12. G. Wald, P. K. Brown, P. H. Smith, *Science* **118**, 505 (1953).
13. C. D. B. Bridges, *Vision Res.* **7**, 349 (1967).
14. F. I. Harosi and E. F. MacNichol, Jr., *J. Gen. Physiol.* **63**, 279 (1974).
15. The response magnitude of NBT reduction to NBT-DF is a sigmoidal, saturating function of log photon capture, and 18 of the 28 points utilized in generating the response spectra fell on the log linear portion of the function.
16. This work was supported in part by NSF grants GB-27561-X and GB 41460, NIH grant EY-00381, and grant FD-00687 from the Food and Drug Administration.

23 June 1975; revised 20 October 1975

## Acceleration and Clocks

Cannon and Jensen (*1*) have given a review of the development of timekeeping and the establishment of internationally recognized standards of time. They have emphasized the presence of relativistic effects at the different locations which would introduce rate differences even if there were no systematic or random errors from the rates of perfect atomic clocks. From the records of intercomparisons of the clocks at seven contributing laboratories for a 1-year period, Cannon and Jensen develop statistical evidence which they see as supporting a theory that adds to the time dilations derived from general relativity a new term attributed to the centripetal accelerations of the clocks. They refer to this evidence as a discovery.

In Cannon and Jensen's derivation from general relativity of the rate differences for the different geographical locations, their equation 44, they have introduced the elevations of the stations relative to the geoid as the relevant parameter. The geoid is a surface on which the combined effects of the velocity due to the earth's rotation relative to an inertial frame and the effect of the gravitational potential combine to a constant, an equipotential surface of gravitation and acceleration. Because the earth's surface is so shaped that it comes close to the geoid, the net corrections are very small except for the National Bureau of Standards station at Boulder, Colorado. The small predicted rate differences are tabulated in their table 4 in the column labeled elevation. Their alternative analysis adds a term attributed specifically to acceleration, which they claim to derive by analogy to the derivation of the gravitational redshift from the principle of equivalence. In the use of the geoid, however, they have already invoked the concept of an acceleration potential as a calculating device to account for the rotational velocities. The principle of equivalence was devised as a method allowing the calculation of the effects of gravity as if they were kinematic. It must surely be circular to analyze an effect which is indeed kinematic, such as acceleration itself, via the equivalence principle. The kinematic effect of acceleration is to allow the stations to move at different velocities and yet conserve their physical separations.

In essence, because the elevations relative to the geoid are small and general relativity predicts only small rate differences, the addition of a second term derived from the rotation, which is exactly the normal one but not compensated by a gravitational effect, results in a net correction which is just that which would come about were there no gravitational redshift. The evidence, interpreted in this way, seems hardly strong enough to be accepted.

There is, in fact, much evidence in support of the straightforward interpretation of the effect of the rotating frame, which is, in itself, just special relativity. The comparison by Hafele and Keating (*2*) of the time displacements of clocks carried around the world in aircraft, eastward and westward, was fit to formulas that contained straightforward kinematic terms (including the airplanes' velocities) as well as the gravitational ones.

The measurement of the gravitational redshift by Pound and Snider (*3*) was compared to $gh/c^2$, where $h$ was the vertical path length traversed, $c$ was the speed of light, and $g$ was the local acceleration in free fall and included the effect of the noninertial frame at about –0.3 percent of the effect of gravity. The experimental precision was just less than could resolve that contribution. However, several experiments that demonstrate the validity of the simple kinematic time dilation for systems possessing far larger accelerations than that of the earth's rotation are well known (*4*).

R. V. POUND
W. T. VETTERLING
*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*

**References**

1. W. H. Cannon and O. G. Jensen, *Science* **188**, 317 (1975).
2. J. C. Hafele and R. E. Keating, *ibid.* **177**, 166 (1972).
3. R. V. Pound and J. L. Snider, *Phys. Rev. B* **140**, 788 (1965).
4. H. J. Hay, J. P. Schiffer, T. E. Cranshaw, P. A. Egelstaff, *Phys. Rev. Lett.* **4**, 165 (1960); R. V. Pound and G. A. Rebka, Jr., *Phys. Rev.* **4**, 274 (1960); D. C. Champeney, G. R. Izaak, A. M. Khan, *Nature (London)* **198**, 1186 (1963); W. Kundig, *Phys. Rev.* **129**, 2371 (1963); F. J. M. Farley, J. Bailey, R. C. A. Brown, M. Giesch, H. Jostlein, S. van der Meer, E. Picasso, M. Tannenbaum, *Nuovo Cimento A* **45**, 281 (1966).

