Plans to Improve The Experimental Limit in The Comparison of the East–West and West–East One–Way Light Propagation Times on The Rotating Earth

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Abstract

The preceding paper describes the results so far (interrupted in the Spring of 1989 because of lack of funds) of an experiment comparing the one-way light propagation times on the surface of the rotating Earth. For the 20 Km path length component in the East-West direction the predicted difference between the opposite sense propagation times would be 160 ps, if the ≈ 360 Km/s surface speed of the Earth gives effective light speeds of $3x10^8$ m/s $\pm$ 360 m/s. This could lead to a prediction of the difference between the clock transport and the light pulse synchronization methods described in the preceding paper: $\Delta T = 0.5\ (160) = 80$ ps. The current upper bound of ≈ 100 ps for Δ T is limited by poorly understood systematic errors. The most important seems to be intensity–dependent time delays in the remote light pulse avalanche photo-diode detector. This will be replaced by a continuously operating circular scan streak camera having single photon sensitivity and a time resolution of ≈ 5 ps. (This camera has recently been developed by the Xian Institute of Optics and Precision Mechanics in the P.R.C.). Better isolation from shocks and vibration for the Sigma–Tau hydrogen maser during transport will be provided. It is hoped that $\Delta T < 20$ ps can be achieved.

Introduction

The experimental results reported in the preceding paper[1] and in greater detail in the Maryland Ph.D. dissertation of R.A. Nelson[2] are, we believe, the most precise comparisons of remote clocks ever achieved, both for the clock transport method and for the laser light pulse method. The experiments are also the first ever to measure directly the difference in the one–way propagation times of light pulses for the East-West and West–East directions between two fixed points on the rotating Earth. Several experimental difficulties have limited the comparison to an uncertainty of $\approx$100 ps. These will be discussed briefly. Improved techniques which may overcome them and allow an uncertainty of only 10-20 ps will be described.

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Why the Measurements Need To Be Improved

It is important to achieve an uncertainty substantially less than 80ps in the quantity ΔT defined below. This is the predicted value *if the local group velocity of the short light pulse is not isotropic* but exhibits a vector composition with the local surface velocity of 360 m/s. Let t_1 be the epoch of the transmission of the light pulse, t_2 be the epoch of reflection and detection at the remote site, and t_3 be the epoch of reception back at the initial site. We analyze the measurements in terms of the difference ΔT between the direct reading on the transported clock t_2 and the Einstein special relativistic prediction for the reading of the remote clock in terms of the times t_2 and t_3

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

This can also be expressed in terms of the local speeds of light *if* these are different, having the value $c \pm r\omega$, where r is the distance to the spin axis of the Earth and ω is the angular velocity of the rotation. Let L be the projected path in the East–West direction. Then

$$\Delta T = \frac{1}{2}\left[\frac{L}{c - r\omega} - \frac{L}{c + r\omega}\right] \simeq \frac{Lr\omega}{c^2}$$

[In the preceding paper[1], the product Lr is written as 2A where A is the area of the isosceles triangle with side lengths L, r and r.]

Some of the scientific reasons for performing these one–way light propagation experiment from the standpoint of fundamental physics were given in the PTTI report in 1988 [3]. Let us here note only that actual experiments with atomic clocks and laser light pulses can, and must, play a crucial role in securing our knowledge for the formation of appropriate concepts in a complete and *correct field theory of space, time and gravitation. This could be analogous to the role played by* experiments on electric and magnetic phenomena in the 19th century (e.g. Faraday's iron filings, induction, etc) which led to Maxwell's theory of the electromagnetic field.

On the practical side, the Global Positioning System will not perform at its full accuracy unless the correct relativistic physics is used in the interpretation of the measurements. Let it be noted that in 1976 a mistake in the planned implementations in the GPS of the effect of the gravitational potential difference between the clocks in the space vehicles and those on the Earth was identified by Leonard Cutler, Gernot Winkler and the first author of this paper. This mistake was revealed during discussion after the presentation of the results of our proper time experiments with atomic clocks in aircraft [4,5,6]. It was planned to correct twice for the effect: first, by reducing the rate of the orbiting clocks by a physical offset, and, second, by wrongly allowing for a violet shift even after the physical offset. It took several years for the mistake to be corrected. (Some details are given in references [5] and [6]).

