Timekeeping and the Speed of Light—New Insights from Pulsar Observations

Charles M. Hill

P.O. Box 295, Taylorsville, CA 95983

The pulse rates of some millisecond pulsars have long term stabilities that rival our best atomic clocks. Furthermore, the pulsars are not affected by the dynamics of our solar system, which produce cyclic variations in earth based atomic time standards. Measuring time in "pulsar seconds" and Einstein's "time" in uncorrected atomic seconds leads to two different measures of the speed of light, both of which have important physical interpretations that are discussed. The evidence indicates that Einstein's definition of "time" and his principle of relativity are very useful but not universal "truths" and that Newton's ideas of time and space were discarded prematurely.

Introduction

A few years after Einstein dismissed the idea of absolute stationary space, and introduced his definition of the "time" between events at separated locations, Minkowski [1] gave a lecture presenting his geometrical model of "spacetime". In his opening remarks, Minkowski said: "Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality." This hyperbole seems to have spawned the prevailing doctrine [2] that the Newtonian concept of universal isochronal time must be discarded in order to adopt the new definition proposed by Einstein.

But, this widespread belief rests on a faulty premise. Einstein's method of measuring "time" and the traditional concept of time are not mutually exclusive. They only appear to be contradictory because they use one overworked word—*time*—to identify two different physical quantities, which violates the rules of good science. The obvious remedy is to use different words for different things, and we will continue to use the word time as it has been used historically in physics to mean an interval or duration measured in seconds where the standard second is a stable physical quantity that is independent of other variables. In contrast, Einstein's method of remote clock "synchronization" creates a variable unit of measure, which, lacking a better name, we will call the "einsecond", and the number of einseconds between two events will be called "einstime". The einsecond varies in such a way that einstime is very useful—some of the time.

Experimental data from millisecond pulsars and the traditional concept of time will be used in this paper to explain why and when einstime is useful, and when it is not. A clear understanding of time is essential for dealing with the dependent idea of speed, and we will apply the concepts of both time and einstime to explore some of the mysteries that surround the speed of light.

Basic Concepts

Physics uses mathematical symbols to concisely represent the relationships between physical quantities, but the meaning of these symbolic statements is critically dependent on a set of commonly understood assumptions and conventions. Absolute measurements are implied in physical statements, and such measurements require the development of standard physical quantities along with procedures for estimating the ratio of the unknown quantity to the standard. When we say the length of a beam is 17 meters, for example, we mean the standard meter can be multiplied by 17 (i.e. added to itself 17 times) to become physically equivalent to the length of the beam. Our traditional system of quantitative physical description depends on a reproducible linear scale, so metrology's goals include the ability to form arbitrary sums of standard quantities with each element of each sum being physically identical. In traditional physics, the second has been treated as such an idealized standard for the measurement of time—with the assumption that the duration of the standard second is independent of location (i.e. universal) and independent of when it occurs (i.e. isochronal). While this Newtonian concept of time is easy to imagine, it can be rather difficult to measure.

Conversely, Einstein's "time", or einstime, is easy to measure, but it can be rather difficult to imagine. It is easy to measure because the uncorrected atomic second is an excellent physical realization of the einsecond. The conceptual difficulty arises because the einsecond is neither universal nor isochronal, and it is difficult to imagine physical quantities that are described with variable units. Minkowski's diagrams are actually space-einstime diagrams, and they are helpful in restricted circumstances, but in his 1916 paper Einstein [3] pointed out the basic incompatibility between the traditional system of symbolic physical description and his postulate of general relativity. He chose to abandon the former in order to preserve the latter, which led to the mind-stretching idea of curved space-einstime and non-linear equations that seem to defy a general solution [4]. His choice may be legitimate, but it does not prohibit us from also considering the other alternative; that is, choosing to retain the traditional simple system of physical description and abandoning the relativity postulate.

Although time and einstime are very different concepts, the difference between their numerical values is ordinarily very small and difficult to observe. Thanks to the recent discovery of millisecond pulsars, however, we now have access to

time standards that approach a universal isochronal second, while atomic clocks allow us to measure intervals in einseconds. Therefore, it is now possible to make a direct comparison of these two different physical units by appropriate processing of the data obtained in pulsar timing observations.

Acquiring Pulsar Timing Data

The pulsating radio stars, known as pulsars, have been studied extensively since their discovery in 1967, and a general guide to the literature can be found in reference [5]. This paper will concentrate on the pulsar PSR 1937+21, from which very precise data has been accumulated for over a decade now. This unusual pulsar exhibits a surprisingly short pulse period of 1.56 ms with a long term stability that rivals that of our best atomic clocks [6], so it is an excellent time standard with which the observatory's atomic standard can be compared. In order to discuss the clock comparison, however, we must first understand the normal procedures for acquiring and processing pulsar timing data—procedures that were developed in order to study the behavior of all types of pulsars.

