

A NEW TEST OF RELATIVITY*

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ABSTRACT

A new fundamental test of Einstein's theory of special relativity is currently underway, employing instrumentation of the National Aeronautics and Space Administration Deep Space Network (DSN) and the Global Satellite Positioning System (GPS). The scientific objective of this experiment is to search for a possible spatial variation of the one-way velocity of light. The experiment involves monitoring over a full rotation of the Earth the time of flight of laser pulses transmitted along optical fibers connected to hydrogen maser clocks separated by several kilometers. These clocks are additionally compared by radio link using GPS satellites. This unique experimental configuration, coupled with state-of-the-art technology, allows us to test precisely the assumed constancy of the one-way velocity of light.

I. INTRODUCTION

The determination of the propagation velocity of light is intimately related to the problem of nonlocal clock synchronization. At the most basic level, this interdependence results from the fact that, by virtue of the very definition of velocity, a determination of the velocity of light propagating in a single direction (one-way velocity) requires that spatially separate time measurements be made in order to ascertain the total time-of-flight. In formulating special relativity, Einstein reduced the problem of synchronizing distantly separated clocks to the level of a simple convention: namely, that if we assume the constancy of the velocity of light, then distantly separated clocks may always be synchronized unambiguously by simply propagating a light signal between them. According to the principle of relativity, the Einstein synchronization convention must be valid independently of the velocity of the reference frame of the clocks.^{[1],[2],[3]}

Whether this convention is valid can be tested directly by initially synchronizing two clocks and then comparing them by propagating a light signal between them to see whether the two clocks maintain their initial synchronization independently of their spatial orientation. Until recently, the extremely high velocity of light has prohibited experimenters from performing this direct test meaningfully (see, however, reference [4]). In order to circumvent this difficulty, most previous light propagation experiments have involved propagation in a closed path, the classical example being the Michelson-Morley experiment.^{[5],[6],[7]} Round-trip experiments are limited, however, in that the issue of clock synchronization is completely side-stepped.

In order to perform a more meaningful test of the constancy of the velocity of light, we feel that it is essential to propagate a light signal only one-way between two precisely synchronized clocks. These clocks must have high time resolution and be able to maintain

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synchronization over a time period sufficient to probe all spatial directions. Furthermore, it must be possible to minimize any unwanted effects that may perturb the propagation of the light signal. We are currently involved in performing just such an experiment with the instrumentation mentioned above. The essential details of our experiment and its expected results will be discussed in the remainder of this report.

II. INSTRUMENTATION AND PLANNED APPROACH

At the Goldstone Deep Space Communications Complex, the capability exists now for comparing two atomic hydrogen maser frequency standards separated by a 22 kilometer baseline by using a newly installed fiberoptics distribution link that runs between Deep Space Station (DSS) 12 and DSS 14. The link consists of two identical fibers in a single cable that is buried five feet underground. Calibration for possible variations in the optical path length has been performed. In recent measurements, frequency transfer at a precision of 1.35 parts in 10^{15} over 1000 second averaging times has been verified. For this baseline, the one-way light propagation time is 73 microseconds. With clocks driven by hydrogen maser standards, we can accurately measure time intervals as small as one nanosecond. The clocks employed by the DSN have been characterized to have "jitter" below the 1 nanosecond level. Also, the frequency stability (1 part in 10^{15}) is high enough to allow us to maintain synchronization at this level over twenty four hours; i.e., a full rotation of the Earth.

In performing the experiment, we will locate one hydrogen maser frequency standard at DSS 12 and another identical standard at DSS 14 of the Goldstone complex. These masers can be used to drive Time Code Generators (TCG's), which provide us with ultraprecise local time standards (clocks). Time interval measurements can be made by using Time Interval Counters (TIC's). The TIC's used by the DSN have high time resolution (400 picoseconds for Hewlett-Packard Model 7320), thus allowing us to measure time intervals with nanosecond accuracy. By installing GPS receivers at both DSS 12 and DSS 14, we plan to monitor independently of the fiberoptics link the synchronization of our atomic clocks. The overall experimental arrangement is shown in Figure 1, while the fiberoptics time-transfer method is shown schematically in Figure 2.

