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An Experiment to Measure Relative Variations in the One-Way Velocity of Light

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In this experiment two rubidium vapor frequency standards were placed approximately 500 m apart and the phase of their signals compared as a function of time. The diurnal rotation of the earth was used to introduce a change in the direction of propagation of the signal, thereby providing a test of the assumption of isotropy of propagation of electromagnetic radiation. The relative phase difference between clocks was also compared for negligible separation of the clocks. The drift rate changed detectably for the separated clocks, while the round-trip velocity remained constant to within 0.001% c. Typical variations observed in the one-way velocity imply a diurnal modulation of the order of ± 0.1% to 1.0% c. The relative precision of the measurements amounted to 1 part in 5×10^{13}.

Key words: fundamental constants; precision measurement; velocity of light.

1. Introduction

The assumption of the isotropic propagation of light in the special theory of relativity is traditional. The adoption of a convention involving anisotropic propagation does not necessarily violate the principle of relativity. For example, Winnie [1] formulated three synchrony free principles which include the factual core of the observations which support special relativity. The equations are expressed in ε-generalized Lorentz form, which requires no assumptions regarding the one-way velocity of light. Formulated in this generalized way, the special theory of relativity allows for the possibility of anisotropic propagation of electromagnetic radiation, which is not observable via round trip experiments, or any other similar symmetrical arrangement of the propagation path. However, we have not been able to find any experiments reported in the literature which are free of the symmetries which cancel the effects of possible anisotropies in space.

Sources of possible anisotropy in the propagation of light include anisotropies in the distribution of matter in the universe at large, or possibly the existence of an "absolute space" as advocated by Poincáre [2], in his strong theory of relativity, which has at its base the non-relativistic theory of Lorentz [3]. Giannoni [4] for example, has also formulated a spectrum of non-relativistic theories which satisfy the essence of Winnie's [1] synchrony free principles, and Torr and Kolen [5] have established that the special theory and the Poincare [2] formulation of the Lorentz [3] theory lie at the extreme ends of a spectrum of theories, all of which satisfy the essence of Winnie's [1] principles as modified by Giannoni [4].

There is, therefore, significant theoretical justification for the measurement of the one-way velocity of light, provided that a suitable experiment can be devised for this purpose. In this paper we describe the results of an experiment in which the rotation of the earth is used to introduce changes in the direction of propagation of electromagnetic radiation with the purpose of detecting changes in phase produced by variations in the one-way velocity of light.

2. Historical Problems with the One-Way Experiment

Historically there has been a misconception regarding the feasibility of any experiment designed to measure the one-way velocity of light. Generally it is believed that the experiment is meaningless. The rationale behind this argument proceeds as follows. In order to make the measurement by timing the one-way flight of a light pulse it is necessary to synchronize two clocks separated by some distance d. To do this it is apparently necessary to make some assumptions about the propagation speed as a function of direction, since motion affects the frequencies of clocks, i.e., they cannot be locally synchronized and then separated without some unknown change in phase occurring. Thus a knowledge of the velocity of propagation is required to synchronize the clocks, which introduces a circular argument which in turn renders the concept of the experiment meaningless.

In the experiment reported in this paper we circumvent this problem by not requiring that the clocks be synchronized. We look instead for variations in the relative phases of signals generated by two clocks, which should only occur if the one-way velocity of light is direction dependent. It nevertheless transpires that even the absolute velocity of propagation can be deduced from this experiment as described below.

3. Concept of the Experiment

The experiment that we conducted utilized two Hewlett Packard model 5065A rubidium vapor frequency standards to time the flight of electromagnetic signals across a distance of ~500 m separating the clocks. The experimental arrangement that yielded the best results is schematically illustrated in Fig. 1. Each clock generates a ~1.5 V rms 5 MHz sinewave. The signal from clock A was used to trigger the start input of an HP model 5370A Universal Time Interval Counter. The signal from clock B was used to stop the counter.

The theory behind the experiment argues that if perfect clock stability is assumed, at some arbitrary time

