FIRST COMPARISON OF REMOTE CESIUM FOUNTAINS

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1. ABSTRACT

The frequencies of the cesium fountain primary frequency standards at the National Institute of Standards and Technology and the Physikalisch-Technische Bundesanstalt have been compared. Two-way satellite time and frequency transfer and GPS carrier-phase were the principal frequency-transfer techniques used to make the comparison. For the 15-day interval in which both fountains were in operation the frequencies were compared with an additional uncertainty due to the comparison process of only $5.8\mathrm{x}10^{-16}$. The two standards agree within their stated one-sigma uncertainties of ~ $1.7\mathrm{x}10^{-15}$.

Key Words: atomic frequency standard, cesium fountain, comparison.

2. INTRODUCTION

During the months of August and September, 2000 the new cesium fountains at the National Institute of Standards and Technology (NIST) and the Physikalisch-Technische Bundesanstalt (PTB) were operated at nearly the same time. The NIST fountain, NIST-F1, was in operation during the period MJD (Modified Julian Date) 51764 to 51794, and the PTB fountain, CSF1, was operated over the period MJD 51764 to 51779. Two additional periods of operation for the PTB standard (MJD 51799 to 51814 and 51824 to 51839) are also included in this comparison. In the first PTB run there is a 15-day overlap with the NIST run. These evaluations have all been reported to the Bureau International des Poids et Mesures (BIPM) and details of the frequency standards have been presented in other papers at this conference [1, 2]. The PTB-CSF1 was operated at constant operational parameters and the real measurement time comprised about 94% of the nominal total measurement time of 1080 hours. During the operation of NIST-F1 a range of atom densities was used so it is not practical to shorten the comparison period to coincide exactly with that of the first interval for CSF1. Therefore, the comparison must be made by extending the PTB interval with a stable (but not necessarily accurate) frequency reference. This can be done with either EAL, which is a free atomic scale calculated by the Bureau International des Poids et Measures (BIPM), or the post processed NIST maser ensemble, AT1E. The fact that the overlap of the two fountain runs is not exact means that the stability of the frequency reference contributes to the uncertainty of the comparison.

Long-distance techniques for frequency comparison must be used since the two primary frequency standards are separated by thousands of kilometers, and this also adds an additional uncertainty to the comparison. An evaluation of the extrapolation and frequency transfer-uncertainties is presented in this paper, and overall comparison uncertainties are calculated.

3. FREQUENCY TRANSFER

Three techniques for time and frequency transfer were used for the fountain comparison in order to minimize the chance of a statistical aberration. These techniques are Two-Way Satellite Time and Frequency Transfer (TWSTFT) [3], GPS carrier-phase [4], and GPS common-view [5]. The GPS common-view comparison was made with data from the BIPM publication Circular T, where corrections are made using precise orbits and measured ionospheric data. The TWSTFT measurements followed the standard three days per week (Monday, Wednesday and Friday) BIPM schedule and were made at Ku-band using a commercial communications satellite. The two-way data used for the fountain comparison were the same as that reported to the BIPM, except that data comparing UTC(NIST) to the maser H2 at PTB was extracted. The GPS carrier-phase data comes from two dual-frequency, geodetic-quality receivers located at NIST and PTB [6]. The TWSTFT and carrier-phase data both give the time difference between UTC(NIST) (which is derived from a maser ensemble) and the maser H2. The fountain frequencies can be related to these two standards via internal measurements. At PTB the fountain directly measures the frequency of H2. At NIST an internal measurement system is used to relate the frequency of the specific maser used as the fountain reference to UTC(NIST). The uncertainty of the NIST internal measurement is well under $1\mathrm{x}10^{-16}$ at 15 days. The common-view GPS data relate the fountain frequencies to International Atomic Time (TAI) via the reference clocks for each standard.

Figure 1 shows time-difference data for UTC(NIST) - H2 via the TWSTFT link for a 200 day period that includes the intervals of the fountain comparison. Frequency offset and drift have been removed. It is evident in Fig. 1 that the day-to-day