With this method, the one-way velocity of light can be monitored by measuring the time-of-flight of time codes transmitted simultaneously along the fiberoptics link between the TCG's and the TIC's at both stations. By making dual time interval measurements as prescribed, it is possible to correct for any errors resulting from transmission over the optical fibers. Time-of-flight data can be collected continuously over a full rotation of the Earth. During this twenty-four-hour observation period, the synchronization of the distantly separated clocks can be compared against GPS time. Additionally, this linkage provides us with a one-way propagation path that is orthogonal to the fiberoptics path. It is also possible to use an atomic cesium-based travelling clock to check synchronization completely independently of light propagation, although this technique is not as precise.

As a second approach, we plan to perform maser phase comparisons in order to improve our overall precision. In performing time transfer over the fiberoptics link, we are limited primarily by two nanosecond clock jitter in the time code generators. However, both the TCG's and the TIC's can be completely side-stepped by directly comparing the masers using vector volt- meters (VVM's) as shown in Figure 3. In this version of the experiment, the laser signal in the optical fiber is amplitude modulated by the maser output frequency (100 MHz). The time-varying light intensity is photodetected and converted into an AC voltage which can be measured by the VVM and directly compared to the maser at the other end of the fiber. The VVM can measure signal phase to within one degree, which at 100 MHz corresponds to a time resolution of 0.03 nanoseconds. Performing simultaneous comparisons in both directions again allows us to detect and remove possible phase fluc-

tuations due to the optical fiber itself. In addition, phase comparisons can be performed simultaneously over the same optical fiber. This version of the experiment constitutes a one-way Michelson-Morely experiment, where the masers provide us with a way to compare precisely the signal phases after propagating the light signal just one-way instead of back-and-forth. Furthermore, this approach provides us with the means to fully utilize the high stability of the fiberoptics link, affording a greater degree of precision with a lesser degree of instrumentation complexity.

III. ANTICIPATED RESULTS

The maser phase comparison method provides the most precise means available to perform the experiment. For a baseline of 22 kilometers, it is possible to test for variations in the optical path length between the two masers at a level of 4 parts in 10^7 . At present, we are concentrating on configuring this version of the experiment. We then hope to repeat the experiment using direct time-transfer and the GPS system as described above as an independent check on our maser phase comparison results. With a two nanosecond limitation, the optical path length between the two stations could be monitored in this way at a level of 3 parts in 10^5 . Either limit would set a new constraint on any fundamental variation in the velocity of light.