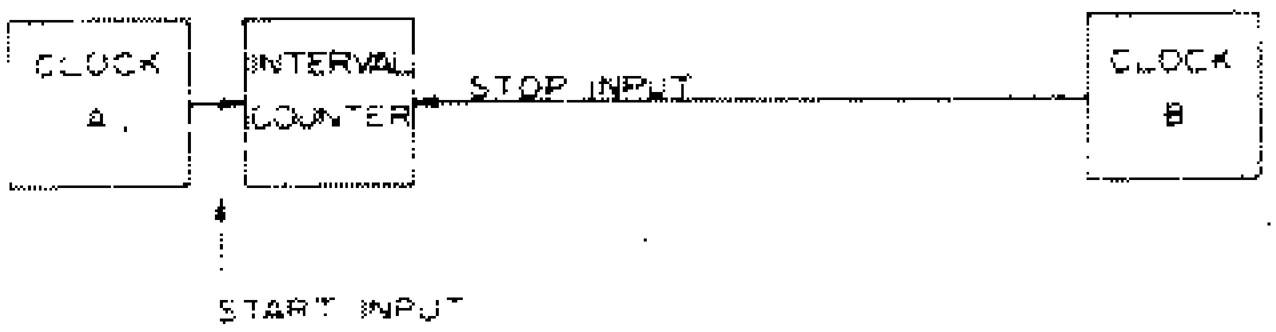

FIGURE 1. *Schematic illustration of the concept of the experiment.*

the interval counter will measure a signal given by

$$\Delta t_1 = \Delta t + \frac{d}{c^+} \qquad (1)$$

where Δt represents some initial phase offset between the clocks, $d = 500$ m, and c^+ is the velocity of propagation at that time and orientation of the experiment. The experiment relies on the rotation of the earth to interchange the positions of the two clocks, so that twelve hours later we measure

$$\Delta t_2 = \Delta t + \frac{d}{c^-} \qquad (2)$$

where c^- potentially represents a different value for the velocity of propagation of the signal. Hence subtraction of the two measured intervals yields the quantity

$$\delta t = \Delta t_2 - \Delta t_1 = \frac{d}{c^-} - \frac{d}{c^+} \qquad (3)$$

$$= d\frac{(c^+ - c^-)}{c^+ c^-} \qquad (4)$$

Naturally if the special theory of relativity is correct $c^+ = c^- = c$ and $\delta t = 0$.

To a first order approximation

$$\delta t = \frac{dv}{c^2} = \Delta t \frac{v}{c}, \qquad (5)$$

$$\text{where } \Delta t = \frac{d}{c} \qquad (6)$$

$$\text{and } v = \frac{c^+ - c^-}{2} \qquad (7)$$

$$\text{Hence } v = \frac{\delta t}{\Delta t} c. \qquad (8)$$

Since a roundtrip measurement yields Δt, c^+ and c^- can be determined as a function of time.

In reality, however, the simplicity of this concept is marred by errors of measurement which we discuss in section 5.

4. Experimental Arrangement

Figure 2 schematically illustrates the details of the experimental arrangement that was used. The clocks were placed 500 m apart in an east-west orientation. The 5 MHz sine wave signal was propagated via a nitrogen filled coaxial cable maintained at constant pressure at ~2 psi above the ambient atmospheric pressure using a 2 stage regulator. Thermal control was achieved to within ± 1 K over a diurnal cycle by burying the cable at a depth of 5 feet below the surface, and the enclosures housing the equipment 10 feet below the surface. Electrical isolation was achieved by enclosing the equipment in a Faraday cage. Figure 2 also illustrates the dc power supply arrangement used to supply regulated power to within ± 10 mV. The power was introduced into the Faraday cages via electromagnetic interference filters.

The performance characteristics of the rubidium clocks were evaluated by running the clocks at a separation of 1 m. Limitations imposed in the measurement due to clock errors were determined, and requirements for a successful experiment established. These findings are discussed in section 6.

