Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

LONG-TERM TIME COMPARISON BETWEEN FREQUENCY STANDARDS AT NIST AND PTB FOR A TEST OF THE VALIDITY OF LOCAL POSITION INVARIANCE

A.Bauch*, L. Nelson[§], T. Parker[#], and S. Weyers*
*Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany
[§]United States Naval Observatory, Directorate of Time, Washington DC,
[#]National Institute of Standards and Technology, Time and Frequency Division, Boulder, CO 80305, USA

Abstract - **The caesium fountain frequency standard CSF1 of PTB has been compared with a hydrogen maser HMNI operated in NIST, Boulder, for more than two years. Two time comparison methods were used for that purpose, Two-Way Satellite Time and Frequency Transfer (TWSTFT) and GPS carrier-phase based frequency comparisons (GPSCP). Standard GPS common view time comparisons performed in parallel were useful to identify the properties of the two methods. Between TWSTFT and GPSCP variations of as much as 10 ns peak-to-peak during the whole period were found. It was nevertheless possible to determine a new limit of the validity of Local Position Invariance (LPI), tighter by almost a factor of 4 than previously possible. The validity of LPI could be tested by comparing two different kinds of atomic frequency standards in the same time-varying gravitational potential $\Delta U(t)$ caused by the earth's annual elliptic orbit around the sun. LPI predicts a null result in such an experiment. A frequency variation between CSF1 and HMNI in phase with $\Delta U(t)$ greater than $6\cdot10^{-6}$ of the amplitude of $\Delta U(t)/c^2$ can be excluded.**

Keywords - **atomic clocks, General Relativity, Local Position Invariance, time transfer**

I. INTRODUCTION

Time and frequency metrology is one of the rare fields in physics where General and Special Relativity manifest themselves immediately and need to be taken into account in the everyday practise of comparing clock rates and time scales over long distances. Therefore the methods of time metrology are also well suited for experimental tests of theories of relativity or for the search of variations of the fundamental constants. Such tests have recently gained renewed interest [1-4], stimulated in part by the availability of frequency standards with improved characteristics compared to the situation in previous years.

This paper deals with Local Position Invariance (LPI). which, among other things, predicts that two clocks subjected to the same gravity potential changes exhibit the same frequency shifts, independent of the atomic species involved as reference in the clocks. The theory and the verification strategies are briefly summarized in Section II. In a previous experiment performed at the Physikalisch-Technische Bundesanstalt (PTB), the caesium fountain frequency standard CSF1 was compared with a hydrogen maser HMP for roughly one year [5]. As the performance of HMP was not suitable for a prolonged analysis, a maser (HMNI) at the National Institute of Standards and Technology (NIST) was used in the present study. The data span across 854 days, ending in November 2002 (Modified Julian Date (MJD) 51744 to 52596). The inevitable time comparisons over an intercontinental distance for which three essentially independent techniques were used are subject of Section III. In Section IV the experimental findings are described and analysed. The paper concludes with a discussion of the results and an outlook at future trends in this field.

II. THEORETICAL BACKGROUND

The principle of equivalence has played an important role in the development of gravitation theory. One part of Einstein's Equivalence Principle (EEP) which is a basic element of General Relativity [6] is known as LPI, stating that "the outcome of any local non-gravitational test experiment is independent of where and when in the universe it is performed" [7]. EEP predicts the so-called gravitational redshift [6]

$$\Delta f/f_0 := (f_U - f_0)/f_0 = (1+\beta_k)\,\Delta U/c^2. \qquad (1)$$

Here f_U is the realised frequency in the presence of a gravitational potential U, f_0 is the unperturbed frequency of the clock, and c is the speed of light. According to theory β_k is zero, and this property shall be tested. The parameter β_k could be either a function of position or a function of the atomic species "k" used, or of both. The most stringent test performed up to today was the "Gravity Probe A" mission during which the frequency of a hydrogen maser (H) on board of a Scout rocket was recorded with reference to a stationary ground based maser. It was shown that the magnitude of β_H is below 7 parts in 10^5 [8].

