Chapter 13
Relativistic Time at the US Naval Observatory

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Abstract Since the nineteenth century, the US Naval Observatory (USNO) has contributed to the science of relativity and also benefited from it. Albert Michelson received USNO support and employment before going on to undertake the Michelson-Morley experiment. USNO first flew atomic clocks around the world as a test of relativity. USNO staff have written articles and a textbook on relativity, and a pedagogical explanation of why curved space-time causes an apple to fall is provided. Two recent tests of Einstein's equivalence principle (EEP) are described, and a section in memory of Dr. Gernot Winkler is included at the end of this work.

Keywords Relativity • U.S. Naval Observatory • Einstein Equivalence Principle • Dr. Gernot Winkler • Apple Falling From Tree

Introduction

The USNO's mission, as indicated on its web pages (http://www.usno.navy.mil/USNO/about-us/the-usno-mission), is the following:

1. Determine the positions and motions of celestial bodies, motions of the Earth, and precise time.
2. Provide astronomical and timing data required by the Navy and other components of the Department of Defense for navigation, precise positioning, and command, control, and communications.
3. Make these data available to other government agencies and to the general public.
4. Conduct relevant research, and perform such other functions as may be directed by higher authority.

The USNO's current mission is similar to earlier mission statements (Dick 2003) and supplemented by acts of law, such as the Naval Appropriations Act of 1849, which called for the publication of the *Nautical Almanac*, and the America

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COMPETES Act of 2007, which assigns coordinated responsibility for the definition of Coordinated Universal Time (UTC) to the Secretaries of Navy and Commerce. We will now describe several instances of USNO's involvement in the development and testing of relativity.

Albert Michelson

Perhaps the earliest involvement of the USNO began in 1878, when Simon Newcomb funded future Nobel laureate Albert Michelson (then a young ensign) to work on the speed of light (Dick 2003). This led to a year's stay at the USNO, during which Michelson and Newcomb jointly conducted experiments with fixed mirrors at the USNO, at the Washington Monument, and at Ft. Myers in Virginia. Michelson later teamed with Edward Morley to make the surprising 1887 discovery that the Earth is stationary with respect to the aether. The constancy of the speed of light and the assumption that all observers are equivalent (the relativity of simultaneity) are the cornerstone of Einstein's special relativity theory (Einstein 1905), in that these two assumptions are sufficient to derive the Lorentz-FitzGerald contraction, time dilation, and the famous formula $E = mc^2$. Figure 13.1 shows an inspirational portrait of Michelson that is on permanent display in the USNO Superintendent's office. Since allowing daylight to enter the laboratory would lower the data's signal-to-noise ratio, one may speculate that the picture reflects an acknowledgment of the importance of calibration and alignment.

Relativity for Educating Both the Scientists and the Public

The USNO has contributed to education and technical training of relativity in many ways, and this is driven by the need to incorporate relativity in celestial mechanics, geodesy, astrometry, and timekeeping. Scientists who are interested in correctly applying the theory to problems involving geodesy can consult the IERS Conventions (2010), which were first developed at the USNO and for which the USNO Scientific Director remains an editor. George Kaplan showed that the corrections used to reduce optical data were consistent with those used in the radio (Kaplan 1998). Researchers interested in the application of relativity to celestial mechanics may consult a recently published 860-page work on the subject (Kopeikin et al. 2011).

The Hafele-Keating Experiment

One of the key consequences of the special theory is that the relative change in proper time is not affected by issues of simultaneity. The first demonstration of time