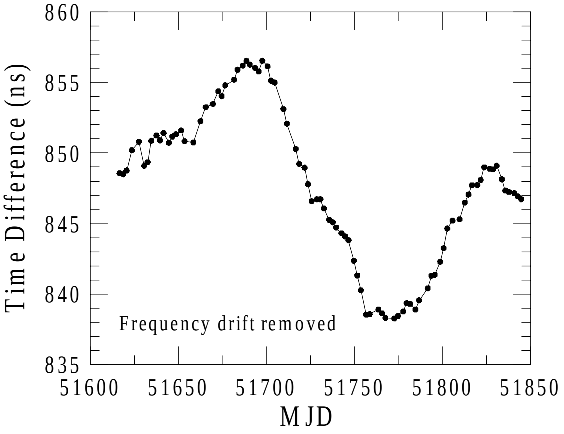

Figure 1. Time difference between UTC(NIST) and H2 via two-way.

variations are typically less than 1 ns. The long-term variations are due to clock instabilities. Figure 2 shows that the time deviation, $\sigma_x(\tau)$, for this data is about 300 ps at a few days. It is very likely that even at a few days the time deviation values are also influenced to some extent by clock noise. $\sigma_x(\tau)$ was calculated for both the unevenly spaced two-way data (solid circles) and for data interpolated to an even spacing (diamonds). If the time difference data were taken with an even spacing $\sigma_x(\tau)$ would fall between the two curves. Measurements between UTC(NIST) and H2 with GPS carrier-phase give time-deviation values at two days of about 200 ps, indicating that carrier-phase may be slightly quieter than two-way in the short term. By differencing the data from both transfer techniques the clock noise can be removed and this gives a clearer picture of the stability of the frequency-transfer processes, particularly in the long term.

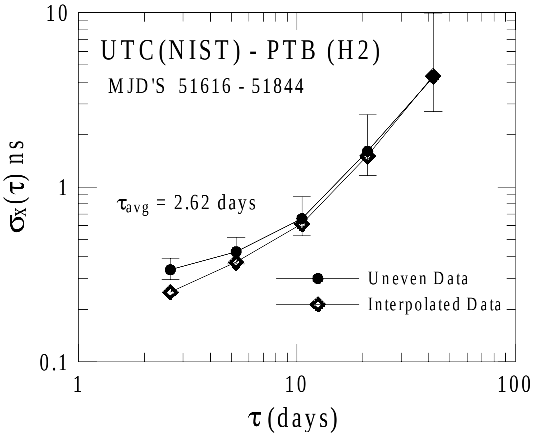

Figure 2. Time deviation of UTC(NIST) minus H2

Figure 3 shows the time difference between the TWSTFT and carrier-phase data for the UTC(NIST) - H2 link over a 100-day period that includes the fountain comparison intervals. The data interval is one day and the two-way data have been interpolated to match this interval. The long-term stability of this data is better than that in Fig. 1, but there is still some drift in the time difference. It is not clear whether this drift comes