Another type of tests of LPI comprise the comparison of stationary frequency standards based on two different atomic species (a and b) subjected to the same variation of the gravitational potential. A variation of the relative frequency difference $y_{ab} := (f_a - f_b)/f_a$, where f_a and f_b are standard frequencies derived from the two frequency standards, synchronous with a variation of the local gravity potential, would indicate a non-zero difference ($\beta_a - \beta_b$). This could happen if the (non-gravitational) fundamental constants which determine the energy of hyperfine states, e. g. the fine structure constant α, would be a function of the external gravitational potential [9,10]. It was shown that the hyperfine splitting frequencies in the ground state of hydrogen and caesium, the two atomic species of interest in the context of this study, have a different dependence on α [11].

In the past, the diurnal variation of the local gravity potential due to earth rotation [9] or the annual variation due to the eccentricity of the earth orbit around the sun [10] were considered. We report here on an experiment of the latter kind which is a continuation of previous work [5] which finally provided $|\beta_H - \beta_{Cs}| < 2.1\cdot10^{-5}$.

The earth's orbital motion entails a temporal variation of the solar gravitational potential on earth, described by

$$U(t)/c^2 = -2\,G\,M_S/(a\cdot c^2)\,e\cos(\varphi(t)), \qquad (2)$$

where the product of the gravitational constant G and the solar mass M_S amounts to $1.327\cdot10^{20}\,\mathrm{m^3/s^2}$, $a = 1.496\cdot10^{11}$ m is the semi-major axis of the earth orbit, and $e = 0.0167$ is the eccentricity of the earth orbit. φ(t) is the true anomaly, which is zero at perihelion early in the year, e. g. on Jan 4th 2001 (Modified Julian Date MJD 51913). According to (2) the peak-to-peak variation in $U(t)/c^2$ amounts to $0.66\cdot10^{-9}$. In this experiment we do not try to resolve the much smaller diurnal variation in the potential frequency shift since it would require multiple measurements with sufficient resolution within each day. We also overlook the effect of the moon which causes a wiggle of the earth orbit with a monthly period around its ellipsoidal path as the resulting effect is smaller by a factor of 4000.

III. TIME TRANSFER METHODS

0-7803-7688-9/03/$17.00

Three techniques for time and frequency transfer were used for the comparison between PTB and NIST which have been in use for similar purposes for several years [12, 13]. These techniques were Two-Way Satellite Time and Frequency Transfer (TWSTFT) [14], GPS carrier phase [15] and, as a back-up, standard GPS common-view [16].

For carrying out TWSTFT, timing information was exchanged via a commercial communication satellite (INTELSAT 307° E, Ku-band) employing pseudo-random phase noise coded signals and code-division multiple-access. Measurements of two minutes duration were performed regularly on Monday, Wednesday, and Friday, and allowed a time comparison with a precision of typically 300 ps. 343 out of 366 scheduled TWSTFT sessions were performed during the study period.

The GPS carrier-phase data came from two dual-frequency, geodetic-quality receivers located at NIST and PTB which produce both pseudorange and carrier-phase measurements at 30s. Data from other receivers in close proximity to each of the comparison sites were used to resolve cycle ambiguities [12]. The final carrier-phase solution is a combination of 3.5-day analysis periods with half-day overlap between data sets. From these analyses in total 823 time differences for 0:00 UTC were derived. The TWSTFT and the carrier-phase data both give the time difference between UTC(NIST) and a hydrogen maser in PTB, HMP.