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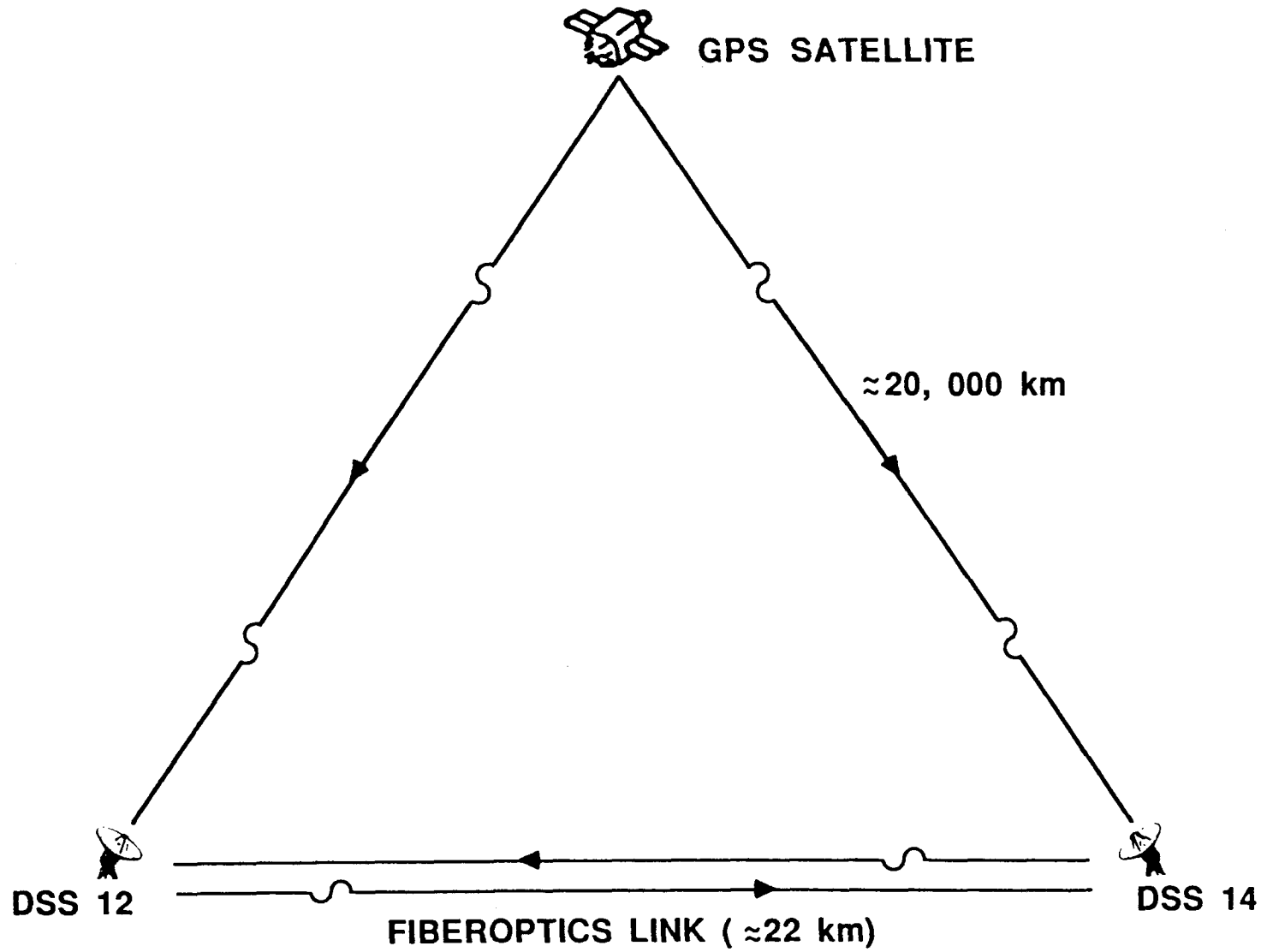


