PERFORMANCE AND RESULTS OF
PORTABLE CLOCKS IN AIRCRAFT

by

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1.0   INTRODUCTION

During the first two weeks of October, 1971, R. E. Keating of the U.S. Naval Observatory and I flew twice around the world on regularly scheduled commercial flights, once eastward and once westward, with four Hewlett-Packard 5061A cesium beam clocks. For about a week before the first trip, between the trips, and for about a week after the second trip we recorded a continuous phase comparison between each clock and the MEAN (USNO) time scale. Time differences between the four clocks were also recorded with a time interval counter at regular intervals before, during, and after each trip, thereby permitting evaluation of the flying mean time scale. The experiment was conducted for two reasons: (1) to compare the known performance of similar clocks under fairly well controlled laboratory known performance of similar clocks under fairly well controlled laboratory conditions, and (2) to try to detect relativistic effects on the time recorded by clocks during terrestrial circumnavigations. It was performed with the interest and complete cooperation of Dr. G. M. R. Winkler and others of the Naval Observatory Time Service Division, and with financial support from the Office of Naval Research. A major portion of the credit for the experiment goes to Richard Keating, whose steadfast desire to perform such an experiment generated the necessary motivation. Although the

performance of these clocks was found to be noticeably degraded during the trips, we also found that the ensemble of four flying clocks produces consistent time differences which are difficult to explain without invoking relativistic effects.

2.0 A PRECISION LONG-TERM TIME REFERENCE - MEAN (USNO)

When a reliable means of counting the accumulated number of periods of an oscillator is combined with a cesium beam frequency standard, the assembly approaches the realization of an ideal standard clock. In fact, a time interval of one second is now, by definition, exactly 9,192,631,770 accumulated periods of an "ideal" cesium beam frequency standard.[1] Experience shows, however, that the times recorded (periods accumulated from a common starting instant) by two "real" cesium beam clocks having no intentional frequency offset differ by as much as several parts in 10^{12}. Though this performance is truly remarkable, certainly beyond any expectations of a decade or so ago, for many purposes it is desirable to establish a stable, continuous atomic time scale which is independent of the characteristics of any particular cesium beam clock. It is not difficult to accept the premise that the long-term average or mean of the times indicated by two or more properly functioning cesium beam clocks is more reliable (or stable) than the individual times indicated. Ideally, the mean of a very large (infinite) number of clocks would provide a perfectly reliable time scale; however, budget limitations prevent realization of this goal. So we compromise by taking the mean of an ensemble of as many clocks as possible, or as is necessary to produce the desired reliability. The mean time scale at the U.S. Naval Observatory (MEAN (USNO)) represents a suitable average of the

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[1]Winkler, G.M.R., R.G. Hall, and D.B. Percival (1970), "The U.S. Naval Observatory Clock Time Reference and the Performance of a Sample of Atomic Clocks," *Metrologia* Vol. 6, p. 126.

of the time recorded by an ensemble of more than 15 cesium beam clocks.[2]

As some of these clocks deteriorate or fail, they are replaced by standby clocks, thereby permitting an indefinite extension of the time scale into the future. The time indicated by MEAN(USNO) is believed by many to be the closest approximation we have today to an ideal long-term atomic time scale.

The basis for confidence in this time scale is the belief that both long- and short-term differences (or fluctuations) between the mean and each clock of the ensemble are random. If one clock of the ensemble increases its rate (relative to the mean), it will not be long before some other member on the average decreases. In this way, ultimately, the mean is correctly maintained. In fact, the stability of the mean is actually improved by taking into account rate changes for each member of the ensemble.[3]

The MEAN(USNO) time comes from a "paper" clock; that is, the mean is calculated after the fact and is not instantaneously available for time comparisons. This presents no real problem, however, because one of the members of the ensemble is chosen as the primary reference or "master" for the ensemble and all clocks are compared with this master. A secondary master is kept in reserve in case the primary master fails. This MASTER(USNO) time is tracked to follow the mean as closely as possible and is physically available for instantaneous time comparisons. Since the difference between MASTER(USNO) and MEAN(USNO) is calculated at regular intervals, it is an easy matter to convert to an equivalent comparison with MEAN(USNO) after the intercomparison measurements are completed.

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[2] Ibid.
[3] Ibid.

3.0   LABORATORY PERFORMANCE OF CESIUM BEAM CLOCKS

Now that we have a long-term reference time scale, it is straight-forward to evaluate the performance of any particular clock simply by comparing the time it indicates with the time of the reference. There is extensive literature on evaluation of the performance of precision atomic oscillators, particularly on the subject of short-term time and frequency stability (see Barnes, J.A., et al and Allan, D.W., et al   and bibliographies therein).[4] There seems to be a consensus in this literature that time domain stability is best described in terms of fractional frequency fluctuations, with the quantitative measure being the Allan variance $\sigma^2(\tau)$. Cesium beam clocks, like all clocks to a greater or lesser extent, are subject to short-term FM noise and this noise limits the precision with which the time or frequency can be determined during short averaging times (several days or less). In most cases, however, this type of noise is not the limiting factor for long-term stability. Long-term performance appears to be governed more or less by instantaneous and randomly occurring rate (or frequency) changes.

The characteristic long-term performance of cesium beam clocks can be described in terms of $\sigma(\tau)$, the square root of the Allan variance. As the averaging time τ increases from zero, $\sigma(\tau)$ characteristically decreases on a log-log plot with a slope of $-\frac{1}{2}$. However, beyond a certain τ , depending on the particular clock, the slope changes rather abruptly to zero, and for longer averaging times $\sigma(\tau)$ remains constant and in some cases eventually

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[4] Ibid.; Barnes, J.A., et al.   (1971) "Characterization of Frequency Stability," IEEE Trans. Instr. Meas. IM-20 (May 1971), p. 105; Allan, D.W., B.E. Blair, D.D. Davis, and H.E. Machlan (1971) "Precision and Accuracy of Remote Synchronization via Portable Clocks, LORAN C, and Network Television Broadcasts," Proc. 25th Ann. Symp. Freq. Control, 26-28 April 1971 (Electronic Industries Assoc.) p. 195.; Martin, D. (1971) "Frequency Stability Measurements by Computing Counter System," Hewlett-Packard Journal Vol. 23 (November 1971) p. 9.

increases.[5] The averaging time for which $\sigma(\tau)$ decreases with slope $-\frac{1}{2}$ gives the time for which the frequency fluctuations are random about a constant mean. If the frequency fluctuations remained indefinitely random about a constant mean; that is, if $\sigma(\tau)$ continued to decrease indefinitely with slope $-\frac{1}{2}$, one could achieve indefinite long-term stability with a single clock simply by increasing the averaging time. In other words, if this were the case, once the average rate relative to MEAN(USNO) was established the average rate could be projected indefinitely into the future. This is not the case, however.

This change in the slope for $\sigma(\tau)$ indicates that "quasipermanent" changes in the average rate for the clock occur randomly with the average time interval between changes comparable to the averaging time for the slope change. By quasipermanent I want to suggest, or imply, that the clock changes (unpredictably) to a new average rate every so often. Uncertainty in the onset and magnitude for each new quasipermanent rate is related to the minimum value of the Allan variance.

