RESULTS OF A NEW TEST OF RELATIVITY*

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Abstract

A modernized version of the classical Michelson–Morley experiment has recently been performed. The purpose of the experiment was to test the constancy of the velocity of light over a long baseline with light propagated one–way instead of back–and–forth. This was performed with instrumentation of the National Aeronautics and Space Administration Deep Space Network (DSN). In particular, measurements were made of the phases of two hydrogen maser frequency standards separated by 29 kilometers by propagating a laser signal over a highly stable fiberoptics cable. Presented are the results obtained for measurements performed continuously during a full rotation of the Earth.

I. INTRODUCTION

Recent developments in the time and frequency technology used by the National Aeronautics and Space Administration Deep Space Network (DSN) have made it possible to compare precisely the phase and frequency of atomic standards separated by several kilometers. In particular, a highly stable fiberoptics network has been installed at the Goldstone Deep Space Communications Complex. A principle advantage of this system lies in the fact that a fiberoptics cable can provide a much more stable propagation path than conventional coaxial cable, microwave link, or waveguides. Because of this attribute, along with high bandwidth, a primary function of the network is to support connected element interferometry for spacecraft navigation and astrometry [1]. Nevertheless, it became clear that the system could also be applied to a possible test of relativity. The test concerns the isotropy of the velocity of light.

Most experiments to test the isotropy of the velocity of light have involved propagation in a closed path over limited spacetime separations, the classical example being the Michelson–Morley experiment ([2],[3],[4]). Because the signal is propagated back–and–forth, two–way experiments are possibly limited, for example, in the sense that it is the isotropy of the average velocity that is tested. There have been attempts recently to test precisely the isotropy of the one–way velocity of light;

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i.e., the velocity of light propagated in a single direction instead of back-and-forth ([5],[6]). However, these experiments did not test the isotropy by propagating a signal one-way between two synchronized clocks. The technology now available at Goldstone has made it possible to perform a precise test of the isotropy of the one-way velocity of light by this approach over larger spacetime separations than has been previously accessible.

The general concept of the experiment was discussed at the previous PTTI meeting [7]. Basically, a fiberoptics cable spanning a distance of 29 kilometers can be used to compare a hydrogen maser at Deep Space Station (DSS) 13 with another hydrogen maser at DSS 14 (see Figure [1]). The cable is buried five feet underground, which helps to maintain a constant and uniform temperature along its entire length, thus minimizing unwanted temperature-dependent cable delays. The relative phases of the 100 MHz output frequency of the separated masers can be measured directly and recorded as a function of time. It can be seen from Figure 1 that the cable provides a propagation path that is mainly along the North-South direction. Nevertheless, the cable spans a distance of about 10 kilometers in the East-West direction. It is this projection of the path in the East-West direction which is most relevant to the experiment, because the orientation of this direction changes with respect to the stars as the Earth rotates in space.

The possible effect of an anistropy in the speed of light on the phase measurements can be modeled at a simple level by considering

$$c = c_0 + \delta(\tau) \tag{1}$$

where c_0 is the average value of the speed of light, or perhaps the value that is determined from laboratory measurements (i.e., $c_0 = 299{,}792{,}458$ m/sec) [8], while $\delta c(\tau)$ represents a generalized perturbation which could vary with time (τ) as the Earth rotates in space. To lowest order, this leads to a phase variation of magnitude

$$|\delta\phi(\tau)| = f(\frac{L}{c_0})\frac{|\delta c(\tau)|}{c_0} \tag{2}$$

where $f = 100$ MHz and L is the baseline pertaining to the possible anisotropy and the geometry of the experiment. Taking $l = 10$ kilometers yields in units of degrees

$$|\delta\phi(\tau)| = 1.2 \times 10^6 \frac{|\delta c(\tau)|}{c_0}. \tag{3}$$

According to special relativity, $\delta\phi(\tau)$ should be zero for all τ. Our goal is to test as precisely as possible the validity of this prediction under the particular conditions of the experiment. A more detailed discussion of the theory underlying a possible anisotropy in the one-way velocity of light is beyond the scope of this report.

For the past year, preparations have been underway to perform continuous phase measurements over several rotations of the Earth. A few tests were performed during this time to evaluate the performance of the system and to determine what improvements needed to be made. Just two weeks before this PTTI meeeting, we were able to successfully run the experiment continuously for nearly five days. In the remainder of this report, we will discuss how the experiment was performed and consider the results of a preliminary analysis of the data that was obtained. The instrumentation and the procedures used in the experiment are described in Section II. Presented in Section III are the results of the preliminary data analysis. Concluding remarks are made in Section IV.