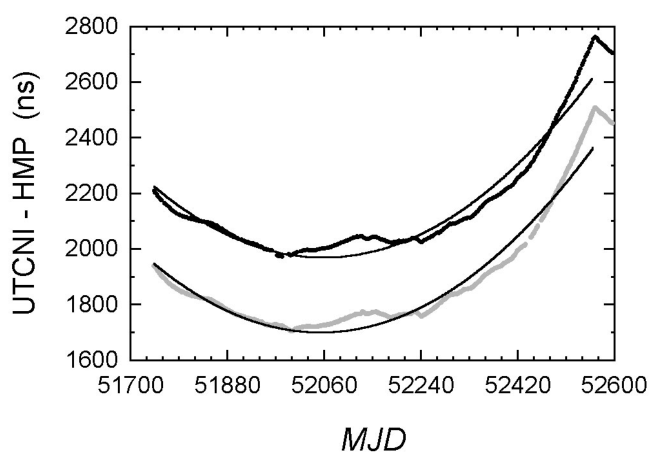

Fig.1. Time difference between UTC(NIST) and HMP via the two methods TWSTFT (black) and GPS carrier phase (grey). Data offset by 200 ns for better visibility. A frequency step of 8 parts in 10^{14} was introduced in HMP on MJD 52560. To each data set a quadratic regression was fitted which represents the maser's mean frequency drift up to that date. Here, and in all other figures, MJD designates Modified Julian Date. MJD 51700 corresponds to 2000-06-05.

In Fig. 1 the raw results obtained using both methods are depicted. The quadratic function reflects the average frequency drift of HMP, deviations therefrom are mostly due to its irregular behavior. The carrier-phase receivers are uncalibrated, i.e. the time offset between both data sets is arbitrary. Closer inspection of the data reveals a few steps in this offset of traceable origin, like changes in the satellite transponder in spring 2001, and maintenance on HMP in August 2001. After removal of these steps the difference between the data from both transfer techniques is free of clock noise and gives a picture of the stability of the time transfer processes. The result is shown in Fig. 2. The maximum observed drift in the time differences would constitute a real systematic error in an absolute frequency measurements of as much as 5 parts in 10^{16} if attributed to either of the two methods. Such behavior was previously noted and taken into account when the two fountains, of NIST and of PTB, were compared [13]. In context with the present study, such variations could mimic a variation between the two standards with a signature similar to the one expected if LPI was not fulfilled. See Section V for further discussions on that.

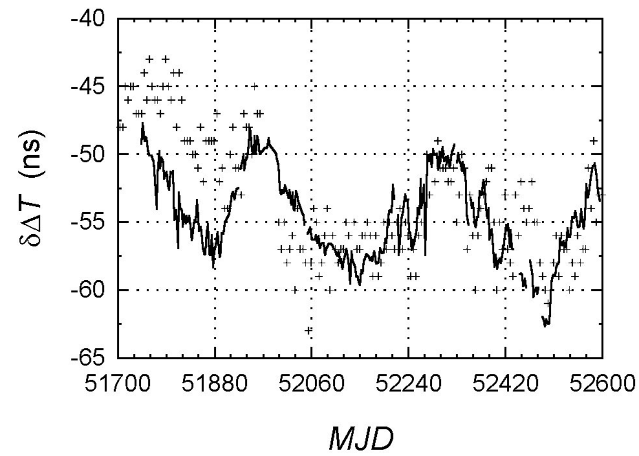

Fig.2. Double differences GPS carrier phase minus TWSTFT (solid line) and GPS common-view minus TWSTFT (symbol +).

GPS common-view time comparisons were performed between UTC(NIST) and UTC(PTB). In this comparison dedicated L1 single channel code-based receivers were used. The time difference UTC(PTB)-HMP was reported as "REFDELAY" in the TWSTFT data header, so that also double differences TWSTFT minus GPS common-view could be formed. Such data were provided by NIST and by the Bureau International de Poids et Mesures (BIPM) [17], and showed slight deviations one from the other. In Fig. 2 the data provided by BIPM is plotted. The resolution is 1 ns, and the point-to-point noise amounts to about 2.5 ns (1σ). There is evidence of some correlation in the two plotted data sets which would indicate that the reciprocity in the TWSTFT signal paths is not perfectly stable in time. But observations on GPS carrier-phase data also revealed that the results may depend on the analysis strategy and on the frequency difference of the two standards under comparison. Further investigation is clearly required. Because of the larger noise in the GPS common-view data it was not used in the LPI data analysis (Section IV C).