Table I illustrates this long-term performance. The table lists quasipermanent rate changes for five cesium beam clocks over a 40-day period at the U.S. Naval Observatory. The data were taken from continuous phase comparison records with MEAN(USNO) as reference. Approximate rate changes are relative to MEAN(USNO). N is the number of changes during this period, the ΔR's are the signed magnitudes of the changes, $\overline{\Delta R}$ is the average rate change, and $\overline{T}$ is the approximate average duration between rate changes.

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[5] Winkler, G.M.R., R.G. Hall, and D.B. Percival; Winkler, G.M.R. (1970) "Requirements and Performance for Today's Atomic Standards," PTTI Strategic Planning Conference, Vol. 1, December 1970, p. 129.

TABLE I. QUASIPERMANENT RATE CHANGES FOR FIVE CESIUM BEAM CLOCKS

CLOCK (s. no.)	N (in 40 d)	ΔR (nsec/day)	$\overline{\Delta R}$ (nsec/day)	$\overline{T}$ (days)
140	3	-25; +28; -54	-17	10
3911	1	-17	-17	20
1471	2	+22; -19	+1	13
60	3	+17; -12; +17	+7	10
283	6	-33, +21; -50; +57; -41; +22	-4	7

The cause for these quasipermanent rate changes is not understood in detail.[6] Both the time of their occurrence and their direction appear to occur at random. Though they are quite unpredictable in nature and, of course, must average to zero over sufficiently long periods with properly functioning clocks (very many $\overline{T}$ periods) they limit the precision with which the rate of any particular clock can be projected into the future.

As can be seen in the table, the average time between changes and their magnitudes depends on the particular clock. $\overline{T}$ for clocks at USNO has been found to range between 1 and 40 days.[7] "Good" clocks are those which go longer than average between rate changes. One of the purposes of the experiment was to study deterioration, if any, in the performance of four good clocks under traveling conditions.

4.0   RELATIVISTIC EFFECTS DURING TERRESTRIAL CIRCUMNAVIGATION

In 1905 Einstein laid a radical new basis for the concepts of space and time. Though Newton's absolute time had proved adequate for most practical

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[6] Ibid.

[7] Winkler, G.M.R., R. G. Hall, and D.B. Percival (1970) "The U.S. Naval Observatory Clock Time Reference and the Performance of a Sample of Atomic Clocks," Metrologia, Vol. 6, p. 126.

purposes, Einstein produced convincing arguments against it. Absolute time contains an element of mystery which is incompatible with precisely defined scientific quantities. Consequently, Einstein defined a new empirical basis for time by accepting a definition which states, in effect, that "time is that which is indicated by a clock," and then proceeded to develop his relativity theories on that basis. Einstein's relativity has proved to be completely compatible with all relevant observations; in fact, no definitive test ever performed has disproved it. The results of our flying clock experiments, at least at the present state of analysis, offer no exceptions.

The special theory of relativity predicts that a moving clock will run slow compared with similar clocks distributed at rest and suitably synchronized in an inertial reference system. In addition, the general theory predicts that a clock in a stronger gravitational field will run slow compared with a similar clock in a weaker field. Most physicists believe these predictions have been verified through studies of lifetimes of elementary particles and studies employing the Mossbauer effect, but a small vociferous minority and indeed, I would say, most of the general public, are reluctant to accept the prediction that these effects also apply to ordinary time indicating clocks, particularly to biological clocks. For an excellent book devoted almost entirely to the "clock paradox," see L. Marder's "Time and the Space Traveler," printed by Allen and Univin, London, 1971.

Relativistic effects on times recorded by clocks are vanishingly small at ordinary speeds, certainly too small to detect with ordinary chronometers. However, the development of portable cesium beam clocks, with stabilities of better than 1 part in 10^{12} over a period of days, makes a direct test with time recording clocks feasible. I have shown that the predicted kinematic effects on the time recorded by clocks during equatorial circumnavigations at ordinary jet aircraft speeds and altitudes are enhanced by the Earth's rotation to a level which is probably above the threshold for

detection with cesium beam clocks.[8] Although the assumption of an equatorial circumnavigation at constant ground speed and altitude is not essential, it does simplify somewhat the calculations for estimating the magnitude of expected relativistic effects. For an equatorial circumnavigation with constant ground speed v (m/sec) and altitude h(m), the predicted relativistic time gain for the flying clock over a similar reference clock kept at "rest" on the Earth's surface is given by[9]

$$\frac{\Delta \tau}{\tau_0} = \frac{\tau - \tau_0}{\tau_0} = \frac{gh}{c^2} - \frac{2R\Omega v + v^2}{2c^2} , \qquad (1)$$

where τ and τ_0 are the respective times recorded by the flying and ground clocks; R (m) is the Earth's radius and Ω (rad/sec) its angular speed; g (m/sec^2) is the surface value of the acceleration of gravity; and c (m/sec) is the speed of light. In Equation 1, the ground speed is positive for eastward and negative for westward circumnavigations. At latitudes higher than the equatorial plane, the term in Equation 1, which depends linearly on the ground speed and gives an east-west directional asymmetry, becomes proportional to the cosine of the latitude,[10] so for latitudes as high as 60°, the directional dependence is reduced by less than one-half. Although Equation 1 is correct only to lowest order in the speed and altitude, it represents an extremely accurate approximation for jet speeds and altitudes because only these lowest order terms are detectable in this case.

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[8] Hafele, J.C. (1970), "Relativistic Behavior of Moving Terrestrial Clocks," Nature, Vol. 227, p. 270; Hafele, J.C. (1971), "Reply to Schlegel," Nature Phy. Sci. Vol. 229, p. 238; Hafele, J.C. (1971), "An Empirical Resolution of the Relativistic Clock Paradox," Bull. Am. Phys. Soc., Vol. 16, p. 611; Hafele, J.C., "Relativistic Time for Terrestrial Circumnavigations," Am. J. Phys. (in press, to appear January 1972).

[9] Ibid.

[10] Cutler, L.S. (1970), "Correction to 'Flying Clock' Comparisons Extended to East Europe, Africa and Australia," Hewlett-Packard Journal, Vol. 21 (March 1970), p. 10.

The actual time gain $\Delta\tau$ is a bit more instructive than the time ratio of Equation 1 and it follows from multiplication of Equation 1 by τ_0. Because standard clocks keep the same time while sitting on the ground anywhere on Earth (at average sea level and to this order of approximation),[11] only the actual time in flight during a trip contributes to relativistic effects. However, ground time does contribute to increasing the random, unpredictable time offset and therefore to the threshold for detection of relativistic effects. (Relativistic effects were not detected during previous flying clock trips because they accumulate only while the clocks are in flight, and for those trips most of the time was spent on the ground.) Suppose for the moment that ground time, for example, for refueling stops, is negligibly small compared with the time it takes to fly around the world. Then the time recorded by the ground clock during the circumnavigation is given by

$$\tau_0 = 2\pi R/|v| \ .$$

Solving for $\Delta\tau$ and inserting this value for τ_0 in Equation 1 gives

$$\Delta\tau = \frac{2\pi Rgh}{c^2}\frac{1}{|v|} - \frac{2\pi R^2\Omega}{c^2}\frac{v}{|v|} - \frac{\pi R}{c^2}|v| \ .$$

Figure 1 is a graph of this equation showing $\Delta\tau$ versus v for altitudes of 0, 10, and 20 kilometers. The dots in Figure 1 correspond to the cruising speed and altitude for a Boeing 707.[12]

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[11] Cocke, W. J. (1966),"Relativistic Corrections for Terrestrial Clock Synchronization," Phys. Rev. Letters, Vol. 16 (1966) p. 662.