II. INSTRUMENTATION AND PROCEDURE

Illustrated in Figure 2 is the instrumentation that was used to perform the phase measurements. Identical instrumentation was used at each site. The 100 MHz output frequency of the masers was split into two signals. One signal was fed directly into one channel of a Hewlett–Packard 8753A Network Analyzer. The other signal was fed into a fiberoptics laser transmitter, which used the signal to modulate the optical carrier along the fiber. This modulation was detected at the far end of the fiber with a fiberoptics receiver, the output of which was fed into the second channel of the network analyzer at that end. The network analyzers measured the relative signal phase between the two channels. Although the fiberoptics cable contains several single–mode optical fibers, a single fiber only was used in the experiment. Because the 100 MHz modulations from each maser were propagated one–way simultaneously in both directions along the same fiber, isolators were required to separate the received and transmitted signals.

In performing the experiment, the relative signal phases between the two masers was measured once every ten seconds continuously for nearly five days and was recorded as a function of time. The observations began on November 12, 1988 at 20:00:00 (UTC) and ended on November 17, 1988 at 17:30:14 (UTC). An IBM personal computer was used at each site to control the network analyzer and to automate the collection of the data. Simultaneous phase measurements were performed at each site in order to provide the capability to difference the data, which would remove common–mode errors, such as due to maser frequency fluctuations or residual temperature–dependent delays along the optical fiber.

III. PRELIMINARY DATA ANALYSIS

In order to reduce the large volume of data that was generated and to filter unwanted high frequency signatures, the data has been sampled at 1000 second intervals. Plotted in Figure 3 is the resulting phase record obtained at DSS 13 only. (A similar plot results from the data obtained at DSS 14 only.) The linear drift in the phase is due to the slight offset in frequency between the two masers. A record of this frequency offset can be obtained by differencing successive phase measurements and dividing by the associated time interval, the results of which have been plotted in Figure 4. It can be seen that the frequency offset is about 57×10^{-6} Hz. Most noticable is a sinusoidal modulation in the frequency offset whose cause we are trying to determine but which appears to be associated with the instrumentation. Also apparent in Figure 4 is an anomalous excursion in the offset starting after about 88 hours.

If we consider only the first three days of data, then we can at least model the bias and drift in the maser offset according to

$$\Delta f = A_0 + A_1 t \tag{4}$$

where A_0 represents the bias and A_1 represents the drift rate. A least–squares fit to this first three days of the frequency record yields $A_0 = 56.566 \times 10^{-6}$ Hz and $A_1 = 1.55 \times 10^{-11}$ Hz/sec. Because phase is related to frequency according to $d\phi = f dt$, the effect on the phase measurements is given by

$$\Delta \phi = A_0 t + \frac{1}{2} A_1 t^2 \tag{5}$$

After the phase measurements are calibrated according to equation (5), the linear drift is removed and finer structure in the phase record becomes apparent, which can be seen in Figure 5. Most apparent is the unexplained sinusoidal variation seen in Figure 4. It should be noted, however, that the phase variations over 24 hours are as small as 10 degrees.

If both the calibrated phase records from DSS 13 and DSS 14 are differenced to remove common-mode errors, then there results the plot in Figure 6. A sinusoidal variation is seen to persist. Nevertheless, it can be seen that the phase variations over 24 hours are again as small as 10 degrees.

IV. CONCLUSION

A preliminary analysis of the data has revealed some systematic effects which appear to be instrumental in origin and therefore need to be corrected. Our future plans are to account for these effects so that we may see what phase fluctuations remain and to perform a more detailed data analysis. For now, the data suggests that the remaining phase variations are probably limited to less than 10 degrees over 24 hour periods. From equation (3), a limit of $\delta\phi < 10$ degrees would imply a limit of $(\frac{\delta c}{c}) < 10^{-5}$. It should be possible to improve upon this limit by at least an order of magnitude.