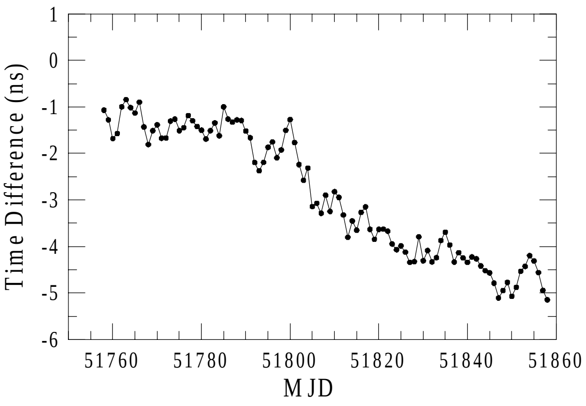

Figure 3. TWSTFT minus GPS carrier-phase for UTC(NIST) – H2

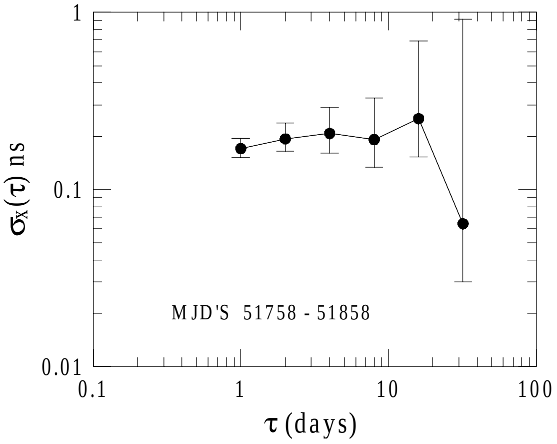

Figure 4. Time deviation of TWSTFT minus carrier-phase for UTC(NIST) – H2

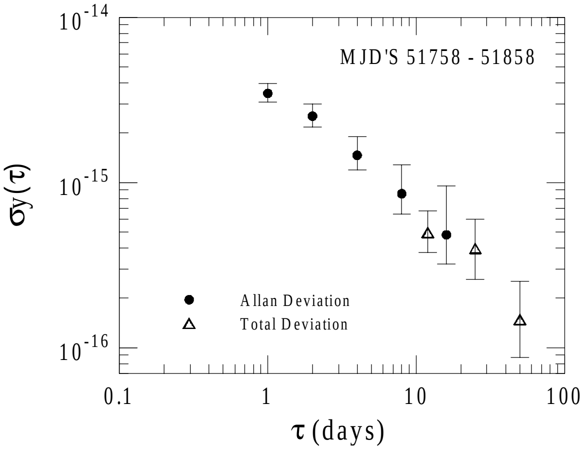

Figure 5. Allan deviation of TWSTFT minus carrier-phase for UTC(NIST)-H2.

from two-way, carrier-phase, or both, but in any case, it would constitute a real systematic error (rate offset) on the order of $5x10^{-16}$ in the frequency measurement if attributed to either one of the methods. It is important to note that the final carrier-phase solution is a combination of 3.5 day analysis periods with half-day overlaps. Therefore the solution is sensitive to the overlapping offsets of the consecutive data series as well as corrections for jumps and gaps in the data.

Figure 4 shows the time deviation for this data and Fig. 5 shows the Allan deviation. The $\sigma_x(\tau)$ and Allan deviation values at one day are both biased low because of the interpolation of the two-way data, but in general the time deviation is flicker-phase in nature at a level of about 200 ps. The Allan deviation plot indicates that the combined frequency uncertainty of TWSTFT and carrier phase is about $5x10^{-16}$ at 15 days. However, this may be optimistic because both the Allan deviation and time deviation statistics are based on the second difference of a time series, which is insensitive to a rate (or frequency) offset.

A slightly larger uncertainty of $6x10^{-16}$ at 15 days is obtained using a first-difference statistic that is the RMS fractional frequency of the time-series data in Fig. 3 [7]. This is more consistent with the observed slope in the data. For the purposes of this comparison we will assume that the instabilities of TWSTFT and carrier phase are independent and that they contribute equally to the combined instability. Taking $6x10^{-16}$ as the combined uncertainty of the two transfer techniques gives a frequency-transfer uncertainty of $4.2x10^{-16}$ at 15 days for each of the two techniques.

For the uncertainty in GPS common-view we will use the BIPM estimate of $2x10^{-15}$ at 15 days, as stated in Circular T.

4. EXTRAPOLATION

A stable frequency reference must be used as a transfer standard since none of the fountain evaluations overlap perfectly. To estimate the uncertainty of comparisons with dead time we have used the method of Douglas and Boulanger [8]. The comparisons have been made with both AT1E [9], a post-processed scale based on a maser ensemble at NIST, and EAL, the free atomic scale calculated at the BIPM. The stability characteristics of these scales are shown in Table 1 for τ in units of 1 day.

Table 1. Frequency Stability Characteristics of AT1E and EAL

Scale	White FM	Flicker FM	RW FM
AT1E	$4x10^{-16}$ ($\tau^{-1/2}$)	$4x10^{-16}$	$1.3x10^{-16}$ ($\tau^{1/2}$)
EAL	$60x10^{-16}$ ($\tau^{-1/2}$)	$6x10^{-16}$	$1.6x10^{-16}$ ($\tau^{1/2}$)

The white FM and flicker FM noise characteristics of AT1E were estimated from internal measurements made at NIST, and the random-walk FM noise level was estimated from measurements against EAL and CS2 (a thermal-beam primary frequency standard at PTB). The stability characteristics of EAL are those published by the BIPM in Circular T. The main advantage of AT1E is its much lower white FM noise. This is expected since EAL is affected by noise from GPS common-view.

5. COMPARISON RESULTS

The results of the various comparison methods are summarized in Tables 2 a-d. The stated uncertainties for the one NIST-F1 run are ub = $1.5x10^{-15}$ and ua = $0.8x10^{-15}$, where ub is the systematic uncertainty and ua is the statistical uncertainty. The combined uncertainty for the NIST-F1 run is $1.7x10^{-15}$. Since the uncertainties for the various PTB-CSF1 runs were not all the same they are listed individually in the tables. All uncertainties that are statistical in nature will be identified as "ua". The frequency uncertainty due to the time-transfer process is identified as ua(TT) and ranges from $0.42x10^{-15}$ for TWSTFT and carrier-phase to $2.0x10^{-15}$ for common-view GPS. The uncertainties due to dead time are identified as ua(dead) and range from $0.4x10^{-15}$ to $2.9x10^{-15}$. The total uncertainty due to the comparison process is ua(comp.), which is obtained from ua(TT) and ua(dead) combined in quadrature. Finally, the uncertainty of the remote standard, u(remote), is calculated from the quadrature combination of ua(standard), ub(standard), and ua(comp.). In this discussion PTB-CSF1 will be treated as the remote standard as seen from NIST, although the roles could be reversed.