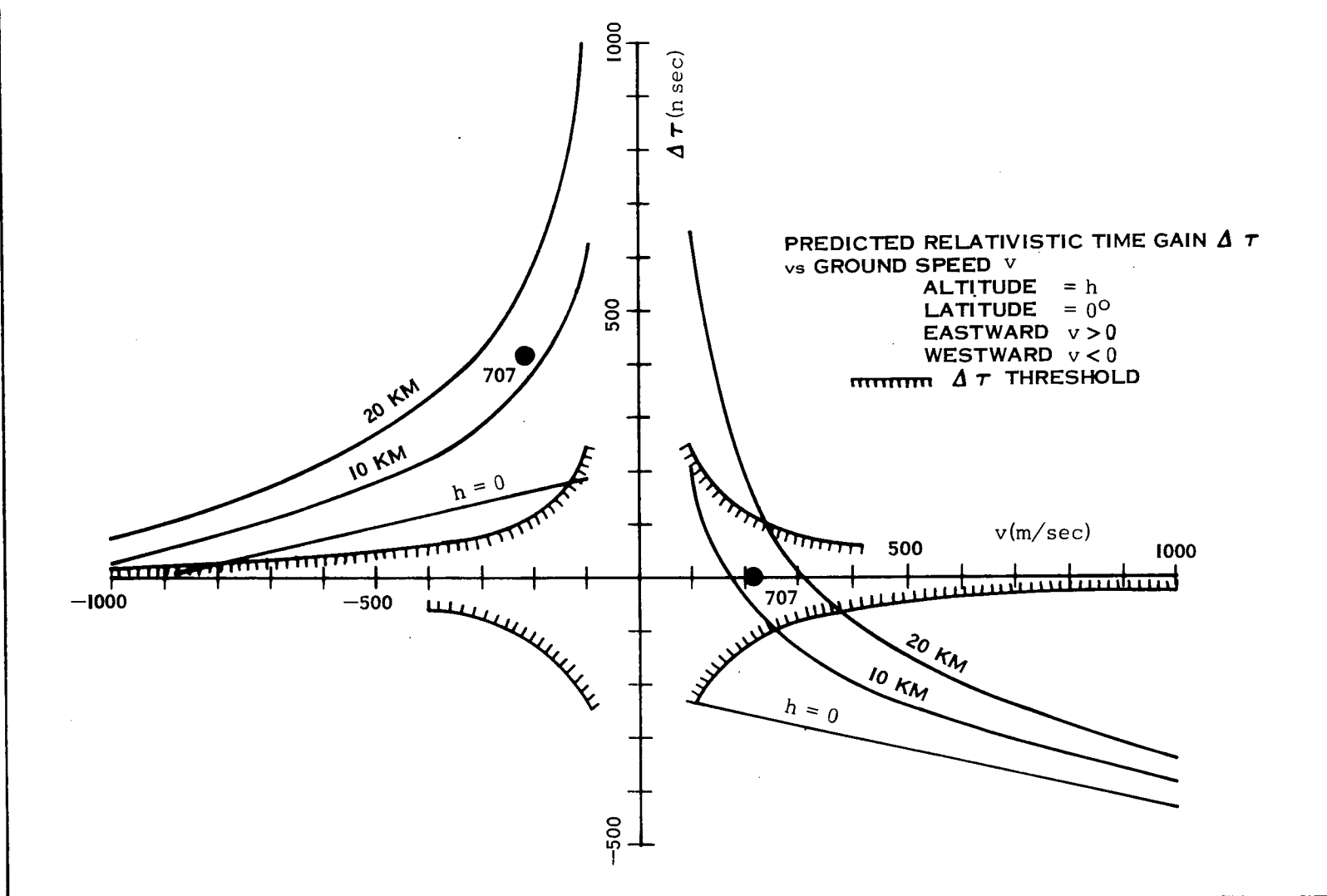[12] Schaefer, H. J. (1971), "Radiation Exposure in Air Travel," Science, Vol. 173 (1971), p.780.

Figure 1. PREDICTED RELATIVISTIC TIME GAIN $\Delta\tau$ vs. GROUND SPEED v
FOR EQUATORIAL CIRCUMNAVIGATIONS

Personnel of the Naval Observatory's Time Service Division have a considerable background of practical experience with cesium beam clocks, both in the laboratory and under traveling conditions. Their experience is that at the end of trips the time difference between the flying clocks and MEAN(USNO) is random with a zero center gaussian distribution having a spread of about 60 nanoseconds per day of trip.[13] Since this spread was for all portable clocks, "good" clocks may be expected to provide a somewhat lower threshold. A conservative estimate for the threshold of detection of relativistic effects with "good" clocks is given by

$$\Delta\tau_{threshold} = \frac{60 \text{ nsec}}{\text{day}} \times \tau_0 \text{ (days)} .$$

The hatched lines in Figure 1 represent this threshold. Figure 1 shows there is a variety of available conditions with jet aircraft which predict relativistic time differences exceeding this threshold.

Commercial around-the-world flights do not, of course, maintain constant altitude, latitude, or ground speed. In this case, it is necessary to perform a numerical integration of the relativistic equations. The necessary calculation is given by

$$\Delta\tau = \int_{\substack{flight \\ path}} \left[\frac{gh(\tau)}{c^2} - \frac{1}{2c^2} \left(2R\Omega\cos\lambda(\tau)\cos\theta(\tau)\,v(\tau) + v^2(\tau) \right) \right] d\tau, \tag{2}$$

where, for each interval of the summation, λ is the latitude, θ is the azimuth or bearing of the plane's velocity relative to east, and the rest of the symbols have the same meaning as for Equation 1 (v is the unsigned magnitude of the ground speed in Equation 2; the azimuth θ accounts for the direction).

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[13] Winkler, G.M.R., R.G. Hall, and D.B. Percival; Winkler, G.M.R. (1970) "Requirements and Performance for Today's Atomic Standards," _PTTI Strategic Planning Conference,_ Vol. 1, December 1970, p. 129.

5.0 PREDICTED RELATIVISTIC TIME DIFFERENCES

Necessary data for each around-the-world flight were provided by the various flight crew captains. (We are greatly indebted to Pan Am, American Airlines, and TWA, and their flight captains, for this extraordinary service, and to Pan Am and TWA for sending a company official as escort.) In most cases the flight paths were traced on appropriate flight maps with the time (GMT), altitude, and ground speed recorded regularly at navigation check points. The least accurate quantities are probably the times over the check points, which appear to have been recorded to only the nearest three or four minutes in some cases. Our own records of liftoff and touchdown times, recorded to the nearest minute, are in good agreement with the corresponding times provided by the flight captains.