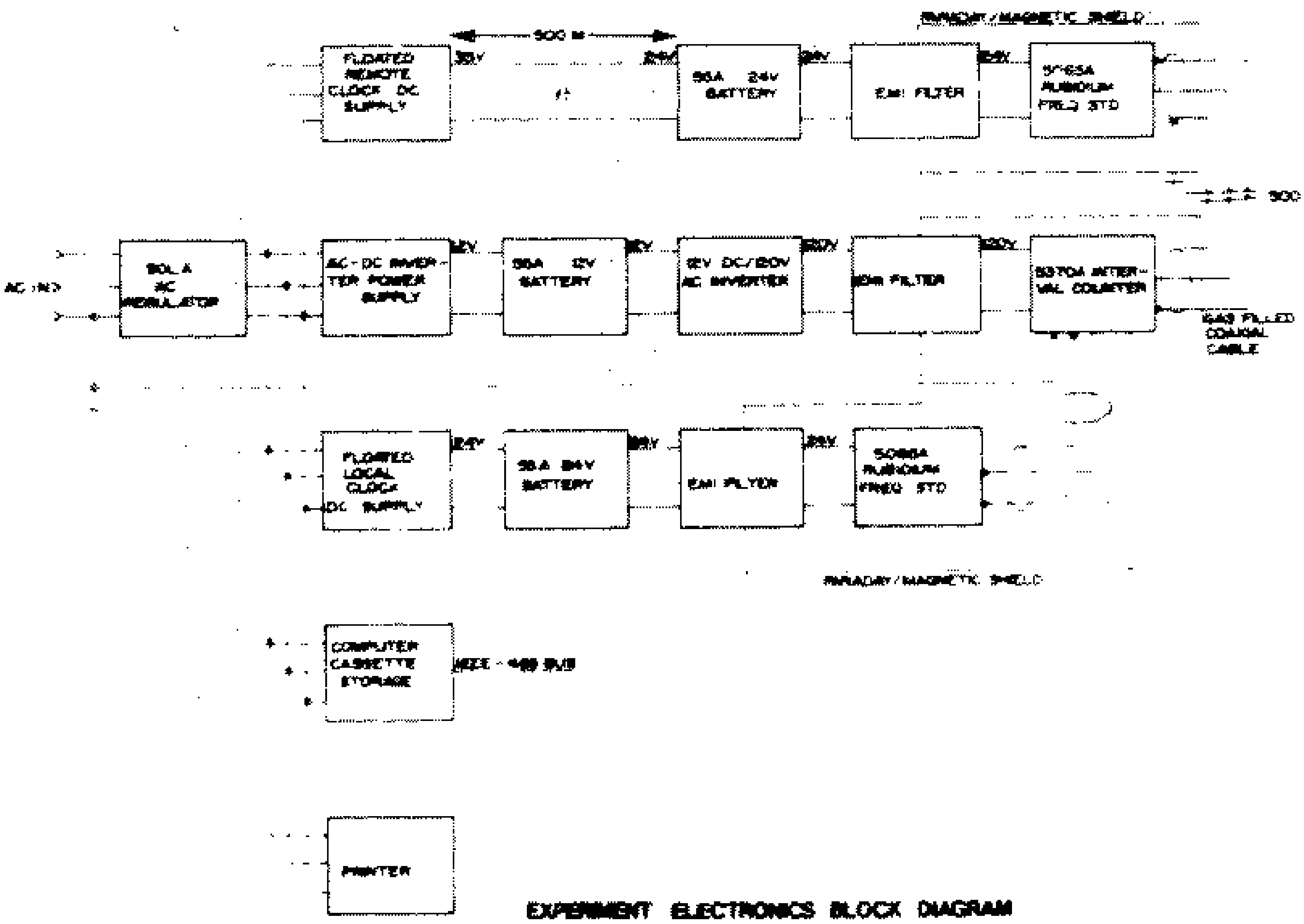

FIGURE 2. *Block diagram illustrating the details of the experimental arrangement.*

5. Evaluation of Errors of Measurement for Rubidium Vapor Frequency Standards

According to manufacturer-supplied information there are two primary sources of error which affect the behavior of rubidium clocks. These are:

a) *Settability*—This represents the practical limit of setting both clock oscillators to the identical frequency. This error accumulates with time.

b) *Long Term Frequency Drift*—This error is introduced by "long term" noise, and produces a non-linear drift with time.

By observing the behavior of the clocks at zero separation (i.e. ≈ 1 m) their relative drift rate could be measured and hence the clock errors functionally fitted and accurately defined. According to the manufacturer's specifications [6] the accumulated error of a rubidium clock can be parameterized as follows:

$$T(t) = (1/2)at^2 \pm bt \pm t_o \qquad (9)$$

where

$T(t)$ = total accumulated error with respect to a perfect time base,

a = frequency drift rate ≈ 1×10^{-11} per month,

b = $(\frac{f_o}{f_r} - 1)$ = settability = $\pm 2 \times 10^{-12}$ seconds/second,

f_o = initial frequency of oscillator at $t = 0$,

f_r = reference frequency, and

t_o = initial time error at $t = 0$.

To calculate the difference in relative accumulated error between two rubidium clocks, Eq. (9) is modified to

$$\Delta T(t) = 1/2(a_1 - a_2)t^2 \pm b_r t \pm t_o \qquad (10)$$

where

$\Delta T(t)$ = relative accumulated error,

$a_{1,2}$ = frequency drift constants of the respective clocks

$b_r = (b_1 - b_2) = \frac{f_{10} - f_{20}}{f_r}$, and

$f_{10,20}$ = initial frequencies of the respective clocks at $t = 0$.

It can be seen from Eq. (10) that if $a_1 = a_2$, $\Delta T(t)$ can be approximated by

$$\Delta T(t) = b_r t \pm t_o \qquad (11)$$

for a short enough time such that the quadratic term can be neglected. This point is important for using rubidium clocks in this application which will be discussed in detail in the data reduction section.

In order to characterize the behavior of the clocks with repsect to each other, we monitored their performance for a period of ~ 8 weeks at zero separation. Figure 3 illustrates the typical relative drift rates observed. We have plotted the relative accumulated clock error $\Delta T(t)$ for 7 days. These results show a pattern that we have confirmed is typical. The clocks tend to drift linearly for periods of time which amount to several days. These linear drift periods are interspersed with non-linear drift periods were the slope of the drift curve changes rapidly, and then settles down to the linear pattern again.

