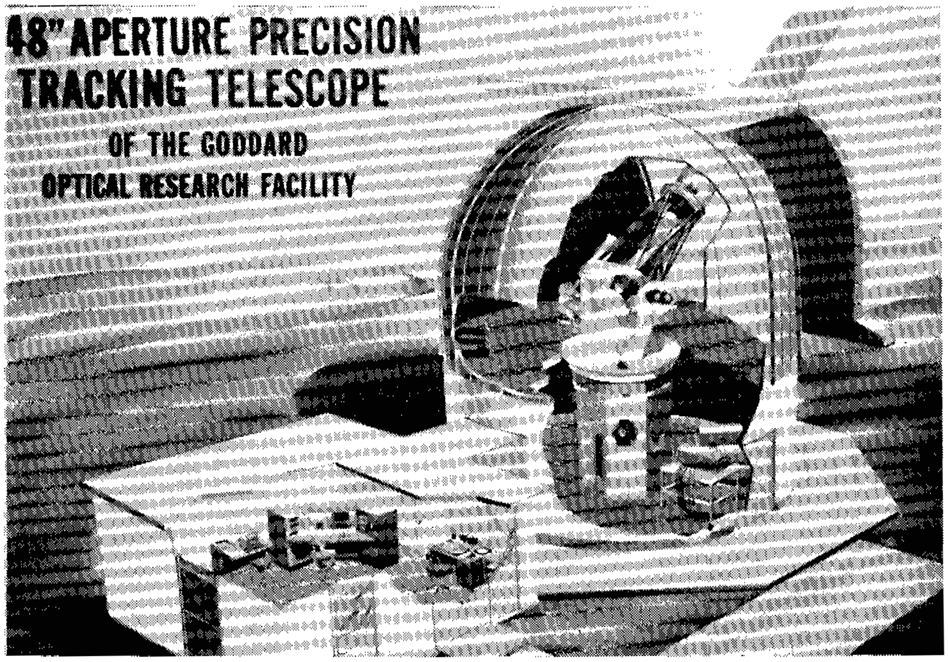

Fig. 12. Transmit/Receive telescope at the GORF.

Fig. 13. Optical and electronic equipment for transmitting and receiving laser pulses.

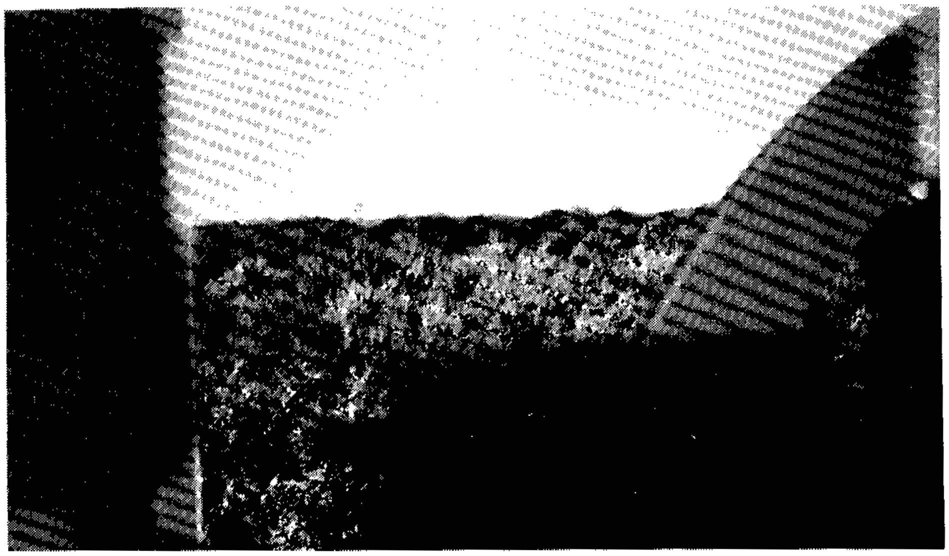

Fig. 14. Water tower seen from the telescope.

Fig. 15. Water tower seen from near its base.