5 May 1975

In their article Cannon and Jensen (*1*) compared the Coordinated Universal Time (UTC) time scales during 1972 of seven laboratories and concluded that the scale of the Royal Greenwich Observatory (RGO) was "running at an anomalous rate," even though they recognized that it was "the most stable clock of all." They went on to say that "the reason for RGO's anomalous behavior is unknown and merits investigation." It is unfortunate that the authors did not seek comments on their comparisons before publication since the explanation is obvious to us. Since the beginning of 1972 several of the UTC scales have been adjusted empirically (or "steered") in order that they should conform closely with UTC (BIH), which is determined in arrears by the Bureau International de l'Heure; UTC (BIH) has the same rate as International Atomic Time (TAI), but differs from it by an integral number of seconds. The rate of the RGO scale was, however, deliberately made equal to that of the stable, independent Greenwich atomic time scale, GA2. No further explanation of the differences in rate and stability of the UTC scales is required.

Since the beginning of 1974 the rate of UTC (RGO) has also been adjusted to bring it into conformity with UTC (BIH), but every effort has been made to maintain the independence, uniformity, and stability of the Greenwich atomic time scale; in particular, no attempt has been made to steer it to bring its rate close to that of TAI. The current evidence suggests that the second of GA2 is closer to the SI (International System) second than is the second of TAI.

C. J. A. PENNY
H. M. SMITH
G. A. WILKINS
*Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East Sussex BN27 1RP, England*

**References**

1. W. H. Cannon and O. G. Jensen, *Science* **188**, 317 (1975).

16 June 1975

We wish to clarify some essential points relative to the article by Cannon and Jensen (*1*). These authors have developed two contradictory equations (their equations 44 and 45) based on different relativistic assumptions and have attempted to "resolve the contradictions between Eqs. 44 and 45" using data tabulated by the Bureau International de l'Heure (BIH) on atomic clocks located at various places in North America and Europe. The principal effects of interest are the transverse Doppler shift (velocity), gravitational redshift, and acceleration. The atomic clock data Cannon and Jensen have used are those for the $UTC_i$, where the $i$ denotes the contributing observatory or laboratory generating a particular Coordinated Universal Time scale. As members of three of these contributors, we are obliged to state that Cannon and Jensen's assumption that the intervals on the time scales $UTC_i$ of the contributing observatories correspond to the adopted definition of the second is not valid at the accuracy they need to test the contradiction between their equations. Cannon and Jensen have calculated the effects to parts in $10^{15}$ and need better than 1 part in $10^{13}$ to resolve the contradiction with any confidence, whereas the manufacturer's accuracy specifications for the atomic clocks involved are only 1 part in $10^{11}$. The standard deviation of the frequencies of the cesium standards as produced is about 2 parts in $10^{12}$. Also, each contributor as it generates its particular $UTC_i$ has as its goal time scale uniformity and coordination with the UTC scale generated at the BIH. This necessitates occasional deliberate frequency changes in the $UTC_i$. As the name implies, these are coordinated time scales. Therefore, the $UTC_i$ are not "proper time" scales, as was assumed by Cannon and Jensen. The basic agreement in frequency of the $UTC_i$ at the level indicated by Cannon and Jensen is due more to the goal of coordination on the part of those originating these scales than to any fundamental physics involved with the definition of the second. In fact, only the time scale at the National Research Council of Canada, UTC (NRC), reflects information on the definition of the second via primary standards.

The available data on the primary cesium beam frequency standards at the National Bureau of Standards (NBS), National Research Council (NRC), and Physikalisch-Technische Bundesanstalt (PTB) are very relevant to resolving the contradiction in Cannon and Jensen's equations. Listed in Table 1 are some results compiled from other publications (*2*) as well as from Cannon and Jensen (*1*). The laboratory measurements of the primary standards are with respect to the $UTC_i$ time scales where frequencies are known with respect to each other via the Loran-C network. The uncertainties on the measurements listed are estimated from the inaccuracies of the primary standards involved as well as that due to the comparison medium. The measured data are in agreement with the gravitational redshift effect within the uncertainties and tend to contradict the combined elevation and latitude effect of Cannon and Jensen. This conclusion is supported by other experimental results showing no acceleration dependence in clocks (*3*).