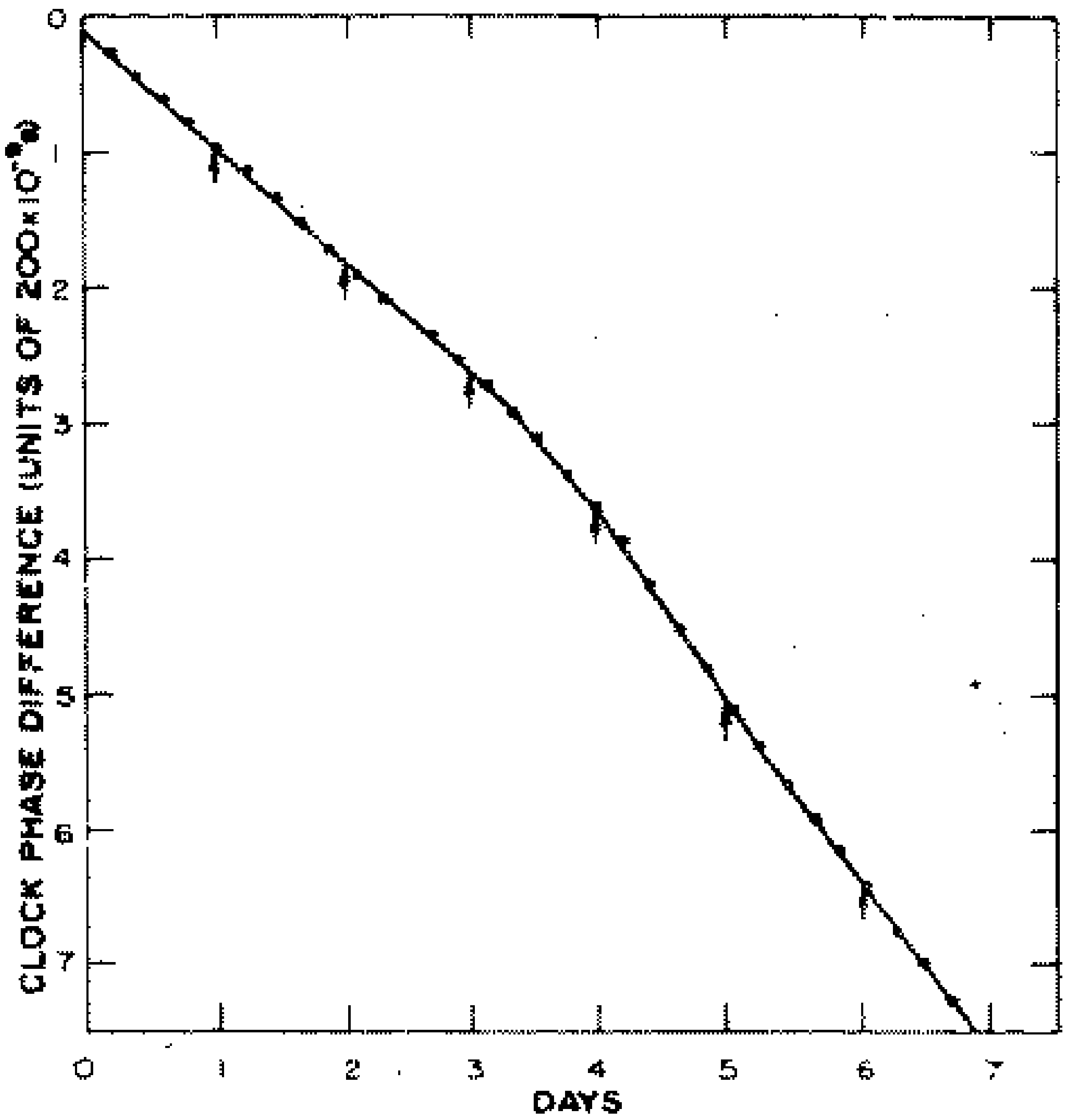

FIGURE 3. *Typical relative drift rate observed for the Rubidium Vapor Frequency Standards over a period of 7 days for zero separation.*

Figure 4 represents a typical linear segment over one day for zero clock separation. Figure 5 shows the residuals, i.e., with the linear trend removed.

While the mean departures from linearity over many days agree with the manufacturer's specifications, these departures occur "suddenly" providing large variations over a few hours which are clearly identifiable. Over the linear segments, the clock error is about a factor of 10 smaller than that specified by the manufacturer. Using the manufacturer's specifications we calculate a mean non-linear component of ~15 ns per day. Typically, however, the observed departure from linearity over 24 hours for a "linear segment" seldom exceeds 1.5 ns, which allows one to make a measurement of relative precision of ~1 part in 5×10^{13}.