Fig. 13.1 Albert Michaelson

dilation was in the increased lifetime of cosmic-ray muons (Rossi and Hall 1941; Frisch and Smith 1963); however, the demonstration that most captured the public's interest was undertaken as a strictly scientific test when Dr. Gernot Winkler was director of the USNO Time Service Department. In collaboration with Dr. Hafele of the University of Colorado (Fig. 13.2), this experiment was to fly a cesium ensemble around the world in an easterly direction, with an expected loss of 40 ns, and again in a westerly direction, with an expected gain of 275 ns. These predictions agreed with the measurements within the 20 ns uncertainties, which were mostly in the predictions (Hafele and Keating 1972). Various versions of this demonstration have since been repeated as demonstrations for the public many times. The BBC produced a documentary in which John Davis transported a clock round trip from the UK's National Physical Laboratory (NPL) to the USA, and most recently, Tom Van Baak's cesium clocks were driven up a mountain to demonstrate gravitational time dilation for the "GENIUS" series by Steven Hawking (http://www.pbs.org/about/blogs/news/pbs-and-national-geographic-channels-international-commission-six-part-series-genius-by-stephen-hawking/ (Episode 1)).

An Illustration of the Principle of Least Action

For pedagogical purposes, we now note that it is possible to provide an equationless explanation for why an apple falls from the tree, given that gravity is considered explainable as an illusion related to the presence of curved space. Without the classical force of gravity, a student might wonder why an apple would "choose to fall." We invoke the slightly misnamed Principle of Least Action, also informally known as the "Law of Cosmic Laziness." In analogy with the classical Principle of

Fig. 13.2 J. Hafele (*left*) and R. Keating

Least Action, this leads to equations that require light and matter to follow the geodesic, which is the straightest possible path in curved space-time. The principle can be reformulated as saying that the proper time (exemplified in the apple's "biological clock") is minimized over the path.

The first step in this simplified explanation is to realize that if there magically appeared a hole just beneath the apple tree, extending all the way through the Earth, the apple would fall through the Earth to the other side and then return to the branch from which it fell. This would be a one-dimensional orbit, as shown in Fig. 13.3.

The question now becomes why would the apple go through this degenerate orbit, rather than simply sit on the tree? Figure 13.4 depicts the two ways the apple could travel, one of them hypothetical. In each case the apple moves from the first event (when it is on the tree and starts to fall) to the second event, in which it is again on the tree. If a uniform density is assumed, the time to reach the Earth's center is about 42 min; more realistic models compute values about 10% less (Klotz 2015).

We now make the assumption that minimizing the action (proper time) over each segment of the apple's path through its fall (a local effect) is equivalent to minimizing the action over the entire path (a global effect); in complex gravitational fields, this would not necessarily be the case. As the distance separation between the start and end points of the two possible paths is zero, the relative change in proper time is not obscured by the issue of defining simultaneity. Therefore, the reason the apple chooses to fall is because it will have aged less with respect to a hypothetical apple that stayed fixed to the tree (and not in free fall). The reason it would have aged less is gravitational time dilation – clocks in a gravitational field go slower. Large slowdowns involving black holes are the substance of movies; in our case the average frequency dilation is of order 10^{-9}. We therefore find that the apple is willing to transverse four Earth radii (2.4×10^4 km) so that after its return about 10^4 s later, its proper time will age less by about 10^{-5} s.

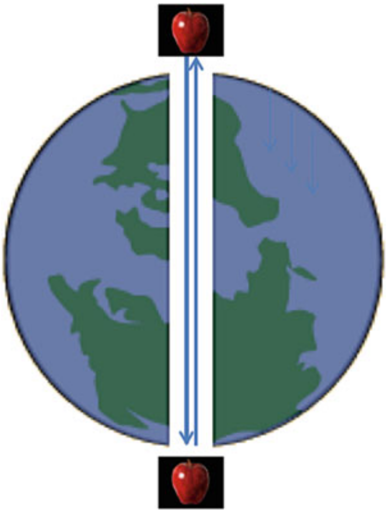


Fig. 13.3 If it didn't hit a hard surface, the apple would travel through the Earth and back