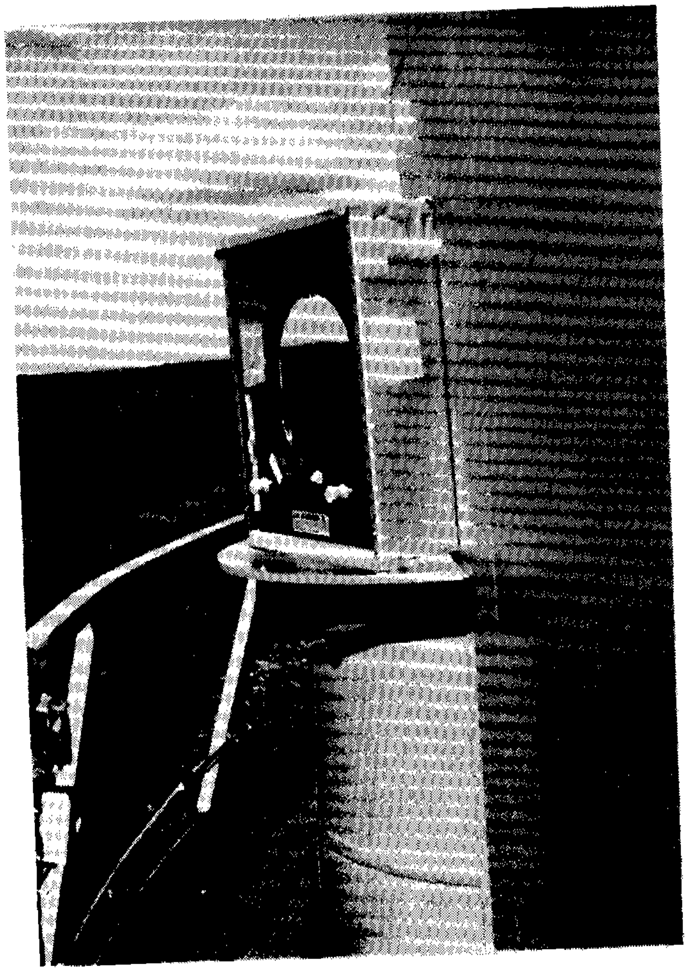

Fig. 16. 30 cm mirror on the water tower.

Fig. 17. National Cathedral on the horizon as seen from the water tower.