The information on the flight maps divided the eastward circumnavigation into 125 intervals and the westward circumnavigation into 108 intervals. The latitude and longitude with the corresponding time for each check point permit calculation of the average latitude, azimuth relative to east, and ground speed for each interval. The average altitude for each interval was estimated from the altitudes recorded at the end points. These calculations and the summation indicated in Equation 2 were carried out with the Washington University IBM 360/50 computer. Table II summarizes the data for each direction, and gives the predicted relativistic time gains based on Equation 2.

6.0 AMBIENT CONDITIONS

In addition to recording time differences between the four flying clocks at regular intervals during each trip, we recorded at irregular intervals the temperature, pressure, and relative humidity with a small aneroid desk-top weather station; the compass direction with a small pocket compass; and the ambient magnetic field with a small pocket magnetometer. Before and after each trip the clocks were kept in an unused darkroom at

TABLE II. SUMMARY OF AROUND-THE-WORLD FLIGHTS AND PREDICTED
RELATIVISTIC TIME GAINS FOR FLYING CLOCKS

EASTWARD			WESTWARD		
Day	GMT	Location	Day	GMT	Location
04[1]	1930	USNO D[2]	13	1940	USNO D
05	0012	Dulles D (Pan Am 747)		2322	Dulles D (TWA 707)
	0656	London A[3] (*Pan Am 707)	14	0400	Los Angeles (*TWA 707)
	0814	D		0503	D
	0909	Frankfurt A		1014	Honolulu A
	1036	D		1313	D
	1248	Istanbul A		2015	Guam A
	1357	D		2113	D
	1513	Beirut A	15	0006	Okinawa A
	1619	D		0107	D
	1813	Tehran A		0209	Taipei A
	1940	D		0303	D
	2241	New Delhi A		0413	Hong Kong A
06	0000	D		1248	D
	0333	Bangkok A		1514	Bangkok A
	0513	D		1632	D
	0745	Hong Kong A		2006	Bombay A
	0855	D		2115	D
	1216	Tokyo A (*Pan Am 747)	16	0403	Tel Aviv A (*TWA 707)
	1432	D		0509	D
	2110	Honolulu A		0645	Athens A
	2314	D		0733	D
07	0350	Los Angeles A (*AA 707)		0903	Rome A
	0447	D		1001	D
	0713	Dallas A		1138	Paris A
	0753	D		1425	D
	0959	Dulles A		1557	Shannon A **
	1255	USNO return		1706	D
				2338	Boston A
			17	0118	D
				0226	Dulles A
				0400	USNO return

Trip time	65.42 hours		80.33 hours	
Avg ground speed	243. meters/sec		218. meters/sec	
Avg altitude	8.90 kilometers		9.36 kilometers	
Avg latitude -	34. degrees N		31. degrees N	
Rel time gain	-40. nsec (loss)		+275. nsec	

[1] October, 1971
[2] D - Depart
[3] A - Arrive

* Indicates clocks transferred to a different aircraft; 707 and 747 indicate
 Boeing aircraft type.

** Indicates an unscheduled fuel stop.

the Time Service Building where the temperature was held between 68 and 73°F. Temperatures during the trips averaged about 75°F with extremes between 70 and 85°F. During each flight between landing points, the cabin pressure dropped from 30 to 25 in Hg, except in one or two cases where it was not lowered that much. For each trip the relative humidity dropped from 60% to about 30%. Noticeably rough flying conditions occured only during the flight between Athens and Rome on the westward trip. At no time during either trip did any of the clocks lose regulation control; that is, the lights indicating momentary loss of feedback control did not light up.

The four clocks were carried as two assemblies, each assembly consisting of a bottom clock, a middle H-P K02-5060A battery pack and charging unit, and a top clock. To suppress any possible magnetic coupling between the clocks, additional magnetic shielding was placed between each clock and the battery pack of each assembly. Each assembly was rigidly bolted together.

For the eastward trip, the clocks were oriented in the airplane with the front of the clocks towards the front of the plane between Washington and London and between Tokyo and Washington, and with the front of the clocks towards the back of the plane from London to Tokyo. The clocks were oriented with the front of the clocks towards the front of the airplane during the entire westward trip. The clocks were strapped in seats in the passenger compartment.

When we discovered that one of the four batteries in one of the battery packs was dead, there was much concern on several occasions when electric power for charging the batteries was not available, because this abnormal situation caused the batteries to discharge rapidly. Fortunately, two of the clocks were never in jeopardy on this account, and our intercomparison data indicate no noticeable effect from low battery voltage for the clocks in question.

Near the end of the data period after the clocks were returned to the Naval Observatory, two environmental tests were performed. First, the clocks were reoriented to see if changes in the direction of the Earth's magnetic field caused noticeable changes in the clock rates; none were found. Secondly, line power charging the battery pack with the dead battery was interrupted for one hour to see if discharge of the remaining three batteries caused any noticeable change in the rates; again, none was observed.

Although environmental studies have shown that cesium beam clocks are susceptible to such effects as temperature changes and AC magnetic fields, it is important to note that no known effect consistently increases or decreases the rates for these clocks. That is, all known environmental effects cause rate changes that are random in direction. This observation gives additional confidence in the mean of an ensemble. (Strong DC magnetic fields cause predictable changes, but the clocks are triply shielded against the Earth's weak field.)

7.0   MEASURED TIME DIFFERENCES

A strip chart recorder with associated phase comparison electronics was used to record a continuous phase comparison between each of the four flying clocks and MASTER(USNO) before and after each of the trips. In addition, at periodic intervals before and after the trips, absolute time differences between the one second pulses or "ticks" were measured to the nearest nsec with a Hewlett-Packard computing counter.[14] The time differences between the ticks of each clock and MEAN(USNO) via MASTER(USNO) provide a calibration of the continuous phase graphs. Thus the rate of each clock relative to MEAN(USNO) before and after each trip is established.

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[14]Martin, D. (1971),"Frequency Stability Measurements by Computing System," Hewlett-Packard Journal, Vol. 23 (November 1971) p. 9.

Identically the same electronic arrangement was used for all time inter-comparisons.

Six intercomparison times between the four clocks (three of them are redundant but serve as a check on the measurements) were recorded with the same computing counter at hourly intervals for a short period before, during, and for a short period after each trip, with additional readings taken shortly before and after each touchdown and liftoff. These intercomparison data permit evaluation of the mean of the flying ensemble (MEAN(FLYING)) in much the same way as MEAN(USNO) is determined. Although evaluation of MEAN(FLYING) is not yet completed, we expect this analysis of the data to produce the highest level of confidence in our results, and we hope to be able to report them soon.

The results reported here depend only on the intercomparison data with MEAN(USNO) before and after the trips. The final analysis is not expected to change these results significantly.

An early and very preliminary estimate of the results was based on extrapolation of the rate for each clock immediately before the trips. The difference between this extrapolated time (to the end of the trip) and the observed time was averaged among the four clocks for each trip. Even with this very simple approach, consistent time differences were found. But even a casual observer would be quick to criticize this approach by pointing out that it is necessary that the rate after each trip be the same as before the trip, because it assumes no quasipermanent changes occurred during the trip. This approach is difficult to defend because quasipermanent changes did occur for each clock during each trip; it represents the lowest level of analysis and produced the least confidence. I wish to present here a somewhat higher level of analysis.