Figure 1. Experimental Arrangement

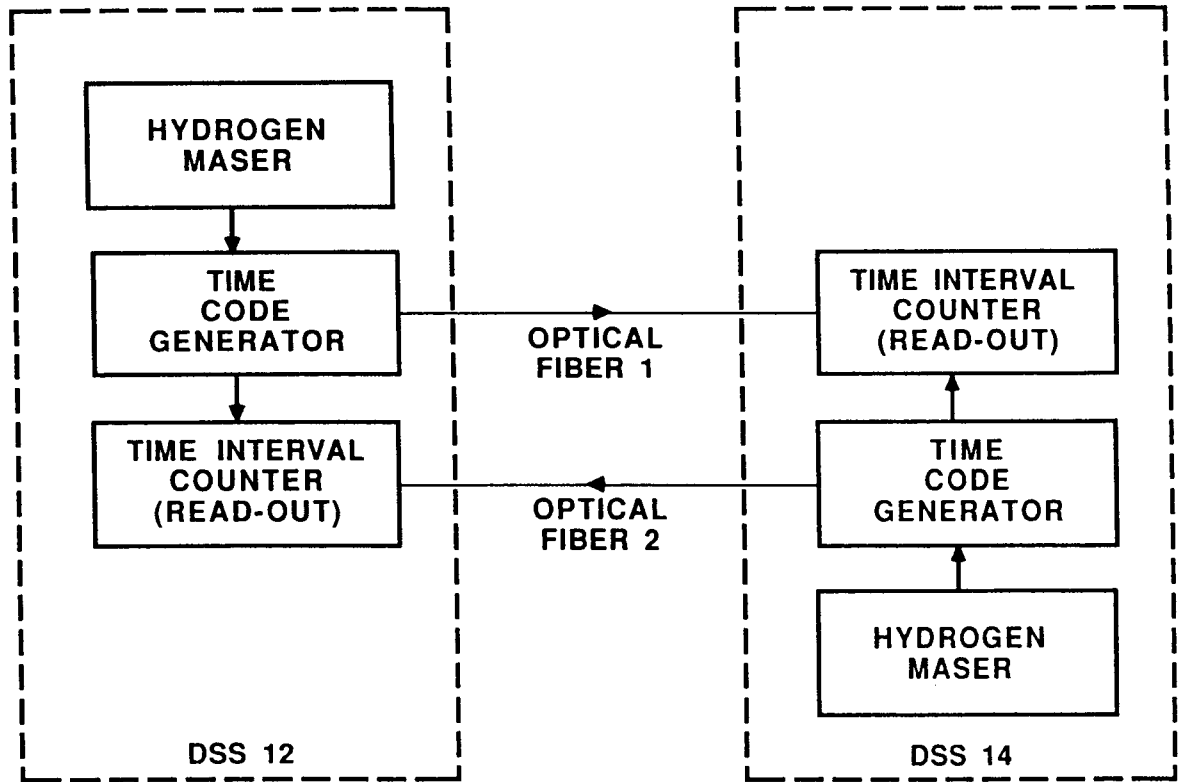


Figure 2. Fiberoptics Time Transfer Method

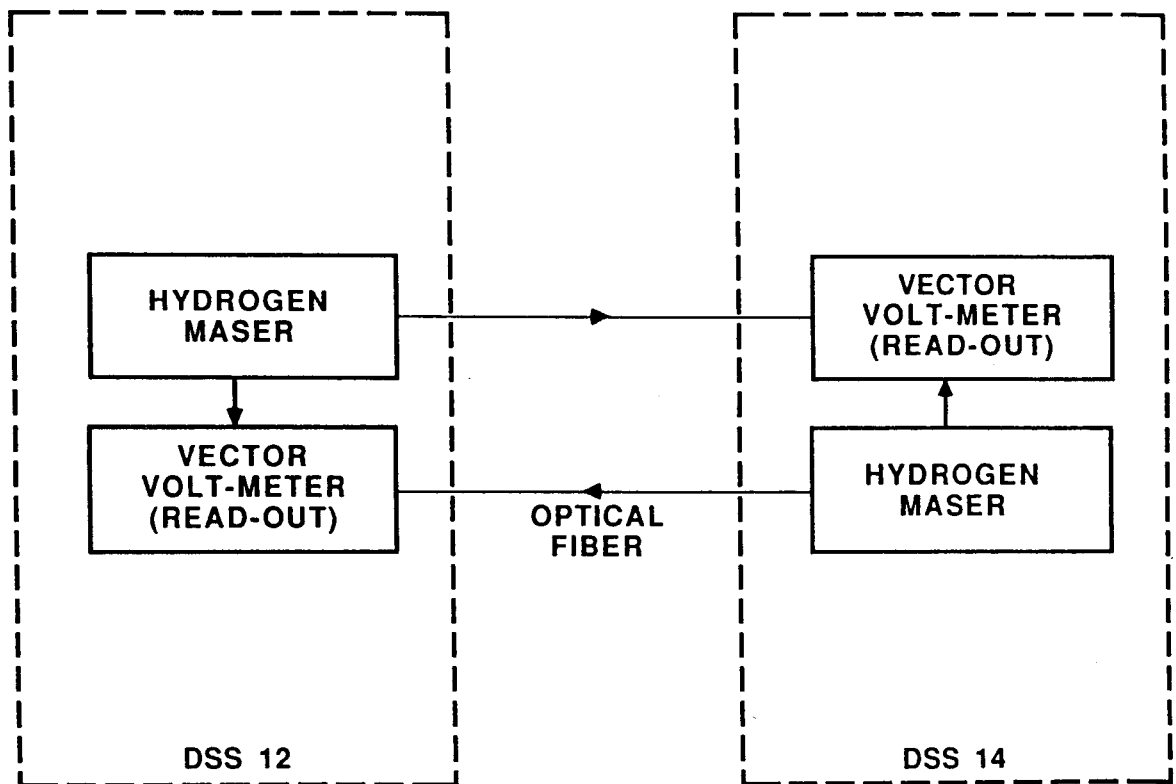


Figure 3. Fiberoptics Maser Phase Comparison Method

QUESTIONS AND ANSWERS

David Allan, National Bureau of Standards: Over such a short baseline, it seems that you should be able to drive the GPS error down, using post-ephemeris and taking full advantage of the knowledge of the ionospheric delays by a two frequency kind of measurement.