IV. Experimental results CSF1–HMNI

A. PTB data

Records of the frequency of an active hydrogen maser HMP with reference to the atomic fountain frequency standard CSF1 are available since summer 2000. Operation and uncertainty evaluation of CSF1 were described elsewhere [18, 19]. The hydrogen maser is operated including a cavity tuning procedure whereby the resonance frequency of the maser's microwave cavity is tuned to the hydrogen resonance frequency. The raw comparison data are displayed in Fig. 3. Each data point (total number 738) represents a relative frequency difference y averaged over at least 16 hours. Several weekend runs of about 65 hours are included. The relative statistical measurement uncertainty for each point varies between $1\cdot10^{-15}$ and $3\cdot10^{-15}$. The excess noise and unpredictable behavior during part of the study period prevented to use only HMP data for a continuation of the previous LPI study [5].

There was no correlation between CSF1 y-measurement periods (including gaps in CSF1 operation) on one hand, and data recording, gaps, or problems in TWSTFT on the other hand. Therefore a paper time scale

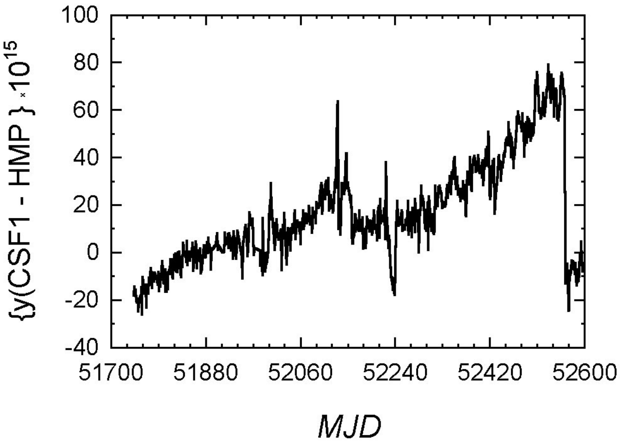

Fig.3. Frequency difference *y*(CSF1-HMP) as a function of time.

CSF1−HMP was calculated. This was straightforward when a *y*-value was reported for the midpoint of a day *m*. If no such *y*-value was available, the integration was continued with the previous *y* until day *m*+2 etc.. Four big gaps had to be bridged, occurring at MJDs: 51892 - 51898, 51904 - 51912, 51941 - 51947, 51973 - 51982. Here the mean frequency was interpolated between data before and after the gap.

B. NIST data

One of NIST's hydrogen maser (internal code #4) proved to work adequately stable during the study period. Comparisons with respect to the very stable time scale TP171 which is an ensemble time scale generated from the available hydrogen masers and commercial caesium clocks of NIST allowed to identify two frequency steps of HMNI occurring on MJD 51820 and MJD 52487. The residuals to a quadratic fit to the time differences TP171-HMNI are depicted in Fig. 4. Records are kept at NIST which prove maintenance work done on the maser on these days, which apparently caused frequency steps, but magnitude and sign could only be inferred from the data itself. The frequency steps of magnitude $-5.8 \cdot 10^{-15}$ and $+7.6 \cdot 10^{-15}$, respectively, were removed from the data UTC(NIST)-HMNI before combining them with the data UTC(NIST)-HMP and CSF1-HMP.

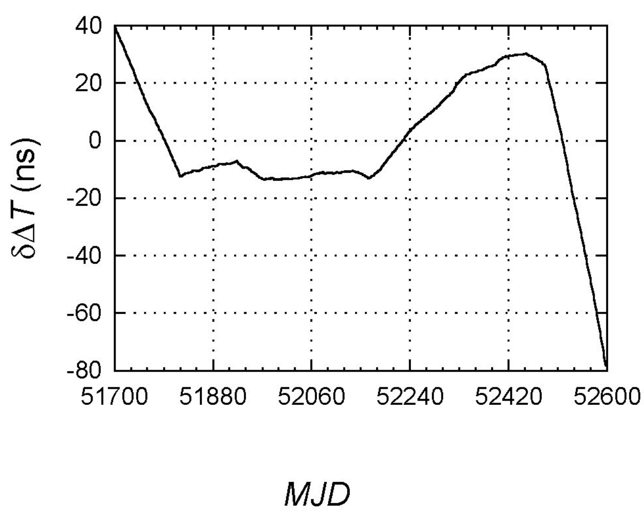

Figure 4. Time difference TP171-HMNI, residuals $\delta\Delta T$ to a quadratic fit.