Let τ_{mean} and τ_c be the respective times indicated by MEAN(USNO)
and one of the clocks of the flying ensemble, and define the rate (difference)
R as

$$R_c = \frac{\tau_c - \tau_{mean}}{\tau_{mean}} = \frac{\Delta \tau_c}{\tau_{mean}}$$

Figure 2 shows measured values of $\Delta \tau_c$ versus τ_{mean} for each clock taken
before, between, and after the trips. (The curves in Figure 2 are displaced
vertically from the original data to improve clarity; this displacement of course
had no effect on the relative rates.) The vertical lines correspond to the
times the clocks were removed from and returned to the Naval Observatory.
Of course, no comparisons with MEAN(USNO) were possible during the trips.
The slope of each trace in Figure 2 gives R_c. A slope of 30° for this graph
corresponds to a rate of approximately 10 nsec/hour (2.8×10^{-12} sec/sec).
It can be seen that all the clocks agree with MEAN(USNO) to within
3×10^{-12} sec/sec. Notice also that numerous quasipermanent rate changes
occurred while the clocks were sitting in the laboratory. Moreover, rate
changes that are noticeably larger than those typical in the laboratory
occurred for each clock during at least one of the trips, except for clock
447. This result suggests that these clocks cannot be expected to perform
under traveling conditions as well as they do in the laboratory; this is not
particularly new information.

A careful study of the data shown in Figure 2 indicates that the rate
for each clock immediately before and after each trip can be evaluated to
perhaps better than 10% (except for the case of clock 361 after the eastward
trip). The following is an attempt to justify the approach used to derive the
results presented in this report.

During both trips each clock suffered one or more quasipermanent
rate changes. On the basis of "the least number of assumptions, assume
only one occurred. This change is then given by the difference in the rates
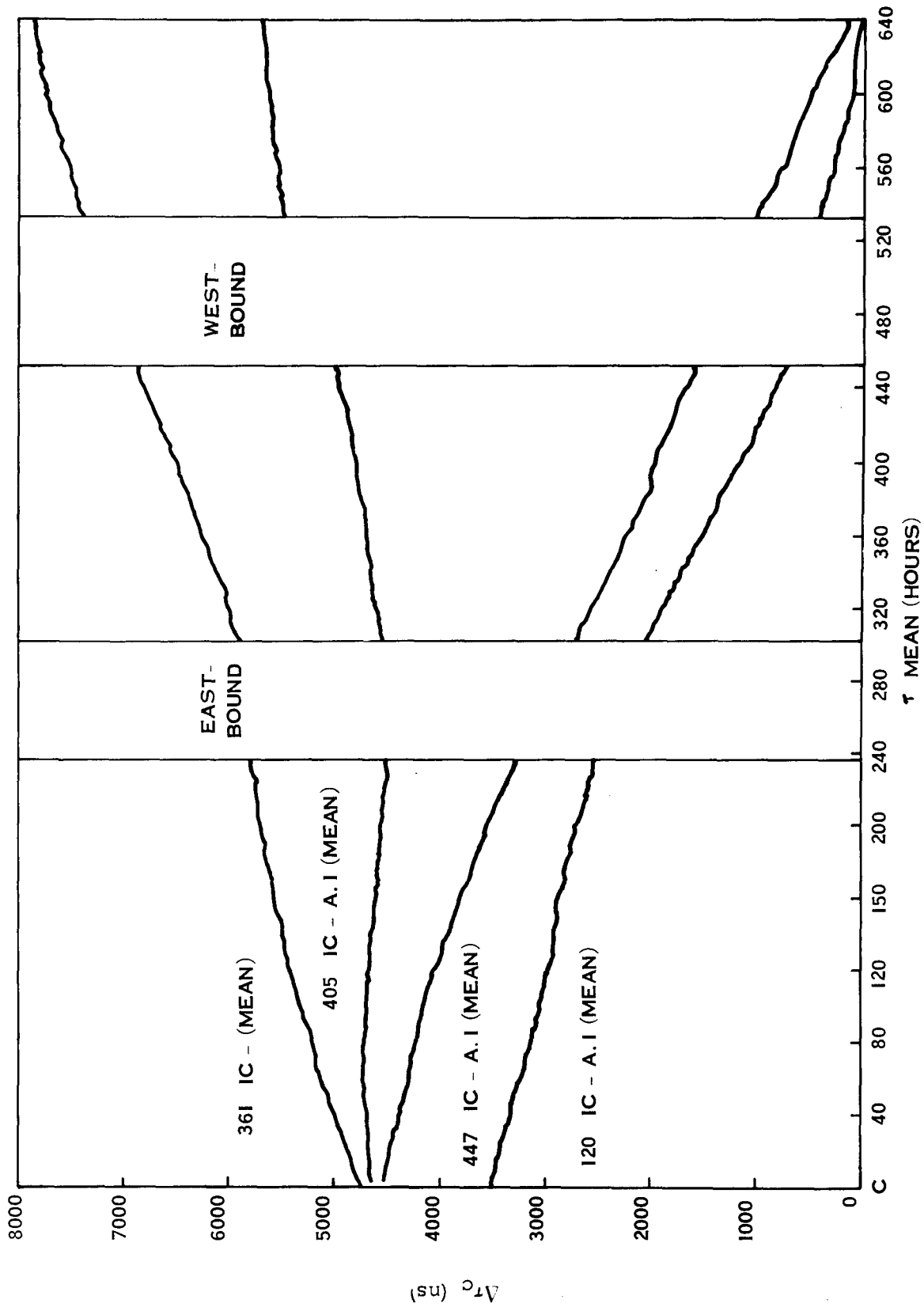
Figure 2. MEASURED VALUES OF $\Delta \tau_c$ VS τ MEAN FOR EACH CLOCK TAKEN BEFORE, BETWEEN, AND AFTER TRIPS

immediately before and after the trips. Without the inflight intercomparison data, we have no way of knowing at what time during the trip this rate change occurred. The least error accrues with the assumption that it occurred at the midpoint of the trip. Thus the average inflight rate (assuming no relativistic effects) is half the sum of the initial and final rates. Extrapolation with this average rate then gives the final times the clocks would have read if there were no relativistic effects. Figure 3 illustrates this approach and defines the symbols used.

Table III lists for each clock and each trip the initial and final rates, the average rate, the rate change, the observed initial and final time difference between each clock and MEAN(USNO), and the difference between the extrapolated time and the observed final time difference. Notice that the the average rate change for each trip is less than 1 nsec/hr (3 x 10^{-13} sec/ sec). Hence MEAN(FLYING) can be expected to produce considerably more reliable results. Most people (myself included) would be reluctant to agree that the time gained by any one of these clocks is indicative of anything, but the rather striking consistency between all four clocks must be taken seriously. The averages of the four final time differences are consistently negative or near zero for the eastward trip and consistently positive for the westward trip. Corresponding standard deviations are also listed in Table III.

Figure 4 summarizes our results at this stage of the analysis. The numbers in the blocks indicate the serial numbers for the corresponding clocks. The average of the observed time gains, with corresponding standard deviations, and the predicted time gains are shown at the bottom of Figure 4. It is amusing to notice that the values for the eastward trip are in excellent agreement despite our expectation that we would not be able to detect a definite effect in this direction. On the other hand, the effect for the westward trip was predicted to be considerably larger and detectable, but the observed value is more than one standard deviation below the predicted value. Hopefully our final analysis will improve the situation.