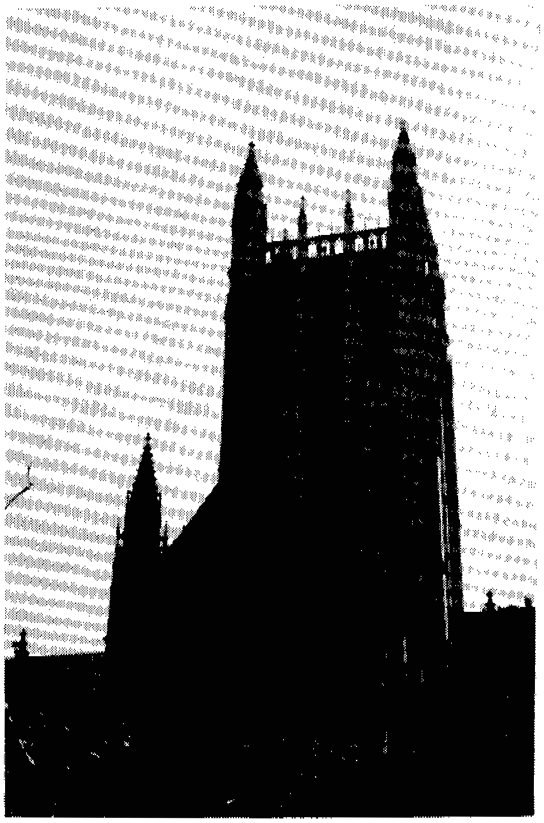

Fig. 18. Cathedral tower

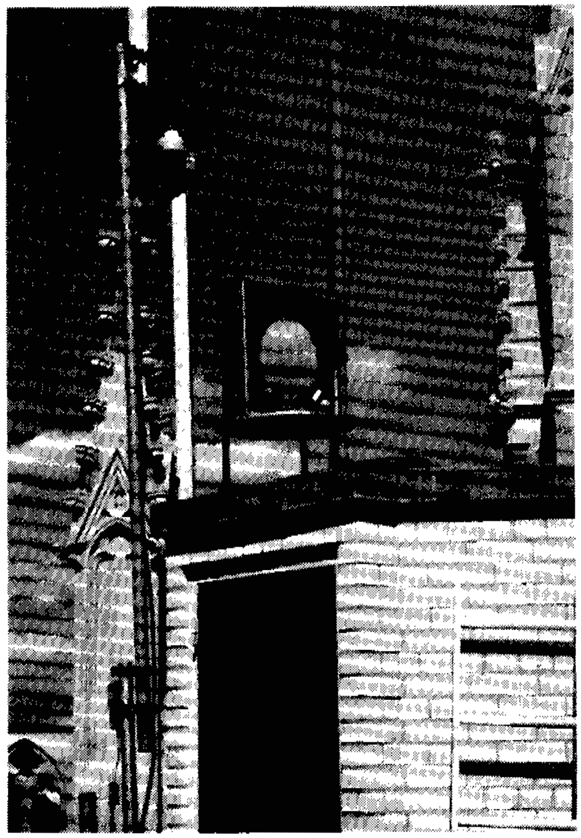

Fig. 19. Mirror on Cathedral tower.

Fig. 20. The USNO from the Cathedral tower.

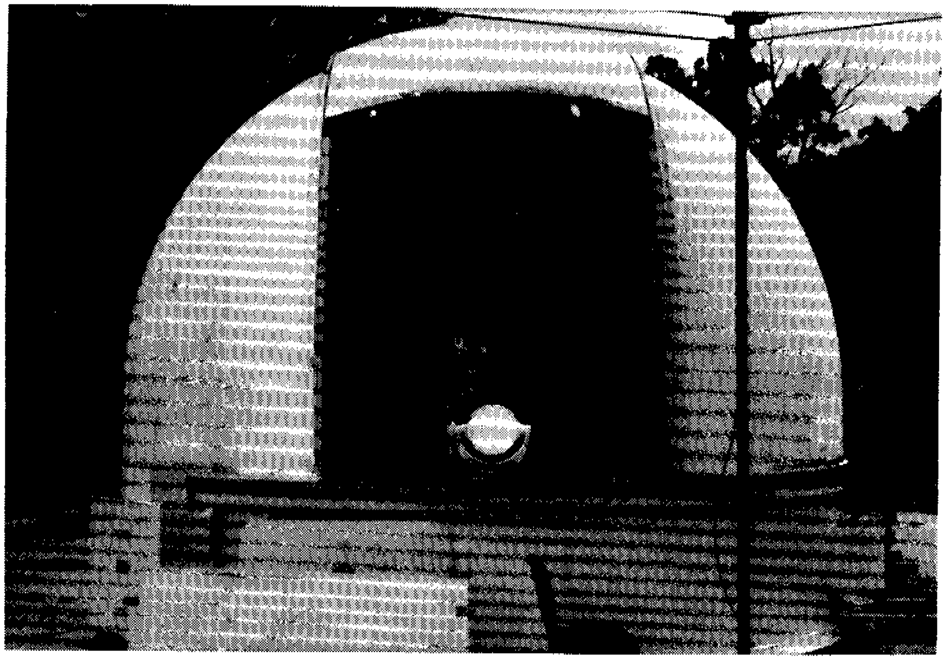

Fig. 21. Dome on the roof of the USNO Time Services Building.