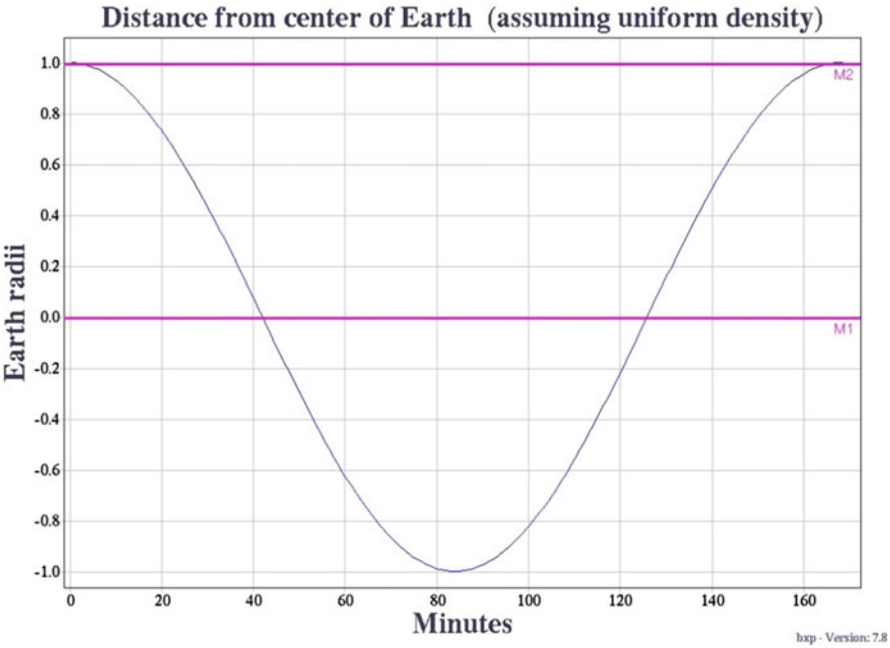


Fig. 13.4 The two possible paths an apple can take between two events at which it is at the tree. The horizontal line at 1.0 Earth radius is the (hypothetical) path in which it remains stationary. The second path takes the apple through a hole in the Earth and back, generating the sinusoid in the figure

USNO Tests of Einstein's Equivalence Principle (EEP)

Einstein's equivalence principle is at the foundation of relativity. It states that an observer cannot, by local measurements, distinguish between a gravitational field and acceleration. It follows that there always exists an accelerating frame for which the laws of special relativity apply locally and in which gravitation should be entirely ignored. This principle has several variants (Will 2014). The strong EEP is that this principle holds even when the energy of gravitation is considered. Lorentz invariance applies to the motion of the observer, and Local Position Invariance (LPI) stipulates that EEP holds anywhere in the universe (and therefore in any gravitational field). The Schiff conjecture is that a violation of any of these variants of EEP implies a violation of the others; this conjecture can be proven if one is willing to assume the conservation of energy (Lightman and Lee 1973). Many theories of quantum gravity predict violations of EEP at some level, and therefore, every test has the potential to constrain these theories.

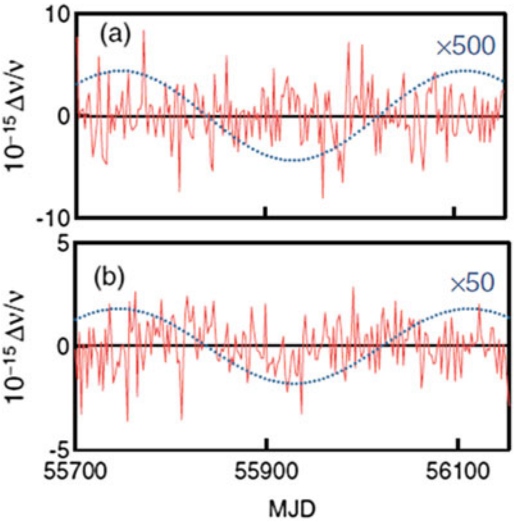
Search for EEP (LPI) Violations in Annual Solar Potential Variations

Piel et al. (2013) looked for dependence on the solar gravitational potential in frequency differences between the four USNO rubidium fountains, the USNO cesium ensemble, and elements of the USNO hydrogen maser ensemble. Since the solar potential, as experienced by the Earth, varies with a 1-year periodicity, any frequency variations in phase with this potential could be ascribed to an atom-dependent violation of EEP. They found no variations, to a 1-sigma upper limit of 1.3×10^{-6} in the LPI-violating parameter β for hydrogen-cesium and 1.7×10^{-5} for rubidium-hydrogen. Figure 13.5 shows best fits to an annual variation in the frequency differences, scaled for display. Figure 13.6 shows how the USNO data have reduced the upper limits to possible variations in the fine structure constant, the electron/proton mass ratio, and the quantum chromodynamic parameter ratio m_q/Λ_{QCD}.