Mr. Krisher: We are hopeful that, just because of the short baseline, we would be able to cancel out those types of errors.

Mark Weiss, National Bureau of Standards: I wonder, though, with such a short baseline you are not looking at a very anisotropic view. In other words, you are looking at a very similar path.

Mr. Krisher: I should comment that the fundamental propagation path is along the fiber optics link between the two stations. Our interest in the GPS system is to allow us to monitor the time synchronization between the two clocks independently of the fiber optic link.

Mr. Weiss: So the anisotropy that you are looking for is along the fiber optics.

Mr. Krisher: That's right.

A comment from the audience, not into the microphone, relative to satellite ephemerides.

Mr. Krisher: I am aware of the problems of determining near-earth satellite ephemerides. Perhaps that could be due to relativistic effects, I don't know.

Ken Martin, Bonneville Power Administration: What kinds of differences do you expect do you expect to see in the measurements.

Mr. Krisher: I showed the equations that derive a possible theoretical interpretation for the variation that you might expect if there exists an absolute reference frame, where there is a $\cos \theta$ dependence. That is something that we might want to filter for, but we really don't want to be limited by any of these theoretical models, even models that had been suggested in the past. There is really no theory for this, so we are primarily interested in doing the experiment and seeing what we get.

Gernot Winkler, United States Naval Observatory: I think that that is an excellent attitude. In fact, there is a predominant feeling that certain theories, such as relativity, are so well founded that no more tests are necessary. I think that that is a very superficial view, we can always get an increase in the precision of observations.

Brad Parkinson, Stanford University: This is very interesting. When do you expect to get results?

Mr. Krisher: We are very close. We have been working since July setting up the experiment and positioning the equipment and so forth. We expect to take data involving that second method, using phase comparison, in the next couple of months. We will be taking measurements, trying to refine them and trying to repeat the experiment using direct time transfer throughout our grant period, which is through July of '88.

Ken Uglow, Uglow electronics: Is the Vector Voltmeter accuracy and resolution sufficient, or would you like to do better?

Mr. Krisher: If we could improve on that, it would increase the precision of the experiment. It is my understanding that the VVM's that we have will let us measure phases at the one degree level. We would like to improve on that in any way possible.

Mr. Uglow: Are you aware of the dual mixer technique?

Mr. Krisher: No, I am not aware of that.

Mr. Uglow: Fred Walls can give you information on that.

Frank Matthews, International Telephone and Telegraph: Has the fiber optics link been baselined so that you know what your absolute link is on that? This could be affected by temperature and other things.

Mr. Krisher: I am not directly involved in that work, but I understand that that link has been well characterized. It was installed for the purpose of distributing the frequency of the hydrogen masers throughout the tracking complex. For example, there is an additional link that was installed between two other stations out at Goldstone. The engineers in the DSN have that problem well in hand and understand the way that that link performs under different operating conditions.

Mr. Matthews: You show sending the timing one way between DSS-12 and DSS-14. Have you considered looping that back?

Mr. Krisher: We could do that, but as I pointed out, we feel that that is a fundamental limitation of previous light propagation experiments. Perhaps we might want to investigate the possibility of doing a closed loop experiment, but that is really contrary to the basic philosophy of this experiment. One-way is the key word in this experiment.

Lute Maleki, Jet Propulsion Laboratory: I would like to comment about the fiber optic link, which is what makes this experiment possible. The link is temperature uncompensated and has a stability of 1×10^{-15} over one thousand seconds. This was reported on at the PTTI last year. We are now in the process of developing equipment for characterization of the link to a 1×10^{-17} .