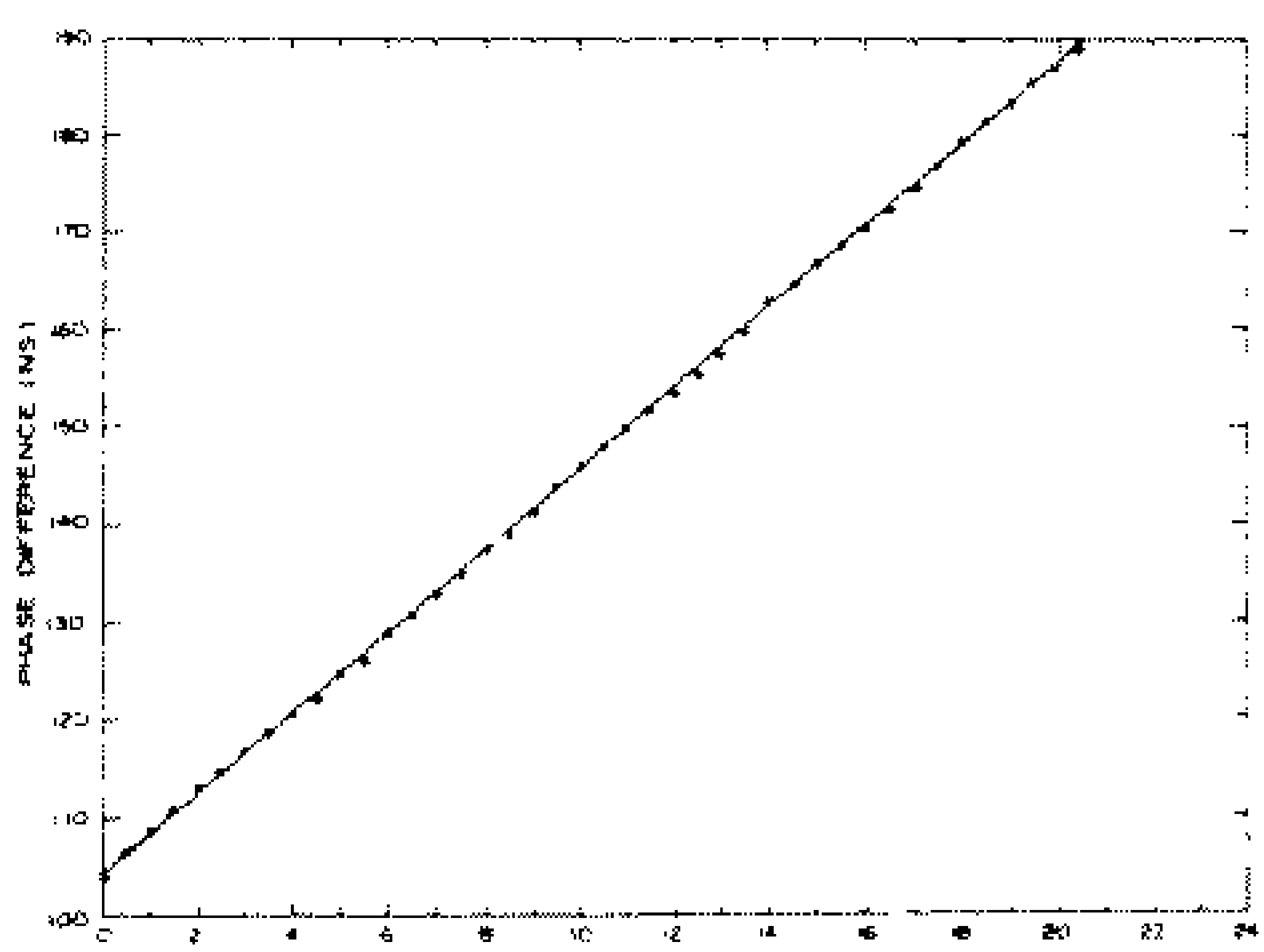

FIGURE 4. *A typical linear drift segment over a 24 hour period for zero separation of the clocks.*