Table 1. Fractional frequency differences between the primary frequency standards in parts in $10^{13}$. The Cannon-Jensen effect is their combined elevation and latitude effect.

| Laboratories | Cannon-Jensen effect | Gravitational redshift | Measured differences |
|---|---|---|---|
| NBS-NRC | 0.5 | 1.8 | $+2 \pm 2$ |
| PTB-NRC | 1.4 | 0.0 | $-1 \pm 2$ |
| PTB-NBS | 0.9 | $-1.8$ | $-3 \pm 2$ |

Cannon and Jensen have taken their basic assumption of proper time intervals for the $UTC_i$ from recommendation 460 of the International Radio Consultative Committee. If one is to read further on in this recommendation, the tolerances for the $UTC_i$ are "that the time signals should not deviate from UTC by more than one millisecond; that the standard frequencies should not deviate by more than 1 part in $10^{10}$." More recent measurements have revealed that in 1972 the UTC time scale was high in frequency by about 1 part in $10^{12}$ with respect to the new primary standards.

We conclude that the experimental data used by Cannon and Jensen contain inaccuracies and systematic effects which render their conclusion invalid. To the contrary, experimental data do exist which contradict their conclusion that an "observer's perception of the world geometry depends on his state of acceleration"; hence, Cannon and Jensen's latitude effect on the surface of the earth has no experimental support.

DAVID W. ALLAN
*National Bureau of Standards,*
*Boulder, Colorado 80302*
A. G. MUNGALL
*National Research Council,*
*Ottawa, Ontario, Canada*
GERNOT M. R. WINKLER
*U.S. Naval Observatory,*
*Washington, D.C. 20390*

**References**

1. W. H. Cannon and O. G. Jensen, *Science* **188**, 317 (1975).
2. A. G. Mungall, R. Bailey, H. Daams, D. Morris, C. C. Costain, *Metrologia* **9** (No. 3), 113 (1973); D. J. Glaze, H. Hellwig, D. W. Allan, S. Jarvis, Jr., A. E. Wainwright, *IEEE (Inst. Electr. Electron. Eng.) Trans. Instrum. Meas.* **IM-23**, 489 (1974); G. Becker, *PTB Mitt. Jahrg. 83* (1973), pp. 319–326; D. W. Allan, H. Hellwig, D. J. Glaze, *Metrologia*, in press.
3. J. C. Hafele and R. E. Keating, *Science* **177**, 166 (1972); *ibid.*, p. 168; K. S. Thorne and C. M. Will, *Astrophys. J.* **163**, 595 (1971).

12 May 1975

Recently we reported evidence for the direct effect of accelerations on the rates of near ideal atomic clocks (*1*). Such an effect, we argued, would be manifest as a latitude dependence of proper time over the rotating earth's surface. Further work has been done on this problem. New data have been studied and the problem examined in greater detail. We now believe that our earlier thesis is not supportable. No strong evidence for direct acceleration effects on the rate of near ideal clocks can be derived from a large set of recent international atomic timekeeping intercomparisons. Our previous conclusions were apparently based on an improbable artifact of the UTC data.

During May and June of 1975, one of us (O.G.J.) reviewed raw data of intercomparisons among all individual atomic clocks contributing to the BIH dispersed throughout North America and Europe. It became clear that the intercomparisons between the international and laboratory UTC scales used in our previous analysis could not have provided a reliable test of our conjecture. In particular, each laboratory's $UTC_i$ time scale proved to be a local physical materialization, generally via a single real and operational clock, of UTC agreeing as closely as reasonably possible with the international scale. Agreement of $UTC_i$ scales with UTC itself has been and is now left to the discretion of each national laboratory. No independent attempt is made to separately and accurately materialize a $UTC_i$ time scale composed of SI seconds directly. Thus, contrary to our previous assumption, these time scales cannot be considered good approximations to local proper time. Furthermore, certain laboratories, particularly NBS, impose clock rate offsets in their attempt to materialize an agreeable $UTC_i$ scale. Other laboratories often merely choose a single most agreeable clock to materialize their scale.