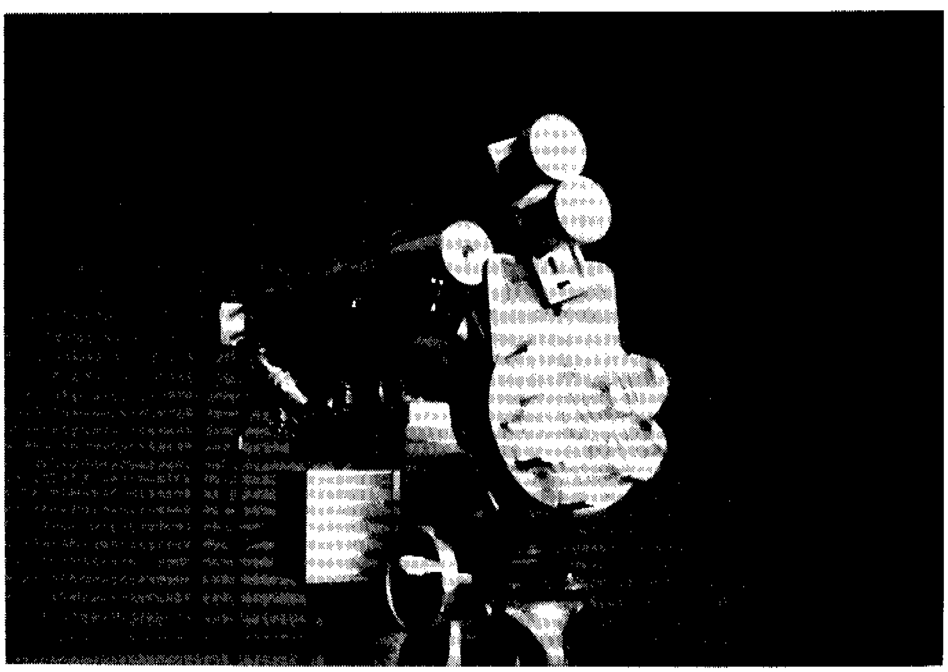

Fig. 22. Detector/reflector assembly at the USNO.

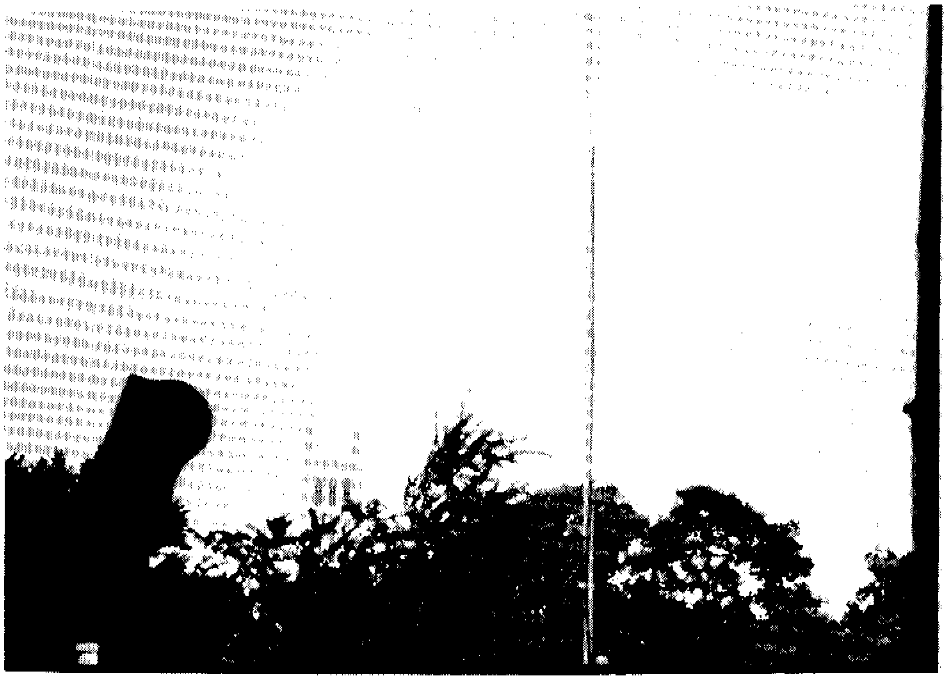

Fig. 23. Top of the Cathedral seen from the roof of the Time Services Building.