The signals received from pulsars are regularly recurring short bursts of broad band radio frequency energy, and the envelope of each burst can be detected in a radio receiver to produce a pulse. Each pulse from a particular pulsar is identified by its sequential number N starting from some initial observation. The acquisition of timing data consists of selecting specific pulse numbers N and noting the corresponding readings of the observatory's atomic clock AT_N when those pulses are received. After the initial investigation of newly discovered pulsars, as described by Taylor [7], their behavior is very predictable, and the expected arrival time for each pulse can be calculated quite precisely. Therefore, the measurement is actually the expected clock reading plus or minus the small observed deviation. The pulsar signals are so weak that very large dish antennas and sophisticated equipment are required, and the demand for such equipment puts a limit on the time available for observing any particular pulsar. A typical observation might accumulate data for several minutes, and a few weeks might elapse between observations, but this is done without loosing track of the individual pulse numbers N.

The received pulse shape can vary significantly from one pulse to the next, so all of the pulses received during the several minutes of an observing session are digitized, and their digital signal average is formed. The sequential number N of one pulse midway through the observation is selected consistently and used as the pulse number for the average. With signal averaging, a very repeatable pulse profile is obtained, and cross correlation with a stored profile template provides a reading of the local atomic clock that is precise to within a few hundred nanoseconds. The observatory's clock is routinely compared with a world-wide network of atomic time standards, and appropriate corrections are made so that the readings AT_N can be regarded as obtained from one of our best atomic clocks. A number of additional refinements are employed, such as synthesizer tuning of the receiver to allow for the signal's Doppler shift and compensating for signal dispersion over the receiver pass band. These refinements and other details are described by Backer [8] and Taylor [7].

Normal Processing of Pulsar Data

If one were to take the data acquired from a particular pulsar and plot the observatory's atomic clock readings AT_N against the corresponding pulse numbers N, the result would be nearly linear, but there are systematic deviations from linearity that contain important information about the pulsar. For example, some pulsars exhibit cyclic variations in pulse rate suggesting the presence of binary or multiple companions; some have abrupt changes in their pulse period called glitches; and a slowing of the pulse rate is associated with a loss of energy.

However, there are additional deviations from linearity that are caused by two other sources, and the data must be corrected to eliminate these unwanted deviations so that those due to the pulsar can be isolated and studied. One class of deviations is caused by variations in the observatory's atomic time standard, and the other comes from variations in the signal path length.

The signal path length from the pulsar to the observatory changes cyclically because the earth is spinning about its axis and orbiting the sun. Modern ephemerides are very accurate, however, so it is possible to calculate what Backer [8,9] calls a space correction and to adjust the clock readings to what they would have been if obtained at the solar system barycenter. As shown in Fig., the correction term is $\cdot \hat{n} \cdot \mathbf{r}(t)/c$ where $\hat{n}$ is the unit vector directed toward the source pulsar, $\mathbf{r}(t)$ is the vector from the solar system barycenter to the observatory, and c is the speed of light.
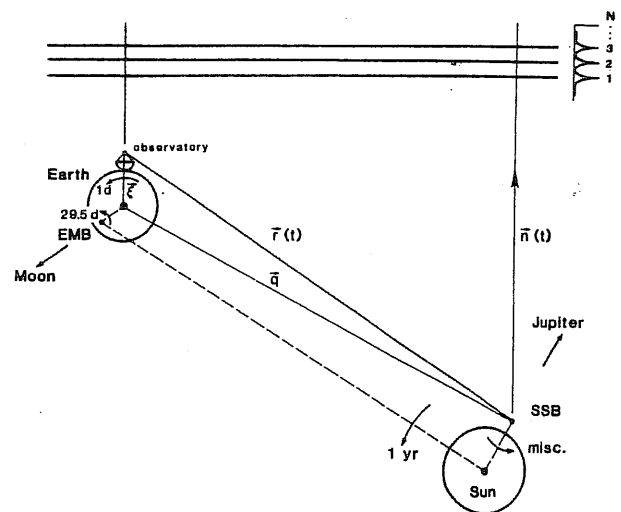

Figure 1: Correcting for the observatory's variable location in space. From Backer & Hellings [9]. Reproduced, with permission, from the *Annual Review of Astronomy and Astrophysics*, Volume **24**, © 1986 by Annual Reviews, Inc.