C. Data analysis CSF1-HMNI

For the CSF1-HMNI comparison only the two links using TWSTFT and GPSCP were analysed. From the quadratic trend in the time difference plotted in Fig. 5 the mean HMNI frequency drift is calculated as about $1.4 \cdot 10^{-16}$/d. After having been corrected for the apparent time steps and the time offset, the two data sets obtained are alike. Independently, two quadratic functions were fitted, and in the residuals, depicted also in Fig. 5, a signature with an annual period was searched for.

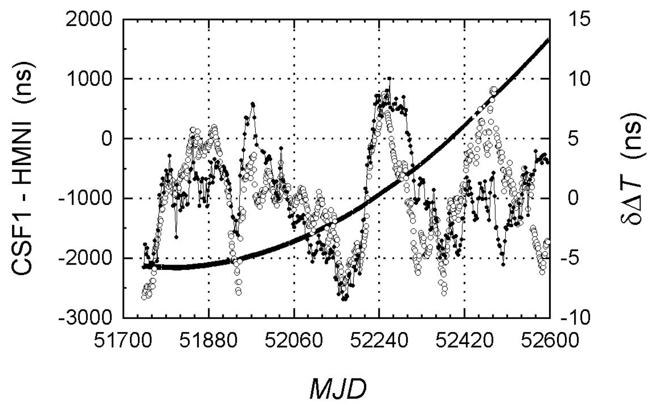

Fig.5. Time difference CSF1-HMNI (solid line, left scale), and residuals $\delta\Delta T$ to a quadratic fit (right scale), obtained using TWSTFT (symbol •) and GPSCP (symbol O).

A violation of Local Position Invariance would eventually manifest itself in a periodic variation of the rate difference between the two clocks with annual period. The *frequency* shift should have maximum magnitude (either positive or negative) around perihelion. The potential sinusoidal variations in the residuals of the recorded *time differences* would thus have a zero crossing at that date. Sinusoids with a period of one year have been fitted to the residuals shown in Fig. 5. The results are depicted in Figs. 6 and 7. In both figures, the large-amplitude sinusoids (dashed) represent variations which would be consistent with the limits on the validity of LPI stated previously [5]. The solid black sinusoid represent a fit with a zero crossing fixed at perihelion, the solid grey sinusoid represent a fit without constraints on the phase in time. It is obvious that the time residuals are not well described by such annual sinusoids. The largest amplitude is observed in the fit to the TWSTFT data in Fig. 7. But it is out of phase by almost $\pi/2$ (3 months in time) with respect to the variation of the gravitational potential $\Delta U(t)$. The amplitude of the solid grey sinusoid in Fig. 7 amounts to 3.69 (1.00) ns, and is thus statistically significant.

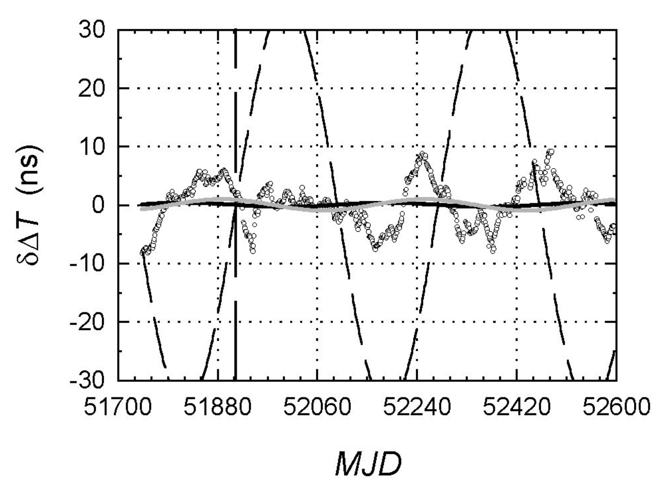

Fig.6. Residuals of time differences CSF1-HMNI, $\delta\Delta T$, to a quadratic fit, obtained using GPSCP (symbol O). Two sinusoidal curves represent least-squares fits: The solid grey line represents a simultaneous fit of amplitude and phase whereas the solid black represents a fit with the phase fixed so that a zero crossing resulted at perihelion (MJD 51913), indicated by a dashed vertical line here and in Figs. 7 and 8. Further explanations are in the text.