The method of interpreting monitor station measurements currently used by the control-segment of the Global Positioning System may be assuming an anisotropy of the speed of electromagnetic wave for the local observers. If this is not the correct physics, it may be one of the sources of systematic error in the GPS/Navstar performance.

The concern about this matter is caused in part by paragraph 20.3.3.4.3.5 in the Interface Control Document 200:

Geometric Range: The user shall account for the effects due to Earth rotation rate (reference Table 20-IV) during the time of signal propagation so as to evaluate the path delay in an inertially stable coordinate system.

The actual measurements by monitor station or users are, of course, made on the surface of the rotating Earth, a non-inertial system. The quoted paragraph is not very clear. One interpretation could be that for such observers the effective speed of signal propagation is $c \pm r\omega$. The interpretation of the measurements by the GPS control segment and the transformation to the Earth Centered Inertial Frame where calculations are done, are being actively investigated.

Effects of the Atmosphere

The total horizontal one-way path is about 27 km which amounts to some 4 vertical scale heights of the atmosphere. The additional contribution of the index of refraction, n (n-1 $\approx 3\times10^4$), to the 87 μs one-way time is 26 ns. However for the difference in one-way times which we are measuring, this contribution cancels if there is no change in the optical path in the atmosphere during the 174 μs round-trip time. It is generally accepted from studies of atmospheric fluctuations related to astronomical "seeing" that vertical paths require more than 2 ms to change appreciably. The scatter in our optical time comparison is about the same for the calibration measurements, with a path length of only a few hundred meters as for the remote measurement (see plots in the Appendix to [1]). This gives some confidence that the outgoing and incoming atmospheric delays are the same. The optical path over the city of Washington is far from the ideal location for this experiment. A path over land not occupied by people, or, of course, in an evacuated pipe, would be much better.

Brief Discussion of Sources of Error

Examination of the plots of measurement residuals for the nine trials given in the Appendix to the preceding paper [1] shows that the scatter in the optical comparisons is much larger than the hydrogen maser phase comparison during the calibrations. The traveling maser was compared with other masers at the USNO during the dwell time there and always exhibited good phase stability, but there was no way of determine whether a rate change had occurred during the transport of sufficient size to produce a significant offset. The good parabolic fits suggest that clock performance during transport was not a major source of error.

We suspect that the large fluctuations in intensity of the detected laser pulses, produced by the different optical paths from pulse to pulse (10 Hz laser repetition rate), each with a different spatial mottling pattern, are the major source of error. The cooled avalanche photodiode used as the t_2 detector exhibited sufficiently large intensity dependent time delay for this explanation to be plausible. However these delays have not been adequately understood or characterized.

Attempts were made during the optical measurements to keep the average intensity on the detector constant by visually monitoring the pulse heights on an oscilloscope and adjusting an aperture before the focusing lens of the detector. Inspection of the plots in the Appendix to the previous paper [1] shows that this technique still allowed substantial variation in timing from one 1,000 transmission shot average to the next. The points are the average values and the error bars represent the standard deviation of the mean for the completed triplets t_1 , t_2 , t_3 . Due to the fluctuations many t_2 and t_3 events were not recorded.

One can ask whether the two event timers were performing correctly, the epochs t_1 and t_3 being recorded by the stationary event timer, and the epoch t_2 by the traveling duplicate event timer. There is a known temperature dependence on delays in these instruments but each was kept in a temperature controlled enclosure whose temperature was continuously monitored and kept within sufficient limits [2].

Planned Improvements

The major change will be the replacement of the t_2 and t_3 detectors by circular scan streak tubes containing tandem microchannel plate amplifier structures giving them sensitivity to single photoelectrons and a large dynamic range. The circular scan driven from a hydrogen maser avoids the start jitter in linear scan streak tubes and will serve as a vernier with ≈5ps resolution for the associated event timer. The readout will be by a CCD camera. All photoelectrons produced by the detected pulse (subject of course to the quantum efficiency of the S20 cathode) will be recorded. The centroid can be measured and the problems associated with triggering on the leading edge of pulses undergoing large intensity fluctuation largely avoided. These tubes are made by the Xian Institute of Optics and Fine Mechanics in the People's Republic of China. The Director of this Institute is Professor Hou Xun and the principle streak tube scientists are Drs. Niu Hanben and Zhao Jilai. No other streak tube manufactures can match the combination of circular scan and single photoelectron sensitivity. A schematic diagram of the instrument and its specifications are given at the end of this paper. It is hoped that this technique will solve the problem of intensity dependent time delays. It will also improve the event timing resolution from the current value of 20 ps to 5 ps. A prototype tube is being tested now in our laboratory.