The time dependent vector $\mathbf{r}(t)$ is obtained from knowledge of the observatory's latitude and longitude, an earth rotation model and a solar system ephemeris, which is a table giving the positions and velocities (the ephemerides) of the planets as a function of the time that has elapsed since some specified epoch. An ephemeris is produced by mathematically modeling the solar system in a computer program that increments time

as the independent variable. This mathematical time, or ephemeris time, is assumed to be universal and isochronal with the duration of the second and the initial epoch chosen to match some physically realizable time scale such as Barycentric Coordinate Time (*TCB*). *TCB* can be thought of as the time since the specified epoch accumulated by an atomic clock that is stationary with respect to the solar system barycenter and at a gravitational potential equal to that on the earth's surface at sea level.

Obviously, one must know the Barycentric Coordinate Time TCB_N when each pulse arrived at the observatory in order to make use of the ephemeris. There is a significant difference, however, between TCB_N and the observed atomic clock readings AT_N because earth based atomic clocks do not "tick" at a constant rate. That observable fact is the foundation for this paper, and it will be developed more fully later. For now, let us just point out that the atomic clock readings AT_N are corrected to match ephemeris time or TCB_N. The corrections not only provide access to the ephemeris, but they also eliminate the unwanted deviations from linearity caused by the variations in the observatory's atomic time standard.

After correcting the data to what it would have been if measured with a uniformly ticking clock and received at the solar system barycenter, the remaining variations in the observed pulse rate can be attributed to the pulsar. A mathematical model of the pulsar's behavior is usually developed from these observations, and the parameters of the model are adjusted to minimize the residual deviations from linearity.

A Pulsar Clock

The pulsar PSR 1937+21 exhibits a short pulse period P_0 with no cyclic variability (over the ten years observed) and excellent long term stability. The first derivative of the pulse period $\dot{P}_0$ is very small and it is now accurately known, so we have access to a physical time standard that is not perturbed by the dynamics of the solar system, and it can be used to form a "pulsar clock". Let the symbol TPB_N represent the reading of this clock when the Nth pulse arrives at the solar system barycenter. The clock reading is

$$TPB_N = TPB_0 + NP_0(1 + (N-1)\dot{P}_0 / 2) \qquad (1)$$

where TPB_0 is the Julian date when the initial pulse arrived. From Fairhead [10], the initial pulse period $P_0 = 1557806448862.86 \pm 0.05$ fs; the first derivative of the pulse period $\dot{P}_0 = (1.05127 \pm 0.00001)10^{-19}$ s/s; and the initial pulse arrival time $TPB_0 = 2445303.27316791$ JD.

The performance of the pulsar clock can be judged from Taylor's data as shown in Fig. 2. The timing residuals are the discrepancies remaining after applying the space correction and the atomic clock correction and after modeling the pulsar clock as in (1). Since the residuals are random with a standard deviation well under 1 µs, we can be confident that the pulsar

clock is stable and accurate to a few hundred nanoseconds, which is quite adequate for our purposes.
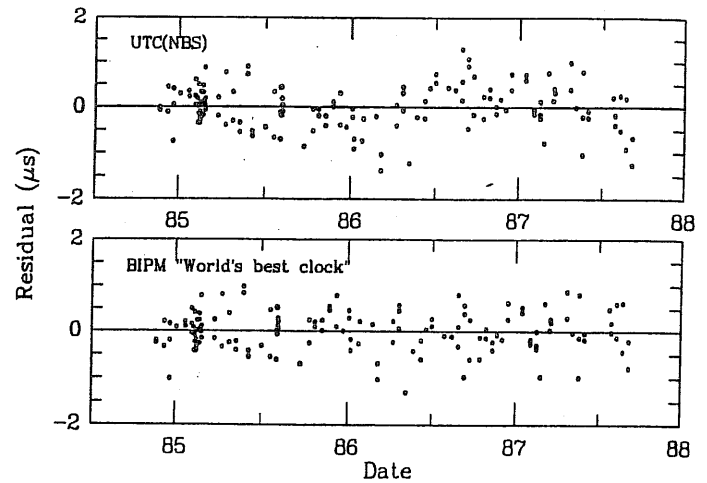

Figure 2: Post-fit arrival time residuals for PSR 1937+21 relative to UTC(NBS) (top) and to the BIPM "World's best clock" (bottom). From Taylor [7]. Reprinted by permission of Kluwer Academic Publishers.