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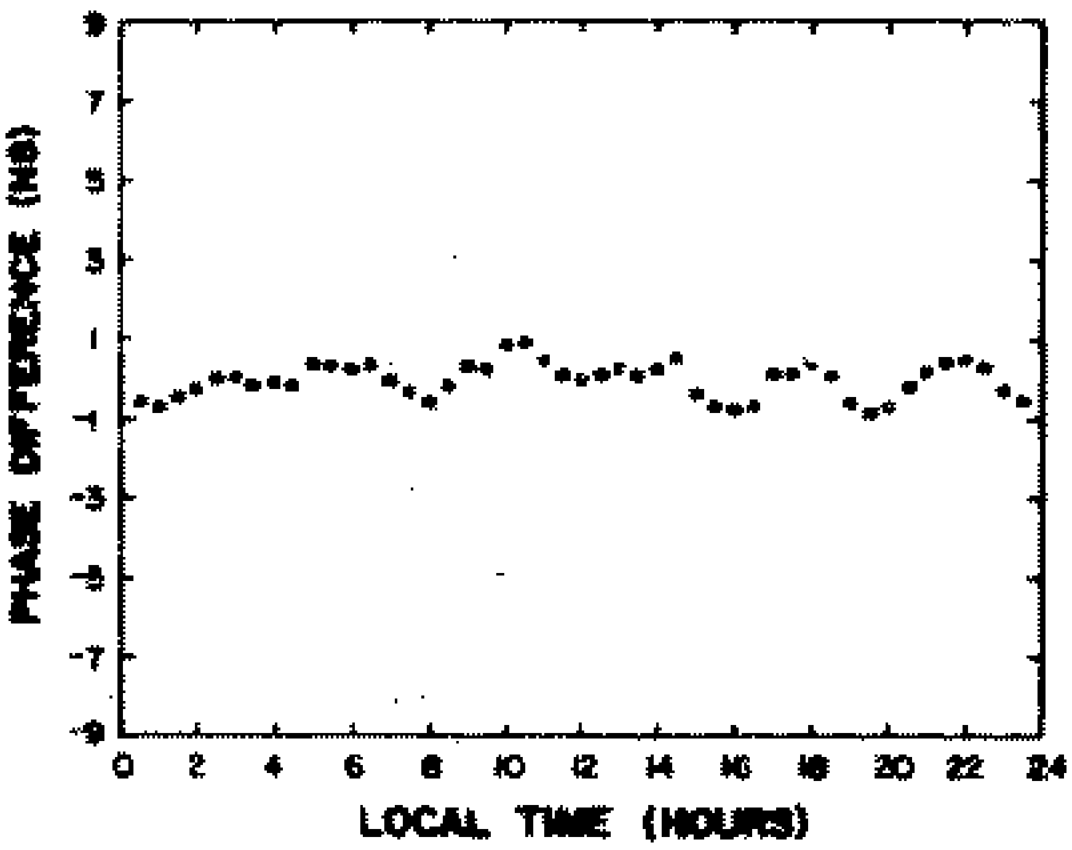

FIGURE 5. *Typical residual drift rate obtained when the linear trend is removed.*

6. Rubidium Results

Several months of data have been obtained for the clocks separated and for zero separation. The separated clocks exhibited a behavior pattern which is significantly different from that observed for zero separation. Very large (~10 ns) departures from linearity have been observed on several occasions for the separated clocks. Two examples are given in Figure 6. However, one cannot be absolutely sure that this behavior is not simply another form of the non-linear pattern identified in Fig. 3 even though the clocks have not exhibited this kind of behavior under zero separation conditions. Our results indicate that departures from linearity for the separated clocks remain below threshold (~1.5 ns) 30 percent of the time. Amplitudes between 1 and 3 ns are most common. However, not only does the amplitude of the signal vary from day to day, but the phase does also. Since there is no theory available which can account for these variations, we believe that it is essential to repeat the experiment with different clocks such as cesium beams