Searches for EEP (LPI) Violations in Diurnal Solar Potential Differences of the Earth

We now describe a test for EEP violations that utilized satellite-based frequency transfer between widely separated hydrogen masers (Matsakis 2016a), whose frequencies might be expected to have an almost diurnal signature as the Earth's

Fig. 13.5 Best fits to annual term in frequency difference between different types of clocks, scaled as shown for display. The *upper plot* is one hydrogen maser minus the cesium ensemble, and the *lower plot* gives one hydrogen maser minus the rubidium fountain average. Figure extracted from Piel et al. (2013)



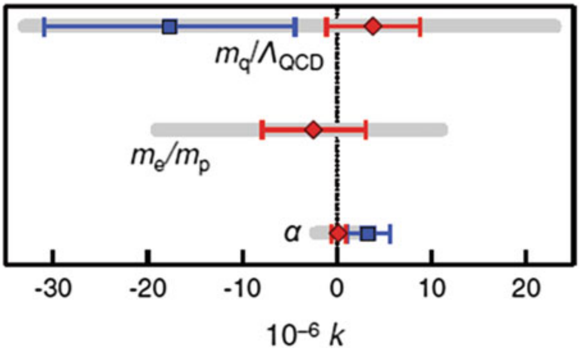


Fig. 13.6 Constraints on the coupling of three ratios of physical constants to the solar gravitational potential. The *gray bands* show the constraints from previous measurements, the *squares* show the constraints imposed using only USNO data, and the *diamonds* show the tighter constraints when all data are combined. Figure extracted from Piel et al. (2013)

rotation carries the clocks deeper into and further out of the solar gravitational potential well. However, it has long been known that there is no observable "noon-midnight" redshift in GPS; this is due to the fact that all clocks are essentially in free fall about the Sun. It was noted by many authors, such as Hoffman (1961) that the large redshift that might be expected in a ground clock and a satellite at noon (roughly four times the 36 ns/day expected between the ground clock and the center of the Earth, ignoring the Earth's gravity) is numerically canceled by the second-order Doppler shift expected from the difference between the satellite and the ground clocks' Keplerian orbits around the Sun. While no one disputes that EEP brings about this instantaneous cancelation, it has been argued in Ashby and Weiss

(2013) that the subsequent motion of the satellite and Earth invalidates this approach because at a later time the cancelation occurs in a different accelerated frame than what is the appropriate frame at the time in question. The authors then show that the nonexistence of a frequency difference can be derived by a more general approach using the relativity of simultaneity.

In Matsakis (2016a), frequency transfer was obtained in two different ways. One was by differencing about 4 years of time transfer data obtained by two-way satellite time transfer (TWSTT, also known as TWSTFT) between the USNO's Washington DC facility and its Alternate Master Clock (AMC), in Colorado Springs, Colorado. In all, there were three USNO antennas and two AMC antennas employed, resulting in six baselines. An independent series of frequency transfer data was obtained using 8 years of monthly Precise Point Positioning (PPP) solutions made publicly available by the International Bureau of Weights and Measures (BIPM). The PPP solutions are in the form of differences with a common reference, IGS time (IGST). The frequency difference between pairs of ground clocks was obtained through subtraction, and this eliminated IGST from the analysis.

For frequency transfer involving TWSTT, a single transponder on a geostationary satellite was employed. Therefore, relativistic effects in the satellite are largely irrelevant. However, PPP data are reduced with clock and orbit models computed by the International GNSS Service (IGS), and the sets of satellites observed by clocks on opposite sides of the Earth have at most only a few satellites in common. This difference was ignored in Hoffman (1961) because the details of how the IGS computes its products are difficult to extract from their average of analysis center products. Since a proper allowance for this effect might be expected to increase the average magnitude of the observed frequency differences, the author concluded that the PPP-derived upper limits may be more stringent than claimed.