We can draw two other important conclusions from the minuscule residuals shown in Fig. 2. First, the space correction is very precise, so we can obtain pulsar clock readings PT_N anywhere in the solar system from the calculation

$$PT_N = TPB_N - \hat{n} \cdot \mathbf{r}(t) / c \qquad (2)$$

where $\hat{n}$ and r(t) are as previously defined. Second, there is no significant difference between pulsar time PT_N when the Nth pulse arrives at the observatory and Barycentric Coordinate Time TCB_N for the same event. Therefore, the somewhat imaginary TCB_N can be replaced by the readings of a real physical clock PT_N if an iterative procedure is used to solve (2).

Furthermore, the equations used to convert the readings AT_N to TCB_N also describe the relationship between the observatory's atomic clock and the pulsar clock.

It is very instructive to imagine a portable pulsar clock packaged with a cesium beam atomic clock so that the readings of the two clocks can be compared as the package is moved about. The pulsar clock's terrestrial position could be supplied by a GPS receiver, and both clocks could be set to measure time from the same epoch (interpreted broadly to mean any specific event). For subsequent events, the readings of the two different clocks can be compared, and any difference in their readings is clearly due to different physical behavior of the two time standards.

Two Clocks At The North Pole

Differences between the two clock readings can be deduced with confidence because pulsars are observed from a variety of terrestrial locations, and the mathematical models used for data processing, including the atomic clock corrections, have proven to be reliable. Let us begin by assuming the dual clock

package is located at sea level and at the north pole. Since the duration of the pulsar second was defined to match the long term average of the atomic second, only cyclic differences between the readings of the two clocks will be observed, and the cyclic differences can be treated as a summation of sinusoidal components. Taylor intentionally omitted the small monthly component from the atomic clock correction to obtain Fig. 3, which shows the observed behavior of a slightly uncorrected atomic clock. Consequently, the behavior of a completely uncorrected atomic clock could be shown in a similar manner if all of the correction components were omitted, and some surprisingly large clock errors would be evident. Let us consider a few of the major components one at a time.
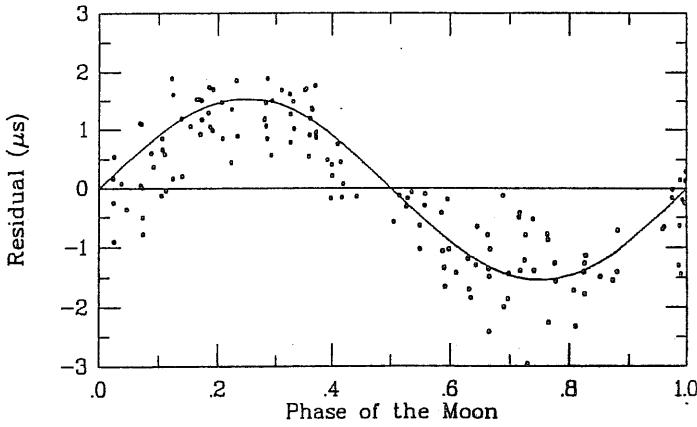

Figure 3: Post-fit arrival time residuals for PSR 1937+21 with the small monthly term intentionally omitted from the atomic clock correction. The smooth curve illustrates the omitted term. From Taylor [7]. Reprinted by permission of Kluwer Academic Publishers.

Fairhead and Bretagnon [11] provide a table giving the coefficients for the 127 most significant sinusoidal components in the corrections applied to AT_N. The largest component cycles annually, and it shows that the atomic clock reads "slow" by 1.66 milliseconds on April 1st (no foolin'), and it reads "fast" by the same amount on 30 Sept. Clock readings are the integral of the clock rate starting from some epoch, and the atomic second is 331 ps longer than average on 1 Jan and 331 ps shorter than average on 1 July. If one thinks of an atomic clock as producing a physically realizable time scale analogous to the way a thermometer produces a temperature scale, it is important to note that an earth based atomic clock's uncorrected time scale is non-linear.

Calculating the complete clock correction is a bit tedious, but the physical principle is quite simple. Uncorrected atomic clocks "tick" at a variable rate, which depends on the atomic clock's gravitational potential Φ_A and its speed v_A. Let t_A and t_P represent the durations of the standard seconds generated by the atomic and pulsar time standards. The relationship between the two is

$$t_A = kt_P / \sqrt{1 + 2\Phi_A / c^2 - v_A^2 / c^2} \qquad (3)$$

where k is a constant of convenience that makes t_P equal the long term average of t_A on the earth. If Φ_{av} is the average gravitational potential at sea level and v_{av} is the earth's average speed, $k = \sqrt{1 + 2\Phi_{av} / c^2 - v_{av}^2 / c^2}$. All values of Φ are negative in keeping with the concept of a potential well.