TABLE III. FLYING CLOCK DATA - RATES RELATIVE TO U.S. NAVAL OBSERVATORY MEAN

CLOCK (ser. no.)	R_i (ns/hr)	R_f (ns/hr)	$\overline{R}$ (ns/hr)	ΔR (ns/hr)	$\Delta\tau_i$ (ns)	$\Delta\tau_f$ (ns)	$\Delta\tau$ (ns)
Eastward flight							
$\tau = 65.42$ hr							
361	+2.66	+4.38	+3.52	+1.72	1790	1910	-110
408	-1.78	+3.22	+0.72	+5.00	-20	30	+3
120	-4.50	-8.89	-6.70	-4.39	-290	-780	-52
447	-7.16	-8.41	-7.78	-1.25	-1140	-1705	-56

$$\overline{\Delta R} = +0.27 \text{ ns/hr} \qquad \overline{\Delta\tau} = -54 \text{ ns}$$
$$\sigma_{\Delta R} = 3.8 \text{ ns/hr} \qquad \sigma_{\Delta\tau} = 46 \text{ ns}$$

CLOCK (ser. no.)	R_i (ns/hr)	R_f (ns/hr)	$\overline{R}$ (ns/hr)	ΔR (ns/hr)	$\Delta\tau_i$ (ns)	$\Delta\tau_f$ (ns)	$\Delta\tau$ (ns)
Westward flight							
$\tau = 80.33$ hr							
361	+6.89	+3.97	+5.43	-2.93	2880	3390	+74
408	+4.84	+2.16	+3.50	-2.68	490	980	+209
120	-8.88	-4.56	-6.72	+4.31	-2100	-2400	+240
447	-7.17	-9.42	-8.30	-2.25	-2840	-3390	+116

$$\overline{\Delta R} = -0.89 \text{ ns/hr} \qquad \overline{\Delta\tau} = +160 \text{ ns}$$
$$\sigma_{\Delta R} = 2.6 \text{ ns/hr} \qquad \sigma_{\Delta\tau} = 78 \text{ ns}$$

$$1 \text{ ns/hr} = 2.78 \times 10^{-13} \text{ sec/sec}$$

$$\sigma = \left[\frac{\sum (\Delta\tau - \overline{\Delta\tau})^2}{3} \right]^{\frac{1}{2}} \qquad \text{(standard deviation)}$$
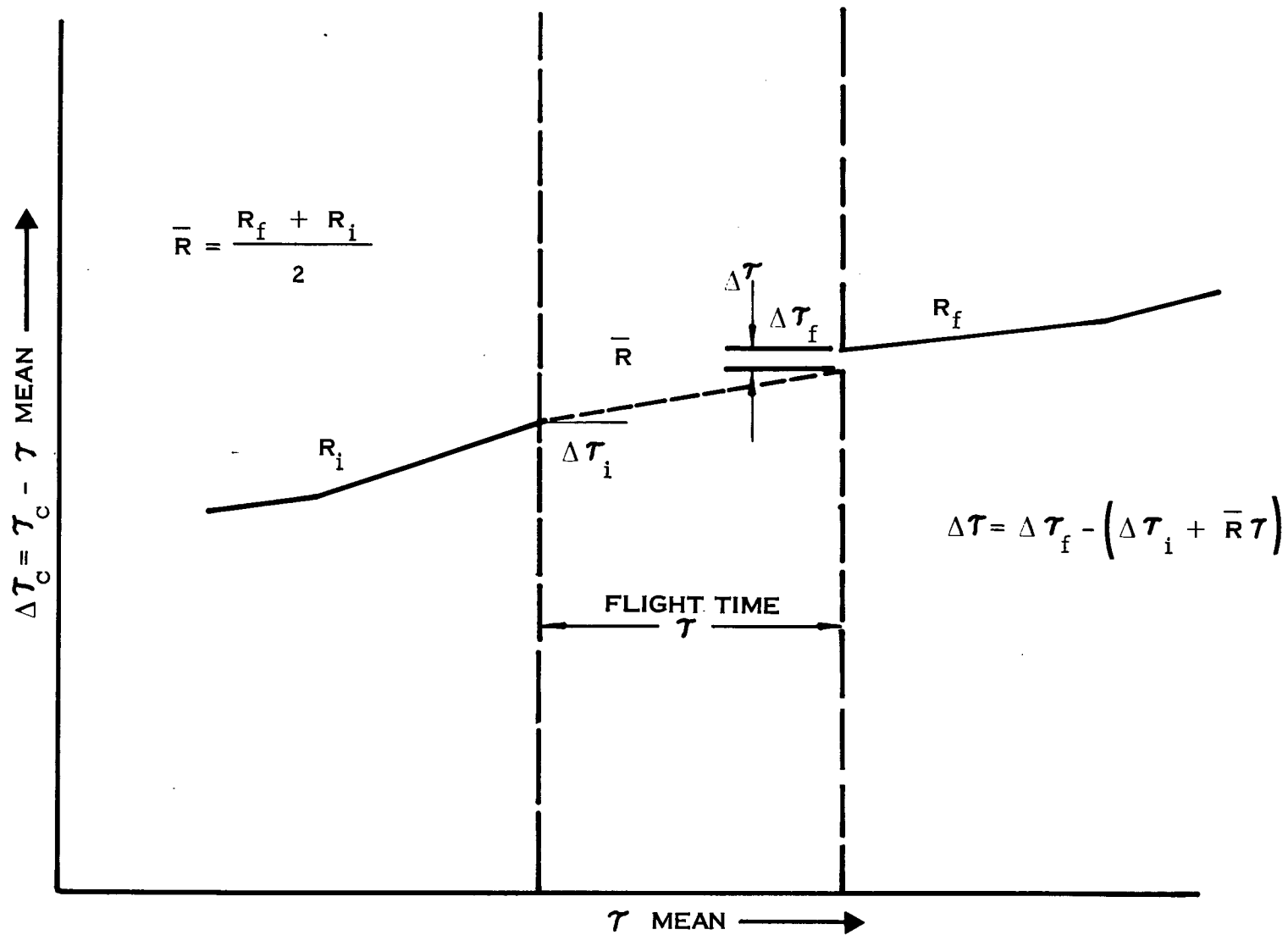
$$\overline{R} = \frac{R_f + R_i}{2}$$

$$\Delta \tau = \Delta \tau_f - \left(\Delta \tau_i + \overline{R} \tau \right)$$

FLIGHT TIME τ

τ MEAN $\longrightarrow$

$\Delta \tau_c = \tau_c - \tau$ MEAN

Figure 3. AVERAGE RATE METHOD FOR $\Delta \tau$

WESTWARD

361   447   408 120

-200   -100   0   100   200   300   400

$\Delta \mathcal{T}$(nsec)

EASTWARD

361   447 120   408

-200   -100   0   100   200   300   400

$\Delta \mathcal{T}$(nsec)