Since 1 January 1972, the BIH has maintained a record of the rate of every individual Hewlett-Packard cesium standard contributing to TAI. The number of such standards has grown steadily from 50 or so at the commencement of the record to more than 80 at the present time. By agreement, each individual frequency standard is left to run at its natural rate derived passively from the microwave transition at 9, 192, 631, and 770.0 hertz between two hyperfine levels of the ground state of $^{133}Cs$. Thus, each clock in this data set obtains an independent measure of the passage of local proper time measured in SI seconds. However, these clocks are not individually accurate enough to test the hypothesis stated in our article (*1*). We had proposed an effect whose magnitude did not exceed $\Delta \nu / \nu = 0.3 \times 10^{-12}$ for the geographic locations considered. Hewlett-Packard's specifications for the accuracy of such clocks are $\pm 1 \times 10^{-11}$ for the 5016-Å cesium beam frequency standard equipped with the earliest cesium beam tube and 0.7 $\times 10^{-11}$ for standards equipped with the "supertube." These clocks fail by more than an order of magnitude in accuracy to test the effect we suggested.

However, as our earlier analysis was based not on absolute but on relative time intercomparisons, the ability of the instrument to materialize the SI second is not the appropriate measure of its usefulness; rather the reproducibility—"the degree to which an oscillator will produce the same frequency from unit to unit and from one occasion of operation to another" (*2*)—becomes the important measure. Hewlett-Packard's specifications for reproducibility are $\pm 5 \times 10^{-12}$ for the standard equipped with the normal tube and $\pm 3 \times 10^{-12}$ for one equipped with the supertube. Their conservative specifications were easily achieved according to our recent analysis of approximately 80 standards, most of which possessed only the normal tube. Reproducibility among the set was found to be better than $\pm 1.2 \times 10^{-12}$ at the level of 1 standard deviation. However, even this level of reproducibility exceeds our maximum predicted effect by a troublesome factor of 4. Since individual atomic clocks are so far incapable of testing our conjecture, it is necessary to appeal to a statistical test.

From the beginning of 1972 until the present the BIH has published the "rate" averaged over 60 days of all individual Cs standards contributing to TAI [tables 19 and 20 in (*3*); table 8 in (*4*)]. The rate of each clock is equal to $1 + \epsilon$, where $\epsilon$ is given by the expression (*4*)

$$\epsilon = \frac{\mathrm{TAI} - \mathrm{AT}_j}{\Delta\mathrm{UTC}}$$

The TAI scale is maintained by the BIH by computation based on the entire set of individual Cs standards through an algorithm called ALGOS; $\mathrm{AT}_j$ is the atomic time scale measured by the particular $j$th clock; and $\Delta$UTC is the interval passed on the UTC time scale, which is equivalent to the TAI scale except for 1-second step adjustments that are necessary from time to time and are properly accounted for by ALGOS. It should be noted that a positive rate indicates that the $j$th clock is running slower (that is accumulating seconds more slowly) than TAI and UTC.

In cooperation with the BIH we have analyzed 18 separate experiments, each of 60 days UTC duration, comprising intercomparisons of all individual clocks against TAI made from 1 January 1972 to 21 December 1974. Three formulas describing clock rates with respect to TAI were compared to the results of these experiments:

1) Cannon-Jensen hypothesis

$$\epsilon = -\frac{1}{c^2}(gh - \pi G \rho_b h^2 - \frac{1}{2}\Omega^2 r_e^2 \cos^2\phi)$$

Table 1. Variances of rate.

| Modified Julian date | Uncorrected variance (nsec/day)$^2$ | Corrected variance (nsec/day)$^2$ | | |
|---|---|---|---|---|
| | | Cannon-Jensen | Gravitation theory | Special relativity |
| 41,379 | 30,086 | 30,612 | 29,903 | 30,833 |
| 41,439 | 31,620 | 31,672 | 31,554 | 31,777 |
| 41,499 | 38,861 | 39,298 | 38,748 | 39,449 |
| 41,559 | 31,644 | 31,825 | 31,551 | 31,964 |
| 41,619 | 33,422 | 33,380 | 33,337 | 33,509 |
| 41,679 | 34,892 | 35,213 | 34,807 | 35,321 |
| 41,739 | 33,171 | 33,121 | 33,114 | 33,198 |
| 41,799 | 29,803 | 29,339 | 29,725 | 29,434 |
| 41,859 | 29,044 | 28,638 | 29,252 | 28,463 |
| 41,919 | 28,814 | 28,634 | 28,751 | 28,716 |
| 41,979 | 33,049 | 33,168 | 33,067 | 33,168 |
| 42,039 | 24,292 | 24,346 | 24,320 | 24,348 |
| 42,099 | 20,833 | 20,788 | 20,891 | 20,763 |
| 42,159 | 23,493 | 23,590 | 23,532 | 23,573 |
| 42,219 | 20,343 | 20,256 | 20,312 | 20,309 |
| 42,289 | 22,067 | 21,894 | 21,989 | 22,000 |
| 42,349 | 21,997 | 22,128 | 21,911 | 22,241 |
| 42,409 | 21,406 | 21,453 | 21,294 | 21,591 |