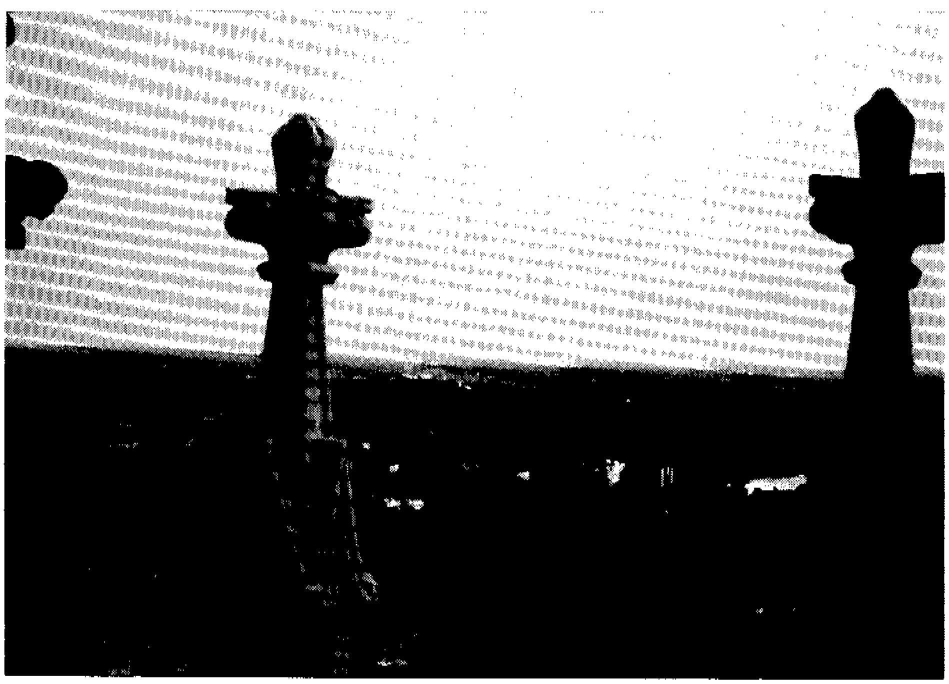

Fig. 24. Looking toward the water tower from the Cathedral.

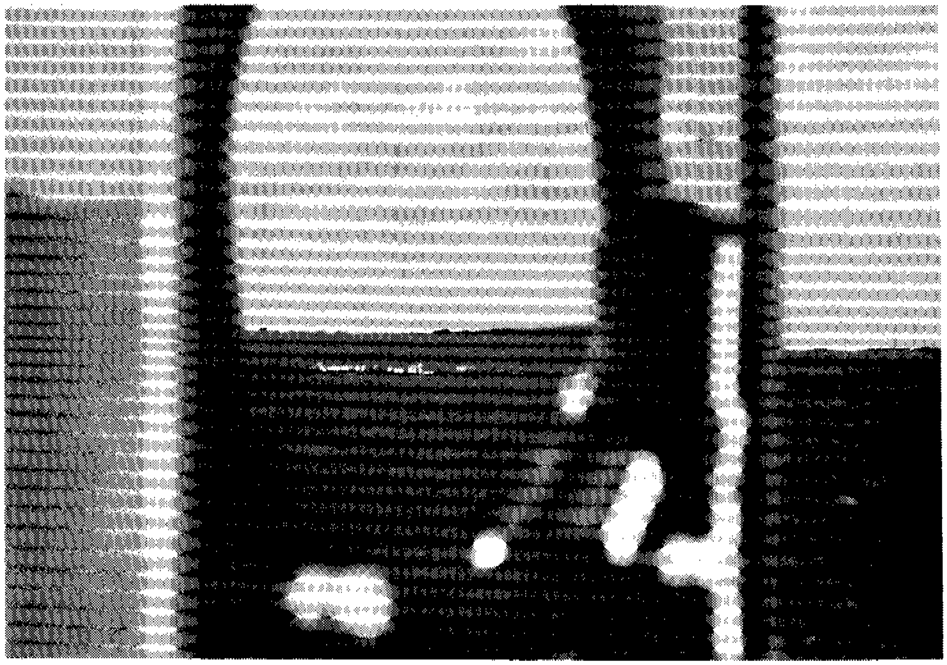

Fig. 25. Domes of the Goddard Optical Research Facility reflected in the water tower mirror.

QUESTIONS AND ANSWERS

DR. KELLOGG:

What's the time constant for aligning the two mirrors that are at D?

PROFESSOR ALLEY:

Oh, No! Our electronics engineer, Mr. Steggerda is also an expert at lining that up and he can do it in a matter of 5 or 10 minutes, I guess. It takes a little longer than that to get all the equipment up on the water tower, and so on. But we typically can get a number of measurements done during an evening's run of several hours, provided the weather permits. We don't have to have freedom from cloud cover. In fact cloud cover is good because it stabilizes these vertical temperature gradients.

MR. KAHAN:

Can you work in rain?

PROFESSOR ALLEY:

No! No!

I should say that we checked with the airport forecasters -- visibility however they define it, and I don't know quite how they define it, but if it's less than 6 miles, we begin to get into trouble. We like to work with visibility of 15 to 20 miles but we can work with 5 or 6 miles. But we cannot work in rain or fog.