We are also pursuing an interim approach to this optical timing problem. This is to experiment with superior performance avalanche photodiodes and active quenching circuits [7]. The diodes have been kindly lent to us by Professor Sergio Cova of the Polytechnical University in Milan and the experimental studies are just beginning in our laboratory.

The laser pulse duration used in the experiments so far has been on the order of 75 ps when it was will adjusted. We plan to use known techniques to reduce this to 35 ps. It is possible to reduce it further to 10 ps but this may not be effective because of the dispersion of the atmosphere which will increase the pulse duration.

During the nearly four years since the experiments were interrupted, the performance of Sigma-Tau hydrogen masers has improved and we hope that one of the latest models for use as the traveling clock can be kindly lent to us again by the Time Services Department of the U.S. Naval Observatory. We also plan to add an air suspension to the van which transports the clock and to provide better temperature control and mechanical isolation for the clock box. These measurements may allow the relativistic effects on clock transport which we know to exist from our early aircraft flights [4, 5, 6].

$$\Delta t_{rel} = \int \left(\frac{\Delta\Phi}{c^2} - \frac{1}{2}\frac{\nu^2}{c^2} \right) dt \cong 50 \text{ ps}$$

to be definitely observed in the ground transport. To this end we shall consider adding a GLONASS or GPS receiver to the van to aid in performing this integral.

Acknowledgments

We thank again the many members and institutions within the PTTI community who have supported our investigations. These are detailed in the preceding companion paper [1]. Here we wish to acknowledge with gratitude the new support of the Federal Aviation Administration Satellite Program Office and the AirForce Space Command whose joint Grant (FAA 92-G-0025) is allowing renewal of these experiments.

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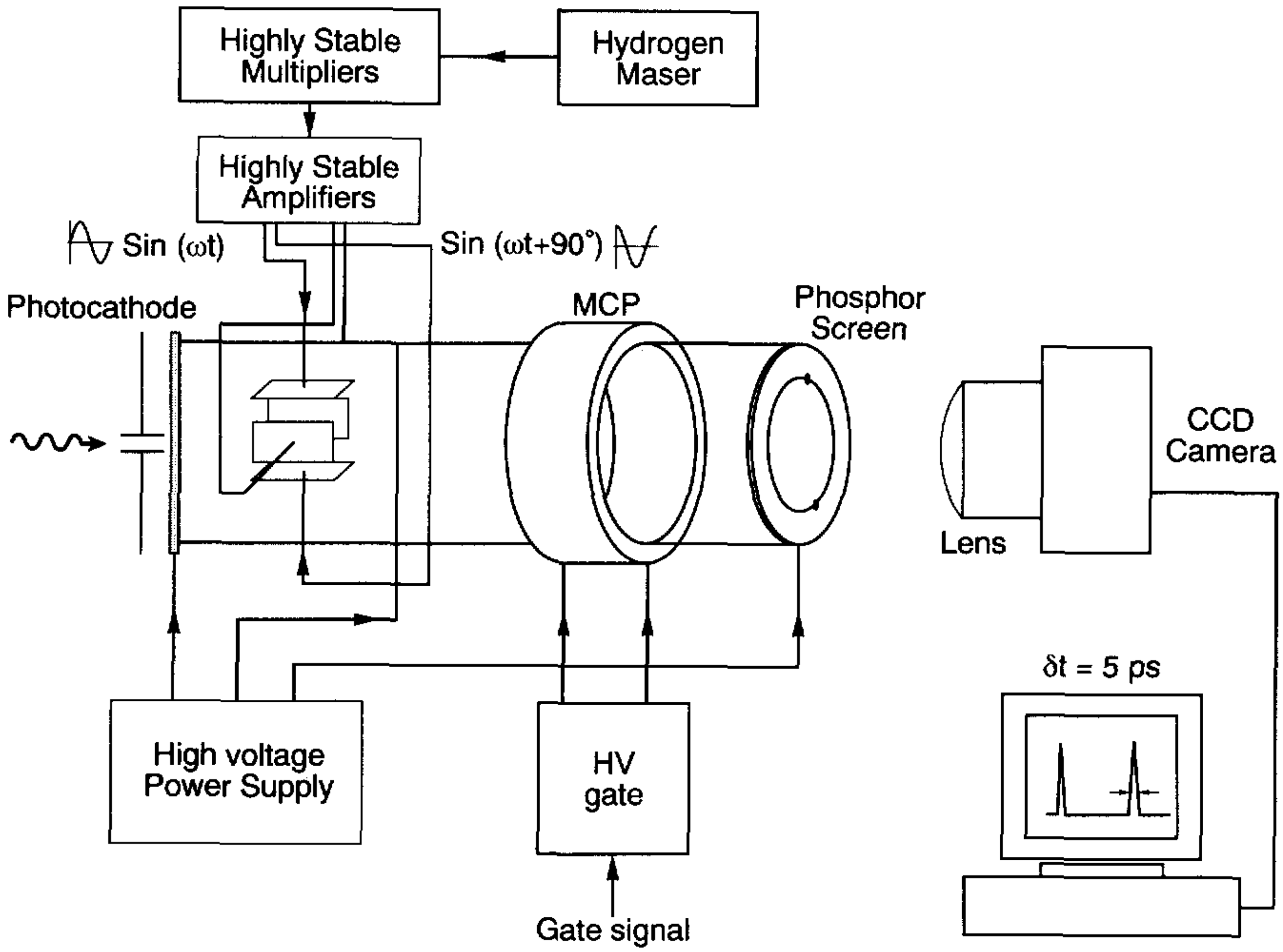