2) Standard gravitation theory (transverse Doppler shift plus gravitational redshift)

$$\epsilon = -\frac{1}{c^2}(gh - \pi G \rho_b h^2)$$

3) Special relativity (transverse Doppler shift)

$$\epsilon = \frac{1}{c^2}\frac{\Omega^2 r_e^2 \cos^2\phi}{2}$$

where $gh/c^2$ represents a contribution to $\epsilon$ from the gravitational redshift, $\pi G \rho_b h^2/c^2$ the Bouguer contribution to $\epsilon$, and $\Omega^2 r_e^2 \cos^2\phi/2c^2$ a latitude-dependent time dilatation. Here $c$ is the speed of light, $G$ the Cavendish constant, $g$ the magnitude of local gravitational acceleration, $r_e$ the radius of an assumed spherical earth, $\Omega$ the earth's sidereal rotation rate, $\phi$ the geocentric latitude, and $h$ the elevation of the clock above mean sea level. In computing the theoretical contributions to $\epsilon$ for each clock, somewhat more exact formulas were used (*1*) to take into account the earth's ellipticity.

The analysis proceeded as follows. Each clock rate was corrected by each of the three formulas according to clock location. The scatter of the corrected clocks was then measured by computing the rate variance. The BIH produces, via ALGOS, weightings which constitute an objective quality judgment on each clock [tables 21 and 22 in (*3*); table 19 in (*4*)]. These weightings were used in calculating the rate means and variances. Table 1 gives the results of this analysis. From Table 1 it is evident that none of the three formulas clearly best minimizes the clock rate variances. These are so large as to mask the effect of any of the corrections and are, in fact, measures of the current limitations on clock reproducibility. The analysis could have been continued toward higher moments of the statistical distributions but this was judged fruitless. One might say, as a result of this analysis, that the question of the effects of acceleration on clock rate is left unresolved. But this would be to neglect the contrary evidence derived from certain other experiments, some of which are pointed out by Pound and Vetterling earlier.

Allan *et al.* have shown the results of fractional frequency differences between the three primary frequency standards (NRC, NBS, and PTB). As suggested to us by Guinot (*5*), these standards come closest to providing the accuracy in realization of the SI second necessary for detection of our suggested effect. However, the past intercomparisons listed by Allan *et al.* possess one serious failing with respect to a test of our hypothesis: the primary standards were individually compared with TAI at different and not necessarily overlapping times. While TAI currently realizes the most stable time scale, there are necessarily limits to its short-term stability; these are of the order of $1/(80)^{1/2}$ times the short-term stability of an individual Cs standard. The result of this is that the implications for this problem of the individual primary frequency comparisons are difficult to interpret unless they are carried out simultaneously.

We conclude that no experimental evidence among international atomic timekeeping intercomparisons suggests that accelerations directly affect clock rates. Our previous conclusions were based on an improbable artifact of the UTC data, which constitute a poor measure of local proper time.

W. H. CANNON

*Earth and Environmental Science Programme, Petrie Science Building, York University, Downsview, Ontario, Canada M3J 1P3*

O. G. JENSEN

*Department of Geophysics, McGill University, Montreal, Quebec, Canada H3C 3G1*

**References and Notes**

1. W. H. Cannon and O. G. Jensen, *Science* **188**, 317 (1975).
2. *Manual, Hewlett-Packard Model 5061A Cesium Beam Frequency Standard* (Hewlett-Packard Co., Cupertino, Calif., 1970).
3. *Annual Reports for 1973* (Bureau International de l'Heure, Paris, 1974).
4. *Annual Reports for 1974* (Bureau International de l'Heure, Paris, 1975).
5. B. Guinot, personal communication.
6. We thank the France-Quebec Scientific Exchange Programme for the opportunity to accomplish this research. We also acknowledge the invaluable aid of the director and staff of the Bureau International de l'Heure, Paris. The work was supported, in part, by the National Research Council of Canada.

1 October 1975