For both data sets, frequency transfer differences were edited by baseline (pair of receivers) to remove outliers. The PPP solutions were edited by day; and any baseline that had even one outlier was completed removed for that day. The next step was to compute the expected shift due to the solar potential alone (which would be canceled by the instantaneous second-order Doppler), given the Sun-Earth separation on each day. The expected shift was taken as a parameter to describe the EEP violation. For reference, an orthogonal second parameter was also fitted. It was equal in magnitude to the EEP-violation parameter but offset in time by 6 h. Although both of these parameters are orthogonal to a constant frequency difference, a receiver-pair-dependent constant was removed from each day's data before the fit, and then two parameters were solved for using all receiver pairs for which data were available on that day. For both TWSTT and PPP, the correlations due to common ground clocks were treated using standard pre-whitening techniques. Pre-whitening requires knowledge of the nonwhite behavior, which is not exactly known. Therefore, reductions were made using either the correlations in the "noise" or an idealized model. For each pre-whitening mode, the sets of 1-day parameter fits were edited to remove 3-sigma outliers (about 7% of the solutions). The fitted parameters were then averaged into 10-day bins, and again 3-sigma outliers were

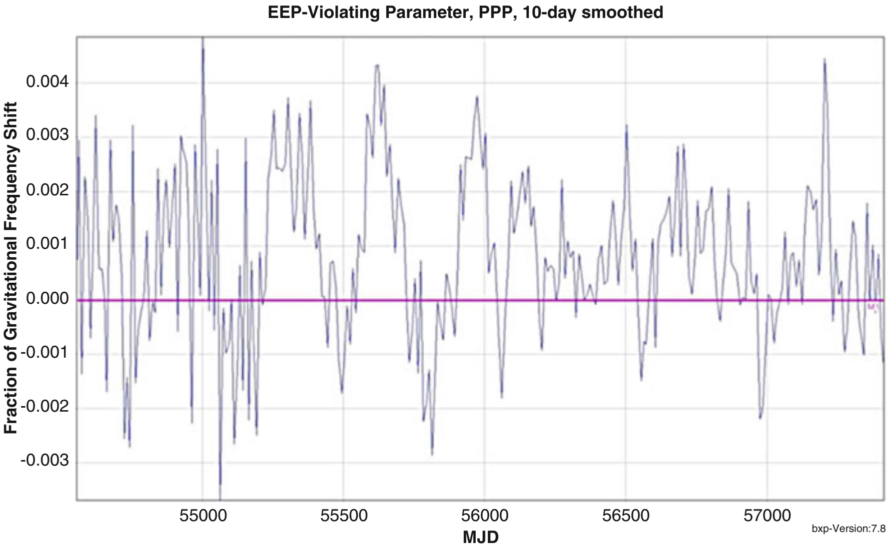


Fig. 13.7 The EEP-violating parameter as a function of time. Note the nonwhite behavior and the improvement in recent data

removed (one or two points per mode). Some results are shown in Figs. 13.7 and 13.8, and all are summarized in Table 13.1. In Table 13.1, the statistical uncertainties are computed using the standard Gaussian formula for the standard deviation of the mean; however, it is obvious that the data are nonwhite. Since the recent PPP data are less nonwhite and quieter (reflecting improvements in the technology), averaging was also done excluding the older data.

Since the uncertainties are merely formal computations, the high "signal-to-noise" ratio of some of the solutions does not imply an EEP violation. The quadrature parameter shows almost as large of a variation, and this would be expected to be zero even if an EEP violation existed. We ascribe this variation to diurnal signatures in both the PPP and the TWSTT data. The diurnal variations in TWSTT data are well known, and while they will likely be strongly reduced through the use of a software correlator (Matsakis 2016b), in this data set, they vary both in amplitude and with regard to time of day (Huang et al. 2016). At those times when they are in phase with the Sun, they would be indistinguishable from an EEP violation. The diurnal variations in PPP are weaker; however, at times they are strong enough to be directly observed. Figure 13.9 provides an example of data between a laboratory in Italy and one in Japan. These are not typical of all the data, but they are typical of times when there were strong diurnal variations. The diurnals shown were in all baselines involving the receiver IENG, which was removed from the analysis. The diurnals associated with other PPP baselines are weaker than shown here and often not directly detectable.