V. Discussion

The comparisons of CSF1 and HMNI have proven as a valuable tool to test the validity of LPI in the framework discussed in [6,7]. The availability of an extended data set combining excellent frequency sources by two different means allows at first glance a tighter estimate than

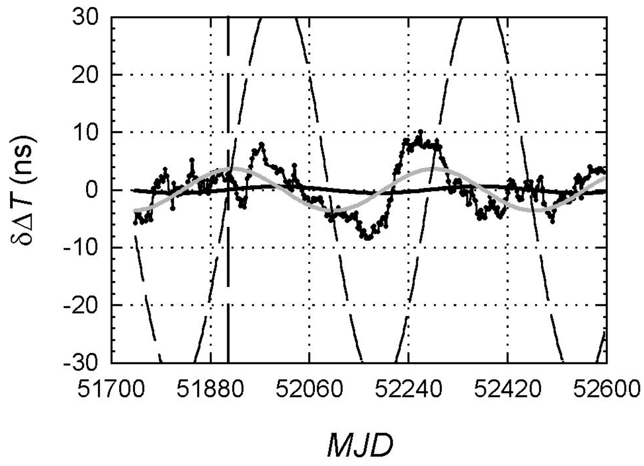

Fig.7. Residuals of time differences CSF1-HMNI, $\delta\Delta T$, to a quadratic fit, obtained using TWSTFT (symbol •). Two sinusoidal curves represent least-squares fits with an annual period: The solid grey line represents a simultaneous fit of amplitude and phase whereas the solid black represents a fit with the phase fixed so that a zero crossing resulted at perihelion (MJD 51913). Further explanations are in the text.

previously possible, which is obvious from Figs. 6 and 7. It is, however, difficult to exclude that systematic variations in the standards and, in particular, in the time transfer equipment cause frequency variations that appear as due to a violation of LPI. Such variations could of course also partly cancel a variation caused by a violation of LPI if it existed.

At first we consider CSF1. Its uncertainty could be reduced to $1.0\cdot10^{-15}$ for a certain standard operation condition [19]. During the study period CSF1 was also operated at conditions which deviated therefrom, and we estimate the "average" CSF1 uncertainty for the whole period to $2.0\cdot10^{-15}$. But, as explained in [20], even if several systematic corrections are known only with some uncertainty they are known not to vary in time as long as the operational parameters are kept within certain limits. It is thus considered as improbable that CSF1 contributes significantly to the observed time variations.

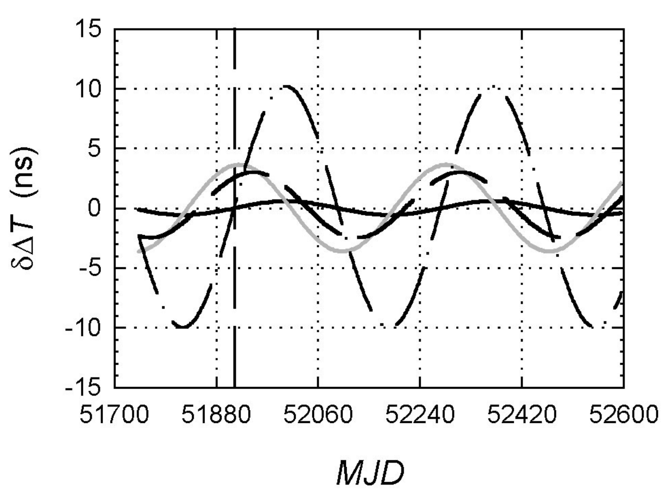

Fig.8. Sinusoidal time variations, $\delta\Delta T$, with an annual period; solid grey and solid black: fits to the TWSTFT residuals of amplitude and phase, and of the amplitude only,(phase fixed so that a zero crossing resulted at perihelion (MJD 51913)), respectively, (from Fig. 7); dashed black: fit to the double differences GPS carrier phase minus TWSTFT (from Fig. 2); dot-dashed (10 ns amplitude): estimate of the potential magnitude of the violation of LPI based on the present study (see text).