EAST

WEST

-200   -100   0   100   200   300   400

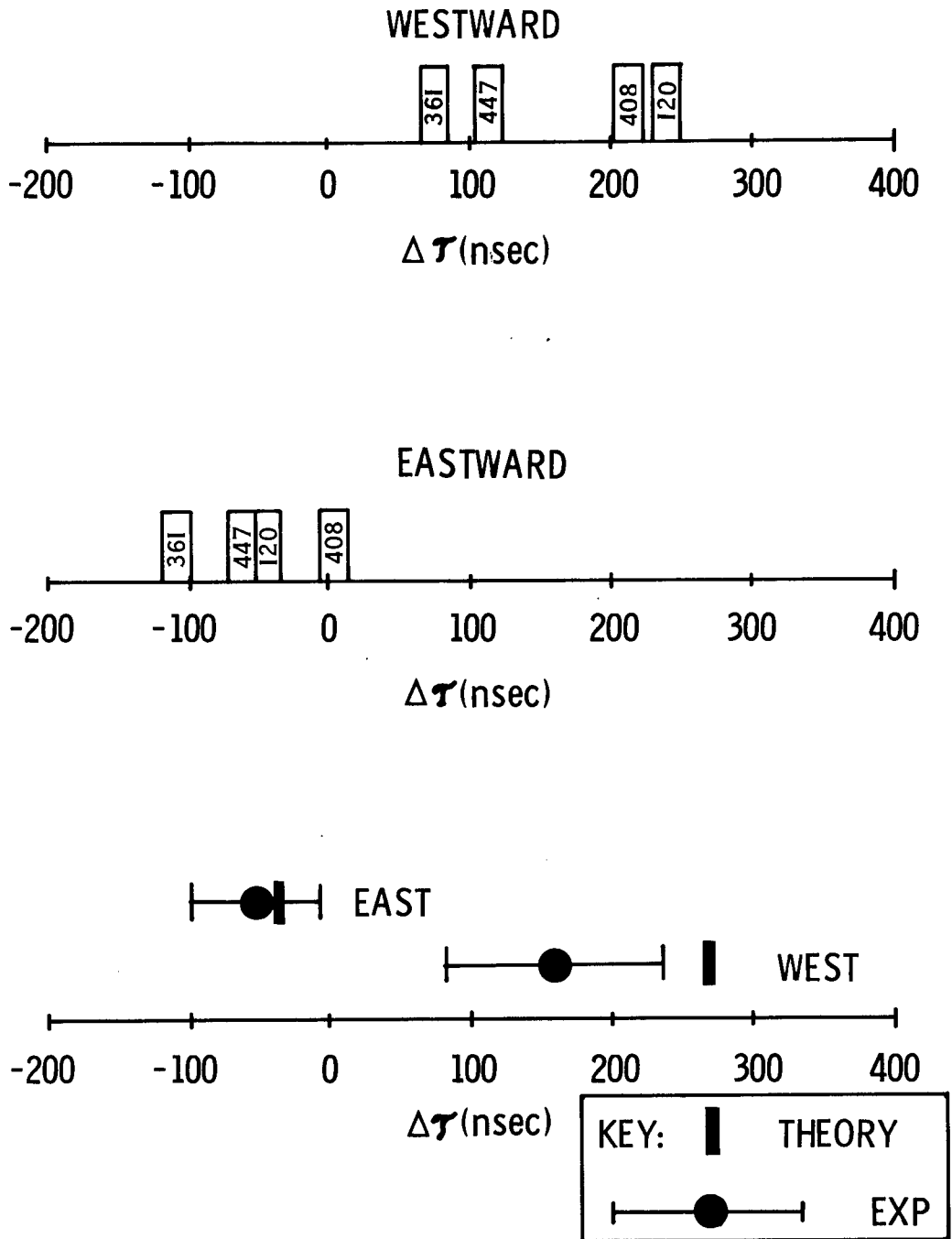$\Delta \mathcal{T}$(nsec)

KEY: ▮   THEORY

●   EXP

Figure 4.   TIME GAINED BY FLYING CLOCKS

8.0 SUMMARY AND CONCLUSIONS

Portable cesium beam clocks (model 5061A) cannot be expected to perform as well under traveling conditions as they do in the laboratory. Our results show that quasipermanent rate changes as large as 5 nsec/hr (120 nsec/day) may occur during trips with clocks that have shown considerably better performance in the laboratory. Of course, such changes reduce the utility of these clocks. For example, if a flying clock changes rate by 5 nsec/hr shortly after the beginning of a two-week trip, and no other significant changes occur, synchronizations with this clock shortly before the end of the trip would be off by 1.6μ sec. However, our results also suggest that the average of four flying clocks permits synchronization with an uncertainty of less than 1 nsec/hr (24 nsec/day), assuming no intercomparison data are recorded. With intercomparison data, it should be possible to reduce the uncertainty even further.

Although the final analysis of our data is not yet completed, we have established, with an intermediate level of analysis, that portable cesium beam clocks are capable of showing relativistic effects with relatively inexpensive commercial jet flights. The results of this analysis are in reasonable agreement with theoretical predictions. However, those who doubt the validity of conventional relativity theory, and there are many people in this category, probably will not be converted by the results shown in Figure 4. Indeed, the difference between theory and measurement in Figure 4 is disturbing, and if our final analysis does not improve agreement, an improved version of this experiment should be given serious consideration. The standard deviation on the measurement could be reduced considerably, probably by a factor of ten, with such improvements as the use of dual beam clocks and circumnavigations with less ground time. In any event, this experiment verifies unequivocally the existence of the predicted east-west directional asymmetry; only more precise magnitudes remain to be established.

DISCUSSION

MR. CHI: Is your predicted time drift, or time change, nanoseconds per day, the initial and final? Are they about the same length of time to determine those values?

DR. HAFELE: What I did was to go from the time, either starting or stopping of the flight, to the first rate change that was obvious in the laboratory. Now all of these included at least twenty-four hours. Many of the clocks changed either a day before the flight (there was a rate change in the laboratory) or a day after the flight (there was a rate change in the laboratory) and that's why, particularly in the case of 361 after the eastbound flight, it is quite uncertain what the rate is after the flight. Hopefully, the intercomparison data will clear this question up a lot. What we'll have is a mean flying rate before the flight and a mean flying rate after the flight, which should be equal; if these four clocks are working randomly, if these effects are random, they will scatter about a constant mean. However, there will be an offset in the mean due to the relativistic effect. The theory of relativity cannot induce any permanent rate changes; it's only while the clock is moving that these changes occur.

DR. ALLEY: I think that Professor Hafele and Mr. Keating and Dr. Winkler and others are to be commended for carrying out, for the first time, an experiment in which a recording clock has actually been carried in a closed path in space-time and returned. I would, however, caution members of the audience, or remind them, that special relativity has been verified in many, many experiments, as has the frequency change of transmitters, like gamma ray emitting atoms and so on. I think the primary significance of this lies in the first time of returning a clock and comparing actual elapsed time.

DR. WINKLER: I would also like to make a comment here and attempt a clarification of the additional data processing which is still to be done, and why it hasn't been done yet. I feel very guilty about the fact that we haven't been able to provide better support to this case. What has happened is that the data set is available in digital form, but there are a couple of errors which are quite evident when you look at the chart. Charts are automatically produced from the data set, and Professor Hafele's assistant, Mr. Keating, had to be sent on temporary analysis duty immediately after their return. Therefore we felt it was wise to let the same people complete the analyses who have collected the data.