The corrections to the atomic clock readings AT_N are required because of cyclic variations in the atomic clock's gravitational potential Φ_A and its speed v_A. Fairhead and Bretagnon calculated the effects of the earth's orbital motion and the motions of the other significant bodies in the solar system, and they expressed the results as a summation of sinusoidal components. The small monthly component shown in Fig. 3 is due to the motion of the earth and the moon around the earth-moon barycenter.

The relatively large annual component occurs because the earth's orbit is slightly elliptical. On Jan 1st the earth is closest to the sun, so Φ_A is most negative, the velocity v_A is maximum and the atomic clock "ticks" most slowly. It is interesting (and probably significant) that the gravitational and the speed effects are equal and that they add rather than canceling each other even though the earth is in "free fall". Pulsar observations confirm this fact that was pointed out by Hatch [12] based on observations of satellite born atomic clocks in the Global Positioning system (GPS).

Other Influences On Atomic Clocks

Next, suppose the two clocks are raised to some elevation above sea level but still at the pole. The pulsar clock is not affected, but the atomic second is shortened because the gravitational potential is less negative. From (3), the shortening is 109 fs/km of elevation, which has also been verified in flying clock experiments and in the GPS system.

Suppose the clock package is moved again; this time to the equator. When the clocks were at the pole, the atomic clock's speed v_A was simply the orbital speed of the earth v_E, but now the clocks also have an additional speed component v_S because of the earth's axial spin. Therefore, the v_A^2 in (3) becomes

$$v_A^2 = v_E^2 + v_S^2 - 2v_E v_S \cos\Theta(t) \qquad (4)$$

where Θ is the angle between the velocity vectors $\mathbf{v_E}$ and $\mathbf{v_S}$. The v_S^2 term in (4) would cause the average atomic second at the equator to be slightly longer than at the poles if the earth were a sphere, but, as reviewed by Hayden [13], it is not. Because of the spin induced centripetal force, mean sea level at the equator is a little further from the center of the earth than it is at the poles. Therefore, the gravitational potential is a little less negative, which causes a slight shortening of the atomic second. The gravitational shortening and the speed lengthening effects exactly cancel each other with the result that the *average* duration of the atomic second at sea level is independent of latitude.

However, there is a diurnal variation about the average value, and the magnitude and phase of this cyclic variation depend on the latitude and the longitude of the clock. At the equator at midnight local time, the atomic second is about 150

ps longer than average and at noon it is about 150 ps shorter. The cumulative effect produces an atomic clock reading that is "slow" by about 2.1 µs at 6 a.m. and "fast" by the same amount at 6 p.m. local time, and the effect can be significantly larger for atomic clocks aboard satellites. This variation in the atomic second is caused by the clock's variable speed as described by the last term in (4), which cycles daily with a small seasonal modulation. Very long base-line interferometry (VLBI) observations confirm the reality of this location dependent variability, the logical implications of which were developed in [14].

The Facts

In summary, pulsar timing measurements are a comparison of two ticking clocks—the observatory's atomic clock and the pulses received from the pulsar. Systematic discrepancies between the two clock rates are observable, and they can be divided into three classes:

1) those correlated with cyclic changes in the signal path length;

2) those correlated with cyclic changes in the speed and the gravitational potential of the observatory's atomic time standard; and

3) those associated with the behavior of the pulsar.

After correcting for the first class of discrepancies, the normal procedure is to also correct for the second in order to observe the third. With stable pulsars, however, it is also possible to correct for the third class in order to observe the second. That is, variations in the duration of the earth based atomic second are now observable facts. The duration changes with yearly, monthly, daily and other cycles, and the diurnal variation depends on the latitude and the longitude of the atomic clock. The relationship between the atomic second and the pulsar second is described by (3) & (4) based on observations extending over a few decades, and other terms might be added to (4) as additional data is acquired.

Implications

The fact that atomic clocks behave as described by (3) & (4) has logical implications that are very significant. The time standard used in an atomic clock is the period (the reciprocal of the frequency) associated with an atomic state transition, and those atoms act as if they "know" the values of both the local gravitational potential Φ_A and the clock's speed v_A; with the speed v_A being a rather complex function as indicated by (4). The existence of some kind of substratum of information is clearly demonstrated even though the physical mechanism for conveying that information is still an intriguing unsolved mystery.