The four tables compare data for: (a) TWSTFT with AT1E used as a transfer standard, (b) GPS carrier-phase with AT1E used as a transfer standard, (c) GPS common-view with AT1E used as a transfer standard, and (d) GPS common-view with EAL used as a transfer standard. All uncertainties are one sigma. The first row of data in each table is for the first PTB run, which overlapped the NIST run by 15 days. In Tables 2 a-c, the uncertainty ua(dead) is small (but not zero) because the two runs overlapped, but were not the same length. Note that ua(dead) is considerably larger with EAL used as the frequency reference (Table 2d) since EAL has a much larger white FM noise level. The observed values for the frequency difference of the two standards, y(F1-CSF1), are $-0.36x10^{-15}$ for comparison by two-way, and $-0.24x10^{-15}$ for comparison by carrier-phase. ua(comp.) is $0.58x10^{-15}$ for both methods and u(remote), the uncertainty of PTB-CSF1 as seen from NIST, is $1.9x10^{-15}$. This is only slightly larger than the stated combined uncertainty of CSF1, which is $1.8x10^{-15}$ for that run. The two standards are in excellent agreement in the first run. The comparison results using common-view GPS with AT1E and EAL are given in the first data rows of Tables 2c and 2d. Note that ua(comp.) is much larger. The agreement between the two standards is not as good as with two-way and carrier phase, but it is still within u(remote) for these comparisons.

The second and third runs of PTB-CSF1 can also be compared to the NIST-F1 run, as shown in the second and third rows of the tables. However, ua(dead) gets larger because the runs don't overlap at all. In general, the agreement in the second run is not as good as in the first. In the second run the frequency differences for the comparisons using AT1E with two-way and AT1E with common-view are large enough that the error bars of the two standards don't overlap. For AT1E with carrier-phase and EAL with common-view they do overlap. The agreement in the third run is much better, even though u(remote) is getting rather large, particularly when EAL and common-view are used.

Table 2. Comparison of NIST-F1 with PTB-CSF1

Table 2a Referenced to AT1E via two-way (units of 10^{-15}) ua(TT) = 0.42

PTB Runs	y(F1-CSF1)	ub CSF1	ua CSF1	u CSF1	ua (dead)	ua (comp.)	u (remote)	y(F1-CSF1) (w. avg.)	uw (remote)
First	-0.36	1.5	1.0	1.8	0.4	0.58	1.9	-0.36	1.9 (1 run)
Second	4.23	1.4	1.0	1.7	1.2	1.3	2.1	1.19	1.7 (2 runs)
Third	2.13	1.4	1.0	1.7	1.7	1.8	2.5	1.36 (?)	1.7 (3 runs)

Table 2b Referenced to AT1E via GPS carrier phase (units of 10^{-15}) ua(TT) = 0.42

PTB Runs	y(F1-CSF1)	ub CSF1	ua CSF1	u CSF1	ua (dead)	ua (comp.)	u (remote)	y(F1-CSF1) (w. avg.)	uw (remote)
First	-0.24	1.5	1.0	1.8	0.4	0.58	1.9	-0.24	1.9 (1 run)
Second	2.72	1.4	1.0	1.7	1.2	1.3	2.1	0.76	1.7 (2 runs)
Third	1.99	1.4	1.0	1.7	1.7	1.8	2.5	0.98 (?)	1.7 (3 runs)

Table 2c Referenced to AT1E via common-view GPS from Circular T (units of 10^{-15}) ua(TT) = 2.0

PTB Runs	y(F1-CSF1)	ub CSF1	ua CSF1	u CSF1	ua (dead)	ua (comp.)	u (remote)	y(F1-CSF1) (w. avg.)	uw (remote)
First	-1.63	1.5	1.0	1.8	0.4	2.0	2.7	-1.63	2.7 (1 run)
Second	5.20	1.4	1.0	1.7	1.2	2.3	2.9	1.41	2.2 (2 runs)
Third	2.20	1.4	1.0	1.7	1.7	2.6	3.1	1.62 (?)	2.0 (3 runs)