Schematic Diagram of Circular Scan Streak Camera

Specifications

24 mm diameter circular scan

2 watts rf at 300 MHz

2 MCP's in series: gain ≅ 10^6

Photocathode: S20

Photocathode sensitivity:
67 μA/lumen

Wavelength Range: 200-850 nm

Photocathode active area:
12 mm diameter

Phosphor: P20

Phosphor active area: 24 mm diameter

Deflection sensitivity: D_1 9.4 cm/kv
D_2 11.2 cm/kv

Space resolution: 24 line pairs/mm

Dynamic range: >390:1

Time resolution: 4.8 ps (test result)

Working frequency: 300 MHz

QUESTIONS AND ANSWERS

J. Levine, NIST: We have been in the Laser distance measurement business for a number of years. One of the problems that you may be facing is the anistropy in the index of a fraction in the two directions. It is an equivalent of multipath, and it does not quite cancel forward–backward because the air near the transmitter counts more than the end near the receiver. The problems are a lot worse on horizontal path than on a vertical path. Lunar ranging is not really subjected to the same kind of problems so that problem is a lot easier. My guess is at the end of the day it is going to cook you, because it varies quickly and it's not the same in both directions.

C. Alley: Yes, I appreciate your comments. I am well aware of the extra work you have done over the years and with welcome some further discussion. Do you find a change faster than 200 microseconds at the telescope? You find it does change appreciably in that time?

J. Levine: That is the order of the speed.

C. Alley: Our fundamental cycle time is 250 microseconds and that is just about fast enough. There were times when our data was changing faster than that and we have to drop the data out.

J. Levine: I think you are going across the city and that is much worse.

C. Alley: That is right; it makes it worse. We would be much better out west where you are, but we are trying to do something with what we have available.

J. Levine: I understand that, but at the end of the day, I think you are doing remarkably well but guess is you will not get a factor of five or ten times better.

C. Alley: I would hope you are wrong. We will find out, but you make a very relevant observation. Obviously, there is more that needs to be discussed.

H. Freer, Falcon AFB: Did you control your atmospheric temperature & humidity or try to control it and what kind of limits did you address in your varying measurements?

C. Alley: Controlling the atmospheric temperature where?

H. Freer: In other words did you take one reading at 6 AM when it was 50 degrees in Washington, another at 2 PM when it was 80 degrees, one when it was humid, and one when it was not humid?

C. Alley: There were very stringent conditions on when we could actually do these measurements. We had to have visibility of about 10 miles before we could even get enough signal coming back. We did record some of these meteorological variables. Unfortunately we can not control the weather, we have to wait until we get reasonably good conditions and these nine or so reasonably successful trips were out of maybe 15 actual all night sessions and out of many more of attempted and aborted measurements. So we probably should wait until the conditions are comparable and good and so on but we have not had that complete luxury. When we borrowed the clocks from the National Radio Astronomy Group we had them for a very limited period. They kindly extended that period twice but we had to make the measurements as we could and get them back. I hope in this next round we might have a somewhat more leisurely opportunity and can make some of the control that you have sensibly suggested.