Next we consider the property of the hydrogen maser. HMNI It must be admitted that the stability ideally required in the present study is rarely found in currently produced commercial hydrogen masers. Fig. 4 is a demonstration that fortunately HMNI and TP171 time scale are indeed stable. But the occurrence of two distinct frequency steps following maintenance work proves that HMNI is not "perfect". After removal of the two distinct HMNI frequency steps from the data shown in Fig. 4, the residuals reveal systematic variations but not with a clear annual period. Thus, it cannot be excluded that less pronounced HMNI frequency changes occurred during the study period. But comparisons of the CSF1 with the ensemble time scale TP171 showed larger excursions of the time differences as seen in the comparison with HMNI. From that we conclude that HMNI was the most stable standard we could presently use.

Finally we consider the time transfer techniques. It is very probable that most of the variations seen in the residuals plotted in Figs. 6 and 7 are due to unaccounted variations in the time transfer equipment. This is most pronounced in the TWSTFT data as Fig. 8 may prove. Here the sinusoids of Fig. 7 are overlaid to a sinusoid (dashed line) fitted to the data depicted previously in Fig. 2, GPSCP minus TWSTFT. Amplitude and phase are very similar. It is currently under debate whether the differential delays in the transmit and receive parts of TWSTFT equipment may be subject of changes of that magnitude. At first glance, TWSTFT is the preferred technique since the *two-way* technique is sensitive only to the differences in the signal delays for the outgoing minus the incoming signal in each station. But the link between Europe and the US utilizes two different transponders on the particular satellite, and there is no knowledge on variations in the signal delays in both propagation directions.

As mentioned before, observations on GPS carrier-phase data also revealed that the time comparison results may depend on the analysis strategy and on the frequency difference of the two standards under comparison. Such problems are currently under study at NIST [21].

In summary, it appears not straightforward to safely state an upper bound for $|\beta_H-\beta_{Cs}|$. The dot-dashed sinusoid shown in Fig. 8 represents our current guess. It encompasses all observed variations in the time residuals, and its amplitude was chosen as twice the maximum amplitude observed in all sinusoidal fits. (Note the change in the scale with respect to Figs. 6 and 7). One could argue that all time comparison techniques might be subject to common-mode delay variations and that the double differences (fig. 2) reveal only the smaller differential effect. However substantially larger variations were to our knowledge never observed in any study, see e.g.[17]. The estimated peak-to-peak amplitude corresponds to a frequency variation of $6\cdot10^{-6}$ of the above mentioned peak-to-peak variation in $U(t)/c^2$ of $0.66\cdot10^{-9}$. For the time being one can with a high probability exclude any violation of LPI beyond that level, i. e. $|\beta_H-\beta_{Cs}|$ is estimated to be less than $6\cdot10^{-6}$.

With the development of more stable and more accurate frequency standards than available in previous years, new and improved experimental tests of gravitation theories have become feasible. In addition to ground based tests as the one reported here, several space projects were proposed [22] or were already approved [23] during which such tests shall be conducted in space environment. For these research projects it is of eminent importance that the performance of the time and frequency comparison techniques keeps pace with the clock development. Otherwise only local experiments, i. e. within one institute, could be performed with the desired accuracy.

ACKNOWLEDGMENT

The authors acknowledge the support of Peter Hetzel, Jürgen Becker and Thomas Polewka for operating the time transfer equipment involved in PTB.