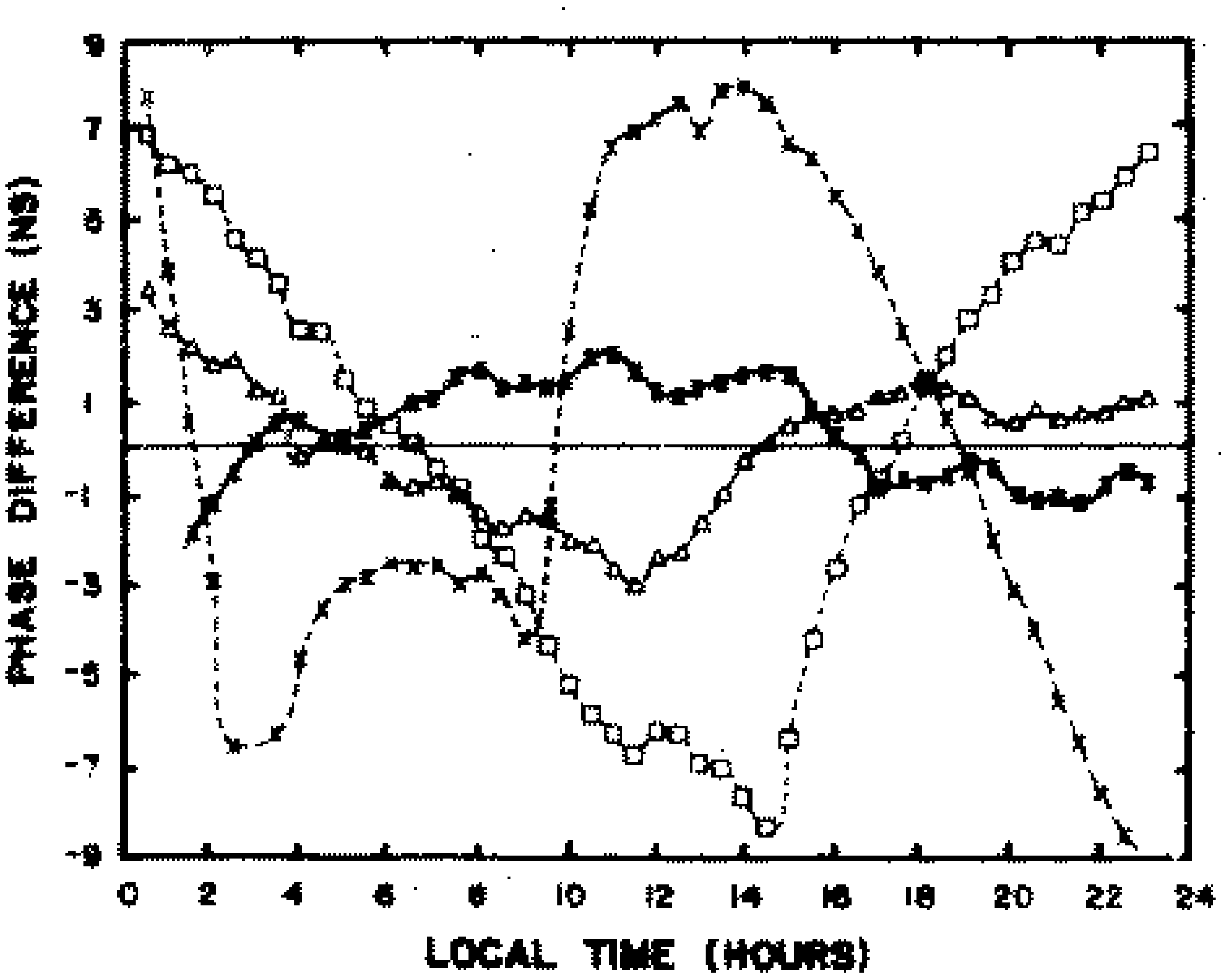

FIGURE 6. *The asterisks show a typical diurnal variation obtained for zero separation when the linear drift component is removed. Results obtained for a typical day for the separated clocks are shown as the triangles. The crosses and squares represent the maximum diurnal variation observed, excluding cases which exhibit sudden "quantum" changes in drift rate which are clearly due to clock errors.*

which do not exhibit the non-linear variations peculiar to rubidium vapor frequency standards.

If these variations are real and the experiment is indicating the presence of a dynamical "absolute space," or the effects of anisotropic distribution of matter in the universe then the motion of the solar system in the galaxy should be embedded in the observed variations. This should be observable as a sine wave modulation of the signal over a 24 hour period. The component of the velocity of the solar system in the ecliptic plane is $\sim 10^5$ m/s^{-1} which translates into an amplitude variation of $\sim \pm 0.5$ ns. In the presence of variations which exceed ± 3 ns for 30 percent of the time, significantly more than a year of integration would be required to detect this signal at a signal-to-noise ratio of 3 to 1. We have therefore used a sample of data restricted to variation amplitudes <3 ns. The time required to obtain a given signal-to-noise ratio (SNR) is given by

$$SNR = \frac{\delta t \sqrt{N}}{\sigma_e} \quad (12)$$

or

$$\text{i.e. } N = \frac{(SNR)^2 \sigma_e^2}{\delta t^2}, \quad (13)$$

where δt = mean signal amplitude,
σ_e = standard deviation of the data, and
N = sidereal day count.
If we let $SNR = 3$,
$\delta_t = 0.5$ ns
$\sigma_e = 3$ ns
$N = 324$ sidereal days at an occurrence rate of 30 percent, which considerably exceeds the number of days of data currently available. Hence the expected signal is not yet detectable with our present arrangement.

Figure 7 shows the result obtained integrating 23 days' data for which the maximum amplitude never exceeded 3 ns. From these results we can place an upper limit on δt of 0.5 ns, i.e.

$$v \leq 90 \text{ km/s}^{-1}$$

This fairly closely approximates the component in the ecliptic plane of the velocity of the solar system in the galaxy.