Table 2d Referenced to EAL via common-view GPS from Circular T (units of 10^{-15}) ua(TT) = 2.0

PTB Runs	y(F1-CSF1)	ub CSF1	ua CSF1	u CSF1	ua (dead)	ua (comp.)	u (remote)	y(F1-CSF1) (w. avg.)	uw (remote)
First	2.5	1.5	1.0	1.8	1.2	2.3	2.9	2.5	2.9 (1 run)
Second	4.3	1.4	1.0	1.7	2.5	3.2	3.6	3.16	2.5 (2 runs)
Third	0.2	1.4	1.0	1.7	2.9	3.5	3.9	2.46 (?)	2.3 (3 runs)

A weighted average of the various runs can also be calculated. The last two columns in rows 2 and 3 show the weighted averages for y(F1-CSF1) and the corresponding uncertainties, uw(remote), for the first two runs, and all three runs, respectively. (Results for the first run are repeated for clarity in the first row of these columns even though there is no averaging.) The weighting was based on the combined statistical uncertainties for each case. It is questionable how meaningful the weighted average is for all three runs because it is very likely that the errors due to the dead time are correlated between the second and third run;

thus the question marks in the tables. However, the weighted average of the first two runs should be meaningful and it also shows very good agreement between the two fountains. Note that uw(remote) for the weighted average of the first and second runs using either TWSTFT or carrier phase is essentially at the level of the stated uncertainty of the PTB-CSF1.

In principle, one could average the TWSTFT and carrier-phase comparisons together to further reduce ua(TT) by another factor of $1/\sqrt{2}$. However, this would have only a small impact, and may not be justified until the assumption of independence between TWSTFT and carrier-phase can be verified.

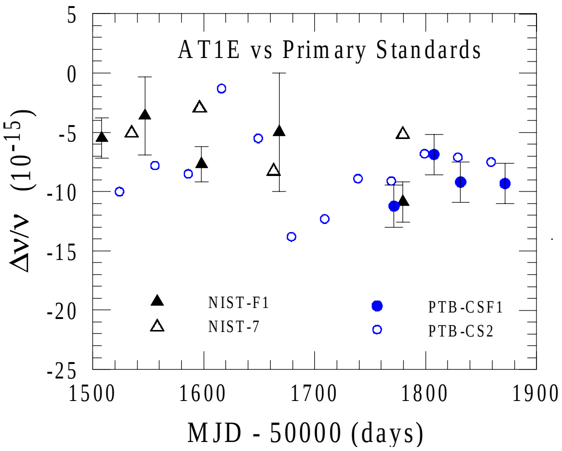

Figure 6. Frequency of AT1E versus four primary frequency standards.

Figure 6 shows the frequency of AT1E relative to the two fountains and two thermal-beam standards, NIST-7 and PTB-CS2, for about the last 400 days. The combined uncertainty for CS2 is typically 12×10^{-15} and for NIST-7 ranges from 5 to 10×10^{-15}. Individual uncertainties are shown for the fountains. The figure provides a qualitative view of the relative frequencies of the four primary frequency standards and also contains a forth CSF1 run that was not included in the tables above. The overall agreement among the four standards is quite good. The slight downward frequency drift is a characteristic of AT1E.

6. CONCLUSION

The cesium fountain primary frequency standards at PTB and NIST have been compared by three different frequency transfer techniques and with two different stable frequency references. This variety of comparison techniques was used in order to minimize the chance that a statistical fluctuation in one technique might give an unusually good or bad result. It has been demonstrated that the uncertainties of the comparison process can be reduced to a nearly negligible level with the use of TWSTFT or GPS carrier-phase if the duration of the comparison is 15 days or longer. Only two cases out of the twelve individual comparisons and the four weighted averages exhibit a frequency difference large enough that the uncertainty limits of the two standards don't overlap. This is entirely consistent with one-sigma uncertainties. In most cases the observed frequency differences were well within the uncertainties of a single standard.

The best estimate of the frequency difference of the two standards is given by the weighted average of the first two PTB runs using either two-way or GPS carrier-phase. The frequency difference is less than 1.2×10^{-15}, which is within the stated uncertainties of either of the two standards. As more fountain evaluations are carried out an even better assessment of the agreement between the two fountains will be obtained.

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