The analyses will be completed when the remaining 90 percent of the information is processed. I think what has been represented is not more than 10 percent of what is actually available by way of measurements. The basic idea is to keep account, by using the internal measurements, of the measured frequency variations of each standard and to be able to connect the average rate across a flight duration to what you find after you return. If the rate that you predict is altered by all corrections following from the hourly measurements made during the flight, and that result is very close to measurements after return, I think you will have a very great confidence in the result. So I am confident that data processing will produce a much more objective and much greater confidence in the final result, because we use an automatic procedure in which judgments are left to the computer.

DR. HAFELE: I wonder if I could respond to Professor Alley's comment. He said that the special theory had been thoroughly proved by all kinds of experiments. Well, I think that in the same respect there's never been an experiment done by anybody on either the special or the general theory of relativity which disproves either one. The general theory just makes some interesting predictions that you can't test. Does a clock on the ceiling run slower than a clock on the floor? We don't know for sure, but it looks as though when you send gamma rays up from a radioactive nucleus, they are absorbed only if you doppler shift the upper nucleus. Does that prove that a clock on the ceiling runs slower than a clock on the floor? Many people will say "yes, it has to, and there's no point in doing the experiment." But then there are a lot of people who don't buy that argument. So the special theory has been tested in the same way that the general theory has been tested so far.

DR. ALLEY: I just want to make clear that I do regard such experiments as worthwhile. In fact, there are people who have questioned the assumption that clocks actually run at different rates in different gravitational potentials. But that is an integral part of the structure of general relativity which has been tested to a certain extent. However, convincing demonstrations of this, I feel, are very much in order.

MR. GATTERER: For what it's worth department, I would not accuse Dr. Bonanomy of saying that this observation is worth very much. He may not even wish to be quoted in this gathering, but he's had recent experience in transporting portable clocks around in cars, and it is his opinion that, or at least it is his suspicion that, the environment in an aircraft is a little more devastating to a cesium standard than it is in a car. His experience indicates that his closing error is smaller than, for example, the Naval Observatory's portable clock trips. It is entirely possible that the environment that may be to blame is a relativistic change, although I think he thinks that the loading and the

unloading process is damaging; therefore your data are varied, perhaps, in knocks and bumps.

DR. WINKLER: If you look at the differential phase plots available on the little paper and follow these differential phase plots which have been using the data throughout, the laboratory stay, the westward trip, the eastward trip and so on, you cannot discern any substantial change in the appearance of these phase plots. There are clock pairs--incidentally not in the same package--which have an extremely uniform performance, and there are instances in which you can identify very well the moment and the magnitude of the frequency change. I don't know if we have labeled them, but cesium 120 has suffered on the westward trip, a very definite and very accurately determined frequency shift. You question the effect of the environment. Well, that has been the main purpose of conducting the experiment; that is why we got the eight thousand dollars from ONR, to study that effect. I think we have plenty of information on it, some of it can be inspected visually, and I meant you to do that. I think the aircraft environment is somewhat better than in a car, it depends whose car. I think that is a very wise comment because Dr. Bonanomy's car may have been particularly bumpy.

DR. RUEGER: Were you instrumented in the three dimensions of the accelerational field during the flights?

DR. HAFELE: No, we don't know what the accelerational fields were, except for those that we felt. The plane jiggled a little bit between Athens and Rome, and there was some rough weather. When we were sitting in the seat we felt about as heavy as we always feel.

DR. RUEGER: But the circling of an aircraft over an airport would be an asymmetrical field you'd get on this instrument.

DR. HAFELE: Very slight. You mean that the force down would not be balanced by upward force; you mean that there would be a sidewise force on the clock. Very slight, I suppose that, yes, if you turned the clocks over it changes them. Well, I'm not the expert on how these clocks perform under various environmental conditions.

DR. RUEGER: Well, we knew that this was a very important parameter in the carrying of crystal clocks, and we've always been very careful to block them up square and do other things to keep them from being the least bit out of square.

DR. HAFELE: I see what you mean. Yes, the clocks sat in the seat and they weren't square in the seat, they were tilting back a bit in the seat, so they weren't sitting level in the plane. It was almost impossible to do that; we weren't rigged to do that. We just plopped them down on the seat and strapped them in.

MR. COCHRAN: Has anyone checked the gravitational effect of a high-altitude ground level against sea level? Or would that be within the accuracy of the clock?

DR. HAFELE: You can see from the plot (Figure 1) the difference between altitude zero and altitude 10 kilometers. With a high altitude balloon you can easily go to 100 kilometers. Nobody's ever done such an experiment.

DR. RUEGER: There was, I think, an experiment done with crystal clocks in eccentric orbits. If you massage the data rather exhaustively, they could show there was indeed an influence on what we call the gravitational redshift which at the surface of the earth is in the order of two parts in ten of the thirteen per kilometer. This is an effect of the difference of gravitational potential.

DR. HAFELE: You're talking about frequency now, though; I'm talking about time. That experiment was done with frequency on a crystal oscillator in a satellite.

DR. RUEGER: Frequency is synonymous with time for most people. Anyway, the experiment did show the periodic effect with the period of the orbit and I think there was a confirmation in that of, perhaps, 20 percent. Is that reasonable?

DR. HAFELE: I looked at those data and you believe what you wanted in there. If you don't want to believe it you don't need to. If you want to, you see it there.

DR. WINKLER: I would like to add an entirely different comment here. The experiments may have been more practical and may have more practical relevance than appears at this stage. Carrying clocks around the earth in a non-inertial frame of reference is essentially the same thing as sending an electromagnetic wave around the earth one way and the other way. If you remember the discussions about utilizing the Defense Communications Satellite System for high precision synchronization, if we have a network which depends on an internal high precision synchronization to within a

few tenths of nanoseconds, then we will have to expect that the network will have some border difficulties. This depends on which way around we have propagated the precision timing, and this is a test which we have considered doing. We have discussed it with some people in DCA; there are some difficulties of an entirely practical nature. On the other hand, it has practical implications for the design of the systems and the operational routines to be employed.

DR. HAFELE: The magnitude of that effect is, I believe, about 250 nano-seconds difference in time. It's a big effect--a quarter of a microsecond.

MR. BARTKO: Why don't you take the predicted offset and get the clock out of synchronization and then try to bring it back in synchronization by going around the world, reversing the experiment so to speak?

DR. HAFELE: I'm not sure I understand. You want to predict where the plane's going to go so you can make a prediction of what the relativistic effect will be, and then you change the setting of the clock before you take off? And then come around and see if it reads zero? What is gained by that?

MR. BARTKO: Well, that's the reverse of what you did originally.

DR. HAFELE: I must admit I don't see the gain. I suppose that changing something in one of these clocks is one of the worst things you can do; just reaching in there and turning a knob, it takes it two weeks to settle down.

DR. KLEPCZYNSKI: I don't believe you could make a prediction in advance as to what the retardation or advance would be, because you wouldn't know what altitude or velocity you're flying at.

DR. HAFELE: That would be a problem.