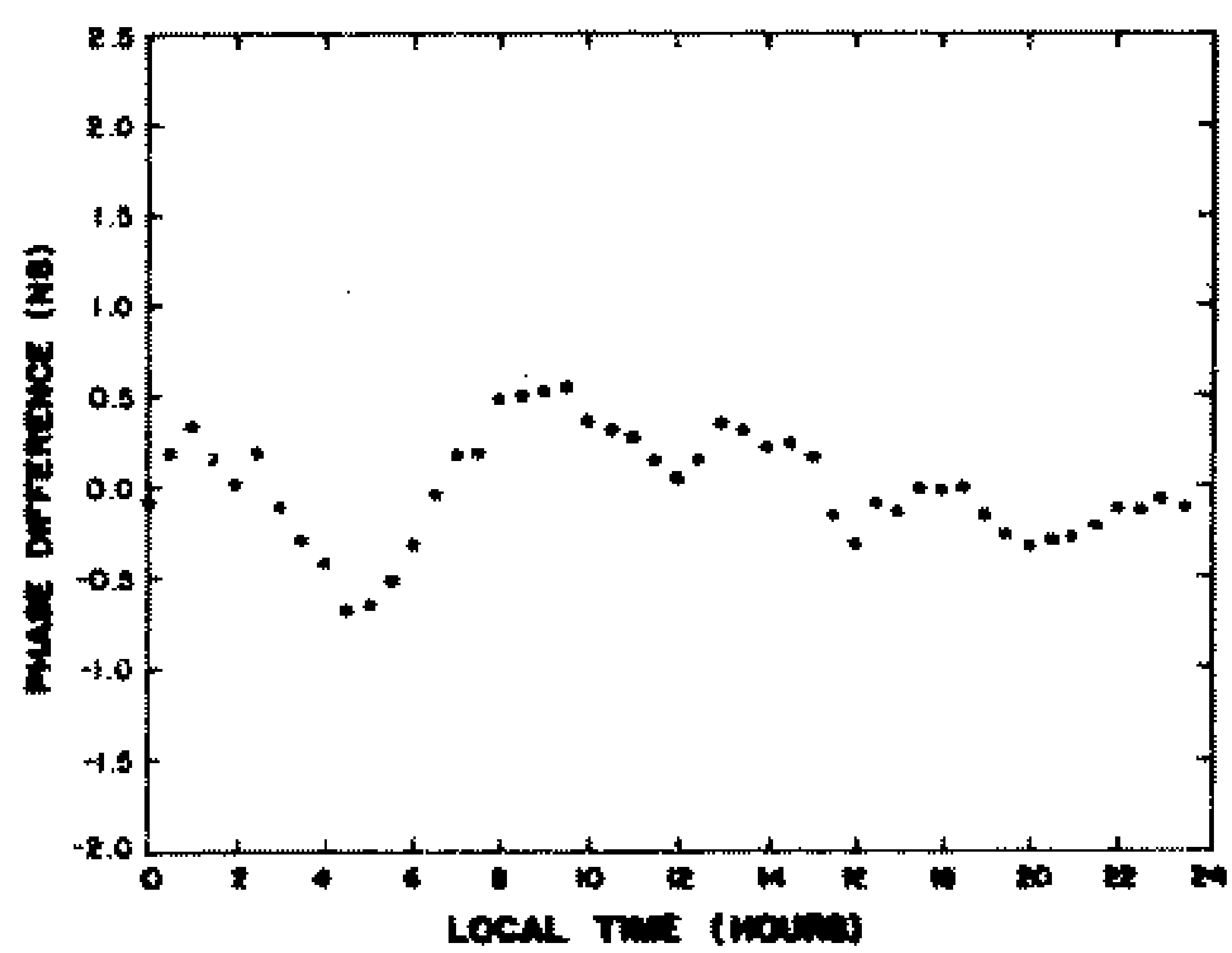

FIGURE 7. *The coherent sum of 23 days' data for the separated clocks for the period February to June, 1981. Summing was carried out using half hour bins.*

7. Conclusion

The main result that has emerged from this work is the demonstration of the viability of a measurement of the one-way velocity of light. Given perfect clocks the absolute one-way velocity could be accurately determined. With rubidium vapor frequency standards integration over 3 years would provide an unambiguous detection of the motion of the solar system in the galaxy, if such motion is indeed detectable by this technique.

The results we have obtained to date exhibit large variations in c (0.1% to 1% c) for the separated clocks, which are not observed (i.e., in the same form) for zero separation. More observational time will be required to unambiguously establish whether the observed variations are indeed due to clock errors or not.

We believe that the ambiguity [illegible] be greatly reduced by using cesium beam clocks with [illegible] performance option which significantly improves the clock stability.

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