Pulsar timing observations are only sensitive to *changes* in the speed of the observatory's atomic clock, so they do not completely identify a state of absolute rest, but they do show that some states are moving more slowly than others. Clocks at the pole travel more slowly than those at the equator, and

those at the solar system barycenter travel more slowly than those at the earth's pole. Extrapolation of this pattern leads one to expect an atomic clock at the galactic center to be traveling even slower, but the pulsar data now available neither confirm nor deny such speculation because the *absolute* direction of the pulsar is not yet known. Nevertheless, the presently observable ranking of clock speeds means that absolute rest is a rational concept with physical significance.

Likewise, universal isochronal time is a rational concept even though its measurement must be approached as a limit—as are some other absolute physical measurements. The opportunity to compare pulsar and atomic clocks makes it clear that the pulsar clock provides better estimates of universal isochronal time than does an uncorrected earth based atomic clock, so it is reasonable to adopt the pulsar second as a tentative Newtonian time standard until a better approximation is found.

Obviously, Einstein's principle of relativity must be reconciled with the observed absolute behavior of atomic clocks and the implied ideas of absolute space and time. The reader is assumed to be familiar with the "clock paradox" resulting from Einstein's conflicting claims that moving clocks run slow and that absolute motion has no physical significance. An excellent review of this topic is provided by Prokhovnik [15], and this paper generally subscribes the position covered in his Chapter 5 in **The Logic of Absolute Motion**. Prokhovnik expands on the work of Builder to show that, in inertial systems, Einstein's measurements (but not his postulates) are logically consistent with the idea of an ether. In fact, the concepts of an absolute substratum and Newtonian time allow one to understand what Einstein's conventions are actually measuring.

The following sections offer a few variations on Prokhovnik's theme, and their intent is to make two points. First, Einstein's postulates do not mean what they seem to say. It is unfortunate that he used the words "time" and "velocity of light" to describe the results of his measurements, which are actually measuring something else. Second, Einstein's measurements are meaningful and useful when restricted to uniform translational motion, but they fail when the motion is severely non-uniform. The failure is not due to the direct physical effects of acceleration but rather it is a logical consequence of nature's subtleties, which are observable when the speed is allowed to vary.

Time and Einstime

The relationship between time and einstime can be demonstrated by reviewing the idea of a "light clock", such as that shown by Feynman [16] and analyzed in detail by Prokhovnik [15 §5.2]. Briefly, a light pulse is assumed to be bouncing back and forth between mirrors at opposite ends of a (Lorentz contracted) rigid rod, and the oscillatory period is used as a standard unit to be accumulated in a clock. The standard unit t_E varies, however, as a function of the clock's speed v with re-

spect to an absolute substratum in which the speed of light is the constant c. The relationship is

$$t_E = t_N / \sqrt{1 - v^2 / c^2} \qquad (5)$$

where t_N is the duration of the standard unit when $v = 0$. Light clocks are known to measure Einstein's "time" or einstime, so t_E is the duration of the einsecond, which is a variable. In contrast, t_N is a constant, which corresponds to the traditional idea of a universal isochronal second in keeping with the ideas of Newton.

Notice that the relationship between the einsecond and the second as described by (5) is the same as the speed relationship between the uncorrected atomic second and the pulsar second as described by (3). Therefore, atomic clocks behave like light clocks, and they can be used to measure einstime in einseconds. For measuring time in seconds, pulsar clocks are our present best (but probably imperfect) standards.

Clocks indicate the time that has elapsed since some epoch event, and they are often used to measure the time between arbitrary events by taking the difference between the readings when those events occur. If the events of interest are at different locations, different clocks must be used for the different events, and the measurement's validity depends on the assumption that the different clocks are synchronized—meaning they "tick" at the same constant rate and they indicate the time since the same epoch.

Consider two light clocks A and B at the origin of a reference frame that is moving in the direction of the positive x axis with constant speed V relative to the substratum. Let us assume both clocks are running at the same rate and that they have been set to have identical readings. Then suppose clock B is moved slowly to a position x_B on the x-axis. Thereafter, both clocks continue to run at the same rate, but they are no longer indicating the time since the same epoch because they were traveling at different speeds, and therefore "ticking" at different rates, as B was moving from the origin to x_B. In the normal sense of the word, the two clocks are no longer synchronized. But, according to Einstein's terminology the clocks are called "synchronized". Let us avoid this obvious source of confusion by calling two such clocks "einsynchronized" but not synchronized. In inertial systems, Einstein's "time" or einstime is the interval between events at separated locations as measured by light clocks that have been einsynchronized. It is einstime rather than time that exhibits the reciprocal relationships under Lorentz transformations, and those relationships are the logical consequences of Einstein's definitions, which are based on specific measurement procedures. These relationships are meaningful and useful because moving light clocks (and atomic clocks) actually do slow down in the absolute Newtonian sense as described by (5).