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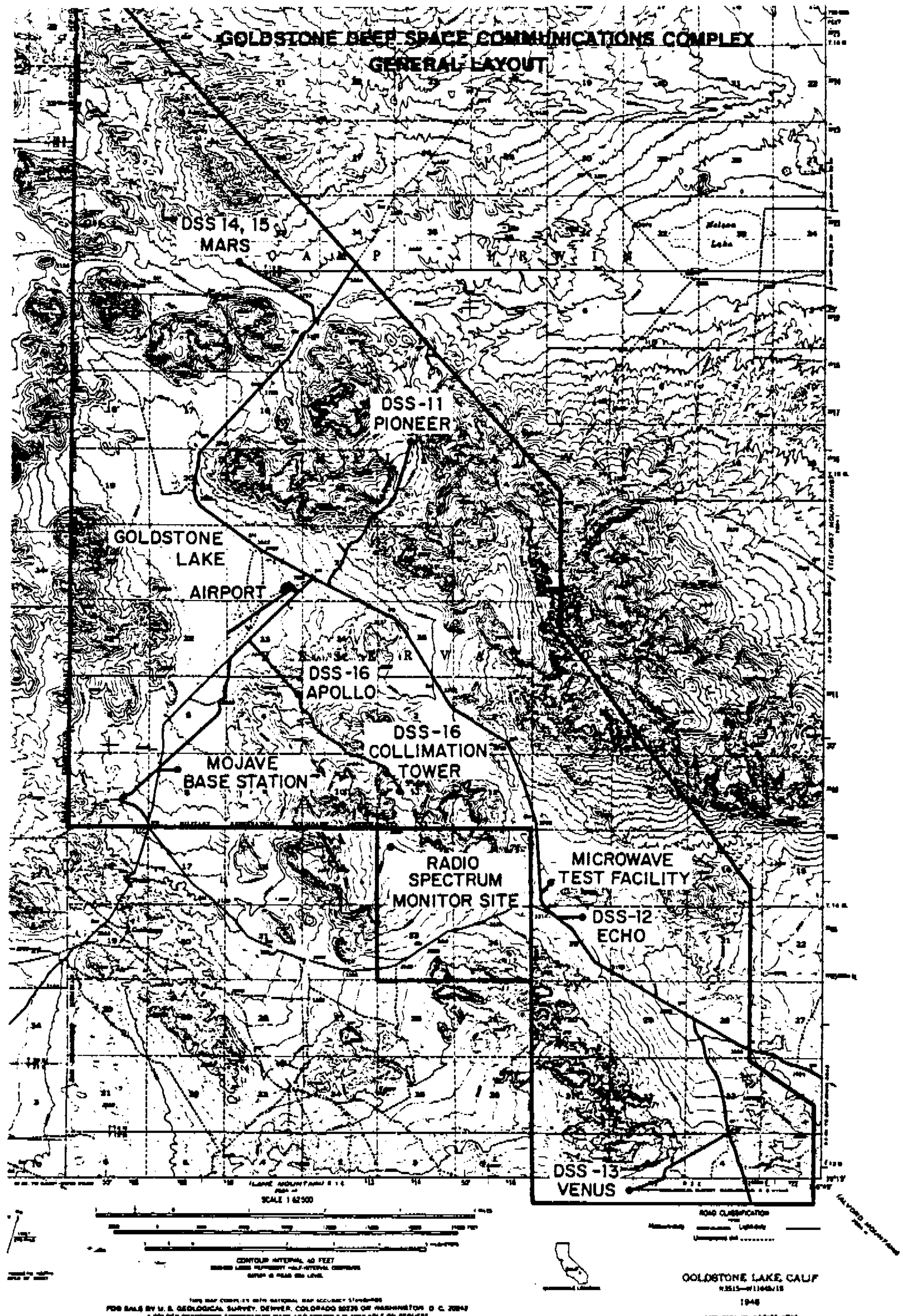