Since diurnals due to unrelated causes would obscure the EEP variation, it was concluded that a reasonable upper limit to the EEP violations would be $<10^{-3}$. This

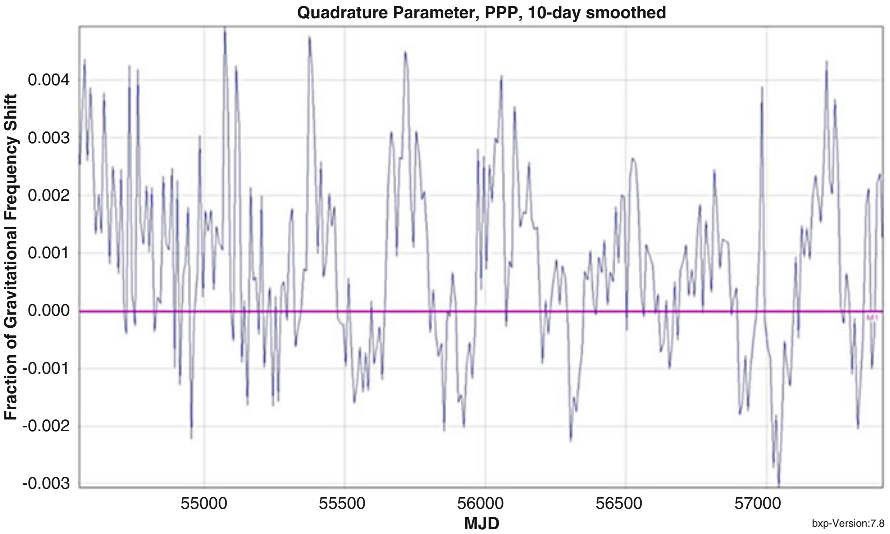


Fig. 13.8 The fitted value of the quadrature parameter, which is orthogonal to the EPP-violating parameter

Table 13.1 Properties of fits to the EEP-violating and quadrature parameters, for different solution and frequency transfer techniques

Technique	# of days	Covariance source	EEP-violating parameter	Statistical uncertainty	Quadrature parameter
TWSTT	1538	Data	-2.2×10^{-4}	$\pm 2.4 \times 10^{-3}$	5.0×10^{-4}
TWSTT	1538	Model	1.4×10^{-3}	$\pm 2.4 \times 10^{-3}$	5.5×10^{-3}
PPP	2865	Data	7.4×10^{-4}	$\pm 1.1 \times 10^{-4}$	4.4×10^{-4}
PPP	2865	Model	7.9×10^{-4}	$\pm 8.9 \times 10^{-5}$	7.8×10^{-4}
PPP	1217	Data	6.8×10^{-4}	$\pm 1.1 \times 10^{-4}$	2.8×10^{-4}
PPP	1217	Model	6.1×10^{-4}	$\pm 9.2 \times 10^{-5}$	4.4×10^{-4}

The last row summarizes the most stringent test and provides the justification for claiming the limit of $<10^{-3}$

would make it the most accurate test to date using widely separated clocks in the solar field (Fig. 13.10).

In the near future, more accurate tests of the EEP in the solar field are expected from the use of optical fibers and optical clocks (Rasel 2015), both of which are very close to achieving operational use. The USNO also has an optical clock development project underway, with a goal of exceeding the frequency precision of its four rubidium clocks by an order of magnitude, perhaps to 10^{-17} s/s. Rockets carrying clocks into orbits passing near the Sun have always had the potential of highly accurate relativity tests; in their case it is simply a matter of when they will be funded.