The Speed of Light

The difference between time and einstime is ordinarily quite small and it can often be ignored, but the distinction is critical when discussing the one-way speed of light. Speed is generally understood to be the rate of change of position with

respect to time with the implication that the standard unit of time is not a variable. The one-way speed of light can now be measured using pulsar clocks (or atomic clocks with (3) & (4) employed to correct the atomic clock readings), and such measurements show that the one-way speed of light is not generally isotropic. This point was addressed in a rather round about way in [14], and it could be made much more directly by using GPS [17] data in combination with the pulsar observations. Briefly, one could correct all GPS clock readings to Newtonian time using (3) & (4), and then the system could be used to measure the light speed anisotropy over the various signal paths.

When concern is limited to uniform translational motion, however, it is also useful to consider a light signal's rate of change of position with respect to einstime. We will call this quantity the *conditional* speed of light. It is known, and shown in [15 appendix 5.10], that remote clocks can be einsynchronized by two different methods that have equivalent results. One method is to slowly transport a light clock between the remote sites as described in the previous section, and the other is Einstein's well known method of sending light signals in both directions between the two locations and setting the clocks so that the speed of light appears to be isotropic. This equivalence of methods is very important because it shows that the variations in the rate of a light clock as it moves (over any path) from one point to another exactly compensates for the light speed anisotropy that exists between those two points. Perhaps the value of Einstein's measurements can best be understood by making use of an analogy.

A Measurement Analogy

Suppose we need to know the length of an aluminum beam very accurately. After carefully measuring its length, we realize that the beam is in the desert in the summer sun and that its length varies with temperature, so we also measure the beam's temperature and record the actual length and the actual temperature. Further suppose the beam is to be used in a precise structure at the south pole with other beams from other sources. If each supplier measures and reports the actual length of his part with its temperature when the length was measured, it is possible to calculate whether or not all of the pieces will fit together, but it is not very convenient. It is simpler to define some standard condition of temperature and to calculate and report what the length of each beam would be if at the standard condition. Such a convention provides a system of length description that is independent of temperature.

If we measured the beam's length with a steel tape, it was also necessary to perform a calculation to correct for the tape's thermal expansion. But, suppose we had an aluminum meter stick that was calibrated at the standard temperature condition. Then the temperature correction for the meter stick and the adjustment of the beam length to what it would be at the standard condition exactly cancel each other, and no calculations are required. Furthermore, there is no need to measure or even think about the temperature as long as there is no temperature gradient between the meter stick and the beam. Under these restricted conditions, the uncorrected length

measurements are easy to obtain and they provide length descriptions that are very convenient to use.

It is essential, however, to recognize that an uncorrected length measurement does not describe the actual length of a beam. Rather, it describes the beam's length under the standard condition, so let us call this quantity the beam's *conditional* length.

Measuring the one-way speed of light with light (or atomic) clocks is somewhat analogous to measuring the length of an aluminum beam with an aluminum meter stick. One has the choice of correcting the clock readings to Newtonian time and measuring the actual speed of light or of leaving the readings uncorrected and measuring what the speed of light would be under a standard condition—which we are calling the conditional speed of light. The standard condition is a reference frame that is stationary with respect to the substratum, so the conditional speed of light is always the constant c. The second choice is often most convenient, while the first choice is most educational and sometimes necessary.

Limitations of Einstein's Measurement Conventions

When using the uncorrected readings of aluminum meter sticks to measure the conditional lengths of aluminum parts, one must be sure that the meter stick and the part are at the same temperature. Otherwise, the convenient balancing of the instrument correction and the description adjustment is upset, and the influence of temperature can no longer be ignored. Likewise, Einstein's measurements of the conditional speed of light relies on balancing variations in the actual speed of light with compensating variations in the time standard in moving atomic clocks. This balance can also be upset if the light path and the path traversed by the synchronizing clock are subjected to different substratum velocities.

For example, consider the GPS system. If it is analyzed in geocentric non-rotating coordinates, there is no substratum velocity component due to axial rotation and the component due to orbital motion is uniform over the entire region of concern. Therefore, uncorrected atomic clock readings can be used along with the conditional speed of light, which is a constant. But, we live on the rotating earth, and it is often convenient to think of things in "our" coordinates, which are rotating with the earth. In these coordinates, the substratum is rotating around the earth's axis, and over the entire GPS system this velocity is far from uniform. Therefore, Einstein's measurement conventions cannot be applied, and one must resort to a Newtonian concept of time and deal with a speed of light that is not isotropic.