Figure 1. Goldstone Deep Space Communications Complex

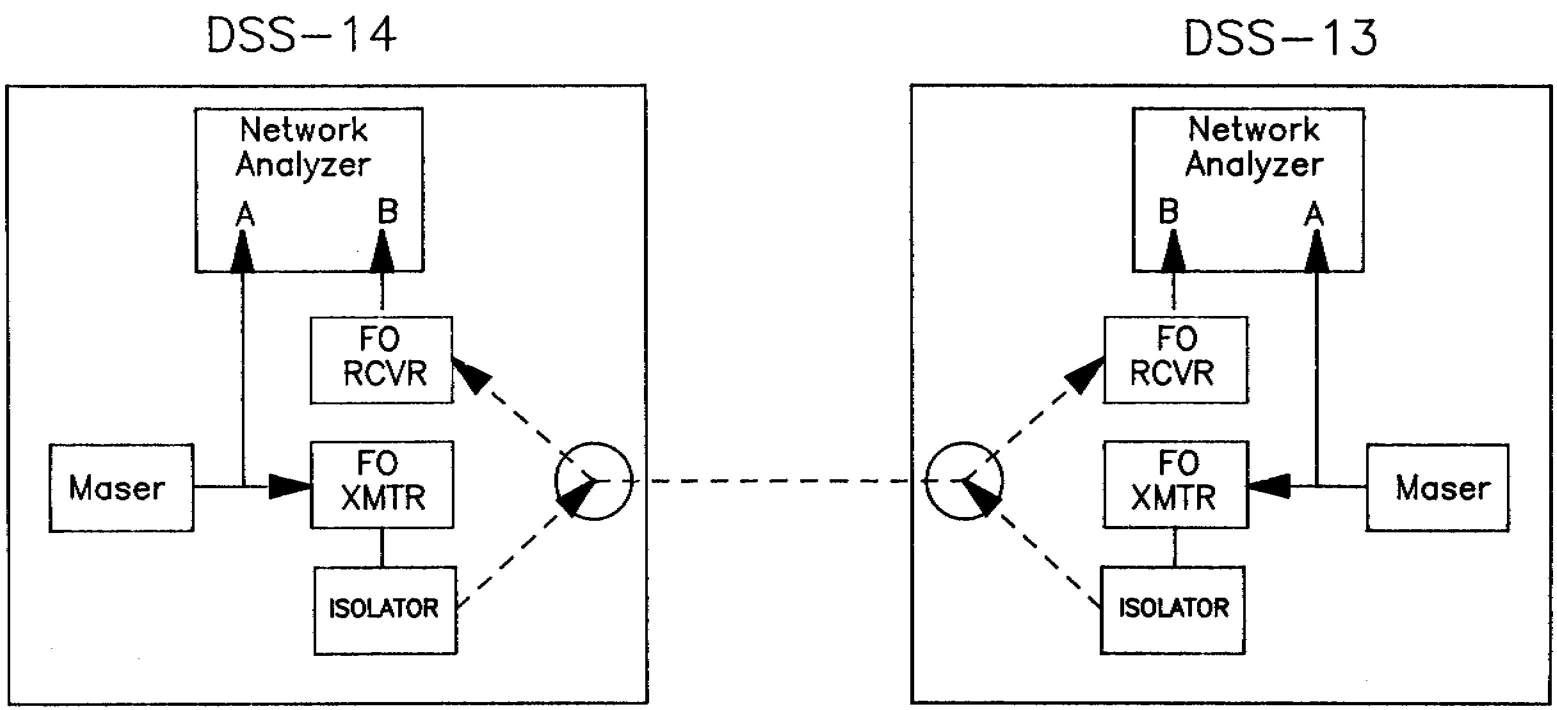

Figure 2. Instrumentation used to perform maser phase comparison.