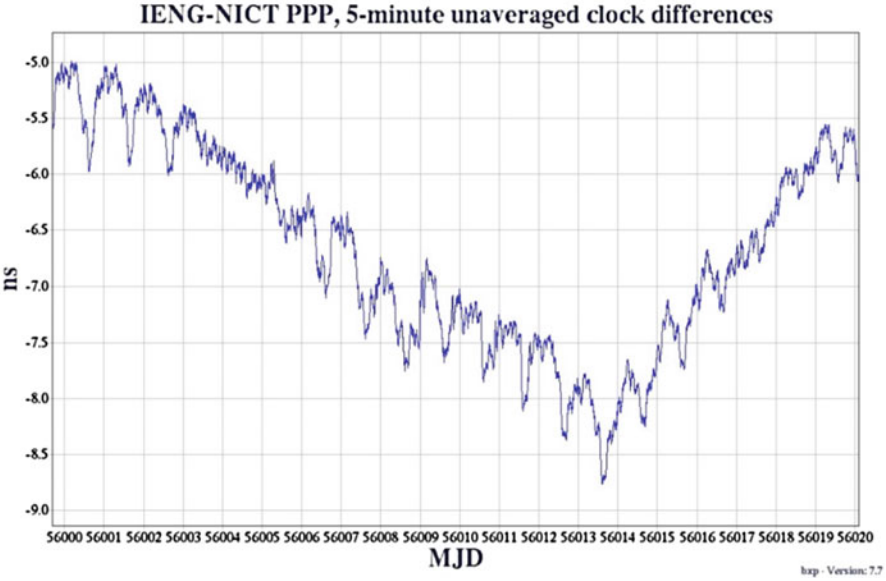


Fig. 13.9 Unedited PPP data between laboratories in Italy (IT) and Japan (NICT). The vertical bars mark the start of each day (UTC = 0). The plot shows a period of strong diurnals. Similar diurnals were seen in all baselines involving IENG at these times, and this site was excluded from the analysis

Conclusion

Relativity, since its inception a fascinating field of fundamental physics, has over the last several decades become just as active in applied physics. The USNO has contributed to this field in the past and continues doing so to this day.

In Memory of Dr. Gernot Winkler

Gernot Winkler served as director of the USNO Time Service Department for 30 years, from 1966 to 1996 (Fig. 13.11). He was brilliant, dynamic, inspirational, and successful. On his second day in office, he made his first improvement to use a cesium clock instead of a quartz clock as the USNO Master Clock. For the next 30 years, he continued to improve not just his department but the timekeeping community in many ways, such as by providing development funding, kick-start funding, and/or operational development of masers, digital 5071 cesium clocks, mercury stored-ion clocks, portable clock trips, TWSTT, and Earth rotation studies through the world's largest photographic zenith tube (PST), connected element interferometry (CEI), and very long baseline interferometry (VLBI). He and Louis Essen independently conceived of the now-controversial concept of leap seconds

Fig. 13.10 Upper limits to LPI violations, from Will (2014)