In practice, one often ends up using a hybrid combination of Einstein's ideas and Newton's concepts of time while choosing coordinates in which a particular situation can be analyzed most simply. Einstime is not a simple consistent physical quantity, and its flexibility results in a rich variety of labels such as "atomic time"; "terrestrial time"; "barycentric coordinate time"; etc., each of which has its appropriate but

restricted realm of convenient usage. It is interesting that these different kinds of einstime form a hierarchy that seems to be approaching Newtonian time as a limiting case, but that limit is still elusive. Time measured in "pulsar seconds" is our present best realization of Newtonian time, but it would be unwise to assume that we have reached the ultimate absolute time standard.

In much the same way that aluminum meter sticks would allow a group of people to build complex aluminum structures without understanding thermal expansion, Einstein's conventions have allowed physics to progress while knowing little, if anything, about an absolute substratum. There is still much unknown, but we can observe some effects of the substratum on the behavior of atomic clocks and on the speed of light thanks to the precise data available from such sources as the world-wide timekeeping network, pulsar timing observations, the GPS navigation system, and VLBI observations. We are now in a position to re-examine Einstein's postulates and to ask the question: "If he knew then what we know now, what would be the fundamental tenets of relativity theory?"

Conclusions

Thanks to the discovery of millisecond pulsars, we now have access to two excellent time standards with different characteristics. It is instructive to think of the "pulsar second" as a tentative standard for the measurement of Newtonian time and to think of the uncorrected atomic second as a physical realization of the einsecond for the measurement of Einstein's "time" or einstime. Light's speed in meters per second is its actual speed, which in general is neither isotropic nor a constant. It is often convenient, however, to measure the conditional speed of light in meters per einsecond because, by definition, the einsecond varies in such a way that the conditional speed of light is the constant c in any inertial reference frame.

With care, Einstein's conventions can be applied in situations where the motion is not strictly translational. But, when one chooses a reference frame that is rotating with respect to the substratum, Einstein's definition of "time" is incomprehensible—at least to ordinary humans, who have no difficulty imagining universal isochronal time and a speed of light that is not isotropic.

Consequently, one is justified in treating Einstein's definition of "time" and his principle of relativity not as universal principles of nature but rather as a convenient, but restricted, convention for measuring and describing what the speed of light would be under a standard condition.

Kuhn [18] points out that choosing between alternative physical theories is a subjective process of weighing various factors that include simplicity and universality. Einstein's conventions offer simplicity of measurement, description and calculations involving the speed of light accompanied by complexity of understanding and limited universality. Conversely, Newtonian time offers universal validity and simplicity of un-

derstanding coupled with complexity of measurement, description and calculations involving the speed of light. The wisest course, therefore, is to treat the two concepts as complementary rather than competitive and to recognize that Newton's ideas of time and space still have an important role to play in "modern" physics.

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In Memoriam

Dr. Carl A. Zapffe

We sadly announce that Dr. Carl A. Zapffe died in his home on 8 December, 1994. Many readers of *Galilean Electrodynamics* are familiar with Dr. Zapffe's many papers critical of Einstein theory, but may not know of his other contributions to science. During the war years, many Liberty Ships were breaking up in stormy weather and sinking for unknown reasons. It was Zapffe who discovered that hydrogen embrittlement was the cause. The U.S. Navy then asked him to set up a laboratory *immediately*, and that meant in his home, because there was no time for erecting buildings. His work in hydrogen as a cause of defects made him the principal American authority in stainless steel, and his book published by the American Society for Metals was translated into Japanese was instrumental in raising that war-torn country from ashes to world supremecy in stainless steel. He was the inventor of fractography, both term and technique, now in universal use in fracture analysis.

Dr. Zapffe held four degrees, from Michigan Technological University, Lehigh, and Harvard. He was a Registered Professional Engineer and Nationally Certified Chemist, with doctorates both in research and engineering, and was author of over 200 papers.

His education and interests were vastly different from Petr Beckmann's, yet they had much in common, including two doctorates, and a penchant for adopting wide areas of interest. The two men arrived at very similar conclusions about Einstein theory, not only as to what was wrong with it, but also what should replace Einstein's light-speed hypothesis. According to Zapffe, light has constant speed with respect to the *geomagnetic* field of the earth—magnetospheric M-space, in his jargon. He disagreed with Beckmann, who thought that light had constant speed with respect to the earth's *gravitational* field. Beckmann, on the other hand, had considered the magnetic field and rejected it. Experimentally, it is very difficult to distinguish the two ideas, and each one has strong merits. It may be that one or the other is right, or that both are wrong, but either man would insist that theory must bow to objective experiment.