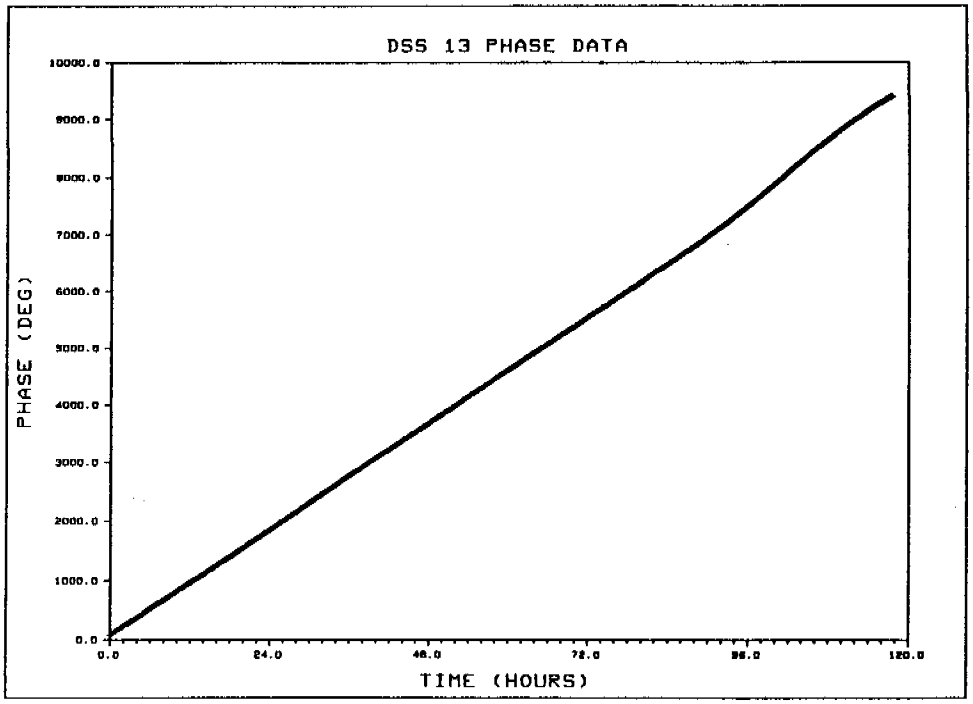

Figure 3.

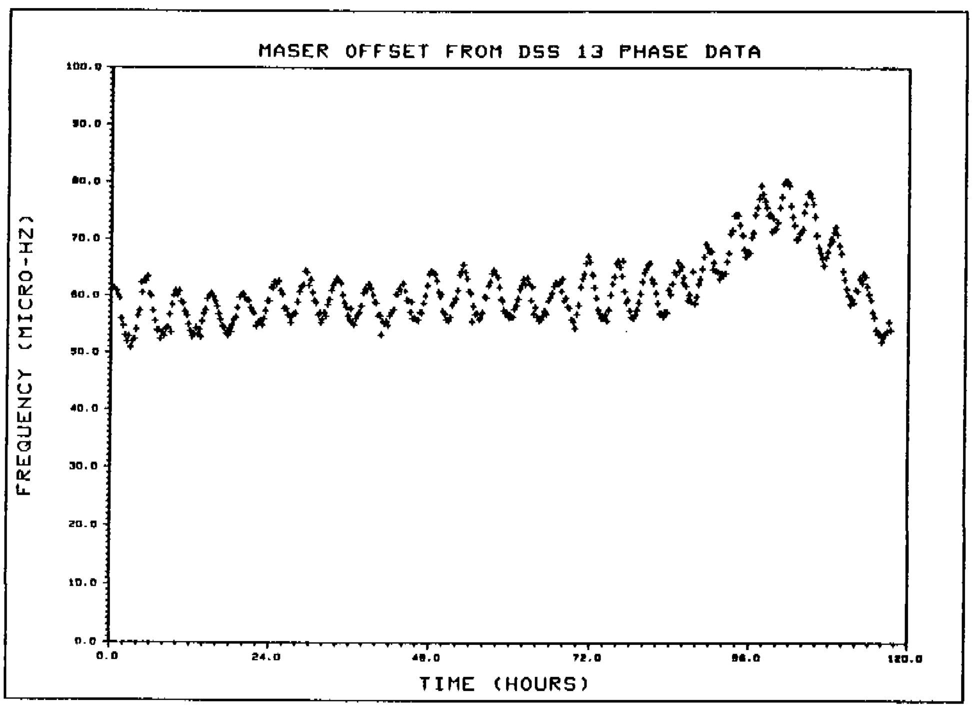

Figure 4.