REFERENCES

[1] J. K. Webb et al., "Further Evidence for Cosmological Evolution of the Fine Structure Constant," *Phys. Rev. Lett*., vol. 87, 091301, 2001.
[2] S. G. Karshenboim, "Some possibility for laboratory search for variation of fundamental constants," *Canad. Journal of Phys.*, vol. 78, pp. 639-655, 2000.
[3] F. Pereira Dos Santos et al., "Rb and Cs Laser Cooled Clocks," in this proceedings.
[4] C. Braxmeier, H. Müller, O. Pradl, J. Mlynek, A. Peters, and S. Schiller, "Tests of Relativity Using a Cryogenic Optical Resonator," *Phys. Rev. Lett.*, vol. 88, 010401, 2002.
[5] A. Bauch and S. Weyers, "New experimental limit on the validity of local position invariance," *Phys. Rev. D*, vol. 65, 081101(R), 2002.
[6] C. M. Will, *Theory and experiment in gravitational physics"* (rev. edition), Cambridge University Press, Cambridge, England,1993.
[7] C. M. Will, *The Confrontation between General Relativity and Experiment*, arXiv:gr.qc/0103036, 2001.
[8] R. F. C. Vessot et al., "Test of relativistic gravitation with a space-borne hydrogen maser," *Phys. Rev. Lett* , vol. 45, pp. 2081 - 2084, 1980.
[9] J. P. Turneaure, C. M. Will, B. F. Farrell, E. M. Mattison, and R. F. C. Vessot, "Test of the principle of equivalence by a null gravitational red-shift experiment," *Phys. Rev. D*, vol. 27, pp. 1705-1714, 1983.
[10] A. Godone, C. Novero, and P. Tavella, "Null gravitational redshift experiment with nonidentical atomic clocks," *Phys. Rev. D*, vol. **51**, pp. 319-323, 1995.
[11] J. D. Prestage, R. L. Tjoelker, and L. Maleki, "Atomic Clocks and Variations of the Fine Structure Constant," *Phys. Rev. Lett.*,vol. 74, pp. 3511-3514, 1995.
[12] L. Nelson, J. Levine, and P. Hetzel, “Comparing Primary Frequency Standards at NIST and PTB,” in *Proc. 2000 IEEE Intl. Freq. Control Symp.*, pp. 622-628, 2000.
[13] T. Parker, P. Hetzel, S. Jefferts, S. Weyers, L. Nelson, A. Bauch, J. Levine “First comparison of remote cesium fountains,” in *Proc. 2001 IEEE Intl. Freq. Control Symp.*, pp. 63- 68, 2001.
[14] D. Kirchner, “Two-way Satellite Time and Frequency Transfer : Principle, Implementation, and Current Performance," in *Review of Radio Sciences 1996 - 1999*, Oxford University Press, pp. 27 - 44, 1999.
[15] K. M. Larson and J. Levine, “Carrier-Phase Time Transfer,” *IEEE Trans. on Ultrason., Ferroelectr., and Freq. Contr.*, vol. 46, pp. 1001 - 1012, 1999.
[16] W. Lewandowski and C. Thomas, “GPS Time Transfer,” in *Proc. of the IEEE,* vol. 79, pp. 991 - 1000, 1991.
[17] BIPM TWSTFT report no. 23, February 2003, data provided in electronic format by J. Azoubib of BIPM.
[18] S. Weyers, U. Hübner, B. Fischer, R. Schröder, Chr. Tamm, and A. Bauch, "Uncertainty evaluation of the atomic caesium fountain CSF1," *Metrologia,* vol. 38, pp. 343- 352, 2001.
[19] S. Weyers, A. Bauch, R. Schröder, and Chr. Tamm, "The Atomic Caesium Fountain CSF1 of PTB," in *Proc. 6th Symposium on Frequency Standards and Metrology*, St. Andrews, P. Gill, ed., Singapore: World Scientific, 2002, pp. 64-71.
[20] A. Bauch, R. Schröder, and S. Weyers, "Discussion of the uncertainty budget and of long term comparison of PTB’s primary frequency standards CS1, CS2 and CSF1," in this Proceedings.
[21] C. Hackman and J. Levine, "New Frequency Comparisons Using GPS Carrier-Phase Time Transfer,", in this Proceedings.
[22] C. Lämmerzahl, H. Dittus, A. Peters, and S. Schiller, "OPTIS: a satellite-based test of special and general relativity," *Class. Quantum. Grav.*, vol. 18, pp. 2499-2508, 2001.
[23] Ch. Salomon et al., "Cold atoms in space and atomic clocks: ACES," *C. R. Acad. Sci. Paris*, Série IV, pp.1-17, 2001, see also contributions in this Proceedings on ACES and PARCS.