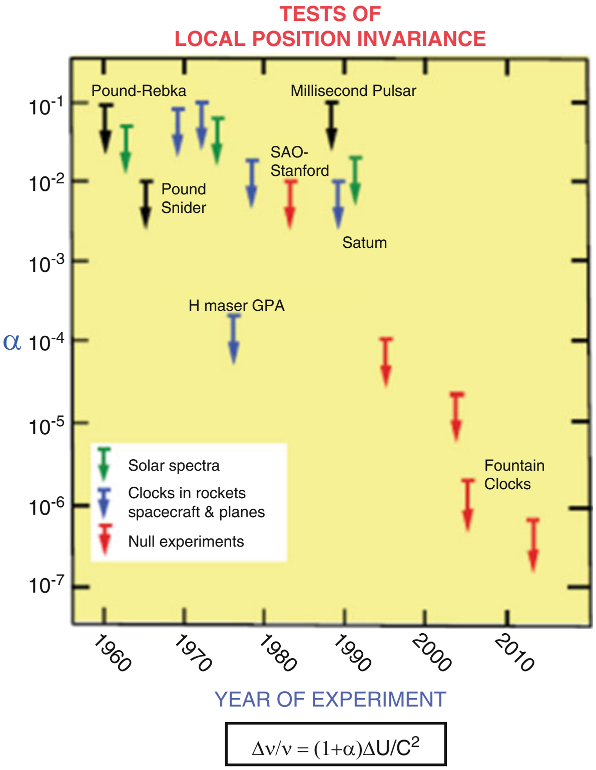


Fig. 13.11 Dr. Winkler with an early model cesium clock

Fig. 13.12 Gernot Winkler in retirement

(http://tycho.usno.navy.mil/papers/ts2014/MatsakisLeapSecondComments-URSI-2014.pdf or http://www.gps.gov/cgsic/meetings/2014/), and this is what enabled atomic time, through UTC, to become the world time standard. He successfully implemented programs so that UTC, via the USNO, would be the time reference for LORAN, transit, and GPS. He also contributed significantly to discussions concerning the operational implementation of relativistic corrections in GPS (Fig. 13.12).

Dr. Winkler was always extremely interested in philosophy. In his later years, he used the Internet to publish his ideas in the form of essays on the philosophy behind physics, science, society, and morality. They can be found in http://gmrwinkler.net.

References

N. Ashby, M. Weiss, Why there is no noon-midnight shift in the GPS (2013), http://arXiv [gr-qc]:1307.6525

S.J. Dick, *Sky and Ocean Joined. The U.S. Naval Observatory 1830–2000* (Cambridge University Press, 2003)

A. Einstein, On the electrodynamics of moving bodies. Ann. Phys. **17**(10), 891–921 (1905)

D.H. Frisch, J.H. Smith, Measurement of the relativistic time dilation using muons. Am. J. Phys. **31**(5), 342–355 (1963)

J.C. Hafele, R.E. Keating, Around-the-world atomic clocks: observed relativist time gains. Science **177**(166), 168–170 (1972)

B. Hoffman, Noon-midnight red shift. Phys. Rev. **121**, 337 (1961)

Y.J. Huang, M. Fujieda, H. Takiguchi, W.-H. Tseng, H.-W. Tsao, Stability improvement of an operational two-way satellite time and frequency transfer system. Metrologia **53**, 881–890 (2016)

IERS Conventions (2010) Gérard Petit and Brian Luzum (eds.) (IERS technical note; no. 36), International earth rotation and reference systems service central bureau bundesamt für kartographie und Geodäsie Richard-Strauss-Allee 11 60598 Frankfurt am Main Germany, available at https://www.iers.org/IERS/EN/DataProducts/Conventions/conventions.html

G. Kaplan, High-precision algorithms for astrometry: a comparison of two approaches. Astron. J. **115**, 361–372 (1998)

A.R. Klotz, Am. J. Phys. **83**, 231 (2015)

S. Kopeikin, M. Efroimsky, G. Kaplan, *Relativistic Celestial Mechanics of the Solar System* (Wiley-VCH Press, 2011)

A.P. Lightman, D.L. Lee, Restricted proof that the weak equivalence principle implies the Einstein equivalence principle. Phys. Rev. D **8**, 364–376 (1973)

D. Matsakis, Investigating a null test of the Einstein equivalence principle with clocks at different solar gravitational potentials, in *Proceedings of International Frequency Control Symposium*, New Orleans, La, 2016a

D. Matsakis, *Characterizing the Diurnal Signature in Two Way Satellite Time Transfer (TWSTT) Data with a Kalman Filter* (ION-PTTI, Monterey, 2016b)

S. Piel, S. Crane, J.L. Hanssen, T.B. Swanson, C.E. Ekstrom, Test of local position invariance using continuously running atomic clocks. Phys. Rev. A **87** (2013)

M. Rasel, *Quantum Tests of the Einstein Equivalence Principle on Ground and in Space* (IFCS-EFTF, Denver, 2015)

B. Rossi, D.B. Hall, Variation of the rate of decay of mesotrons with momentum. Phys. Rev. **59**(3), 223–228 (1941)

C. Will, The confrontation between general relativity and experiment. Living Rev. Relativ. **17**, 4 (2014)