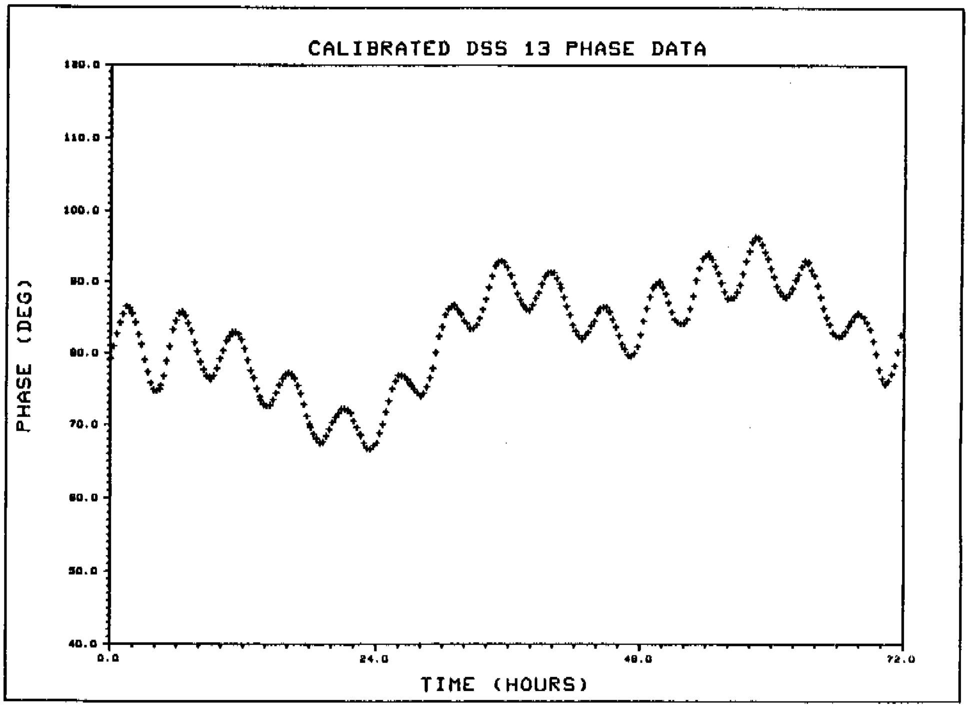

Figure 5.

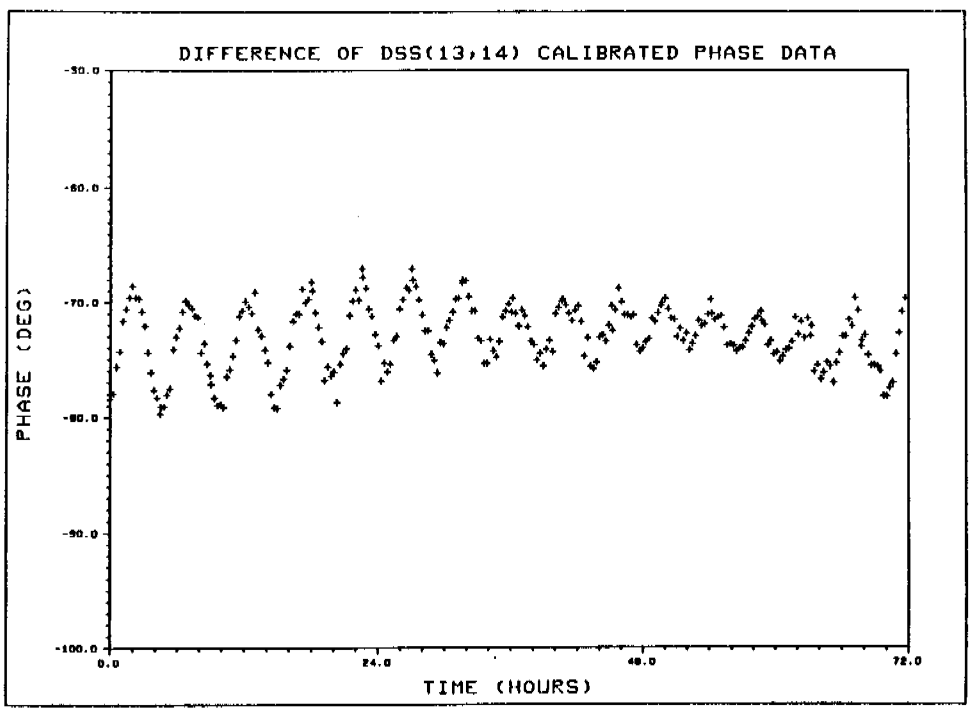

Figure 6.

QUESTIONS AND ANSWERS

DR. GERNOT WINKLER, USNO: Which masers did you use in the two stations?

MR. KRISHER: We used an SAO maser at station 14 and the station 13 maser was built at JPL.

DR. WINKLER: Do they have automatic cavity lock?

MR. KRISHER: No, they free–run.

DR. WINKLER: If I figure correctly, that is almost one part in ten to the fourteenth change, isn't it?

MR. KRISHER: That is correct.

DAVID ALLAN, NIST: One of the things that you are going to have to do is evaluate the differential diurnal variation in the masers, because that is the component that you are looking for. The other question is what is the best previous value of the one–way anisotropy in the speed of light? You have 8 times ten to the minus six, what is the previous value?

MR. KRISHER: Laboratory experiments give a limit of one part in ten to the ninth. However, one point that I would like to make about our experiment is that it is very simple, probably the simplest way to make this experiment. Laboratory experiments try to infer a limit from some sort of atomic frequency measurements or comparing frequency offsets in wave–guides or something of this nature. Here we are trying to measure directly the advance in phase of a signal propagated over the base–line.