Comparisons of Atomic Frequency Standards

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Abstract

Techniques for comparing frequency standards at the $1x10^{-15}$ level are examined, including the impact of displacements in time and space. The additional uncertainties contributing to the comparison process using current technologies in stable frequency references and in long-distance frequency-transfer techniques are quantified. As an example, the results of two frequency comparisons between a pair of cesium-fountain primary frequency standards are given.

1 Introduction

Scientists in metrology laboratories that build and operate primary frequency standards make every effort to evaluate all possible sources of frequency bias. However, it is possible that there are processes occurring in the standard that the builders and operators are unaware of, and sometimes one or more of these processes will cause frequency biases large enough to be significant. Therefore, it is important to perform several tests on operating standards in an attempt to reveal possible problems.

One test is to determine whether the medium- to long term stability of the standard is consistent with its evaluated uncertainty. The other obvious test is to make accuracy comparisons with other primary frequency standards to see if they agree within their stated accuracies. Passing these tests doesn't guarantee that the standards are working correctly: however, if they fail to meet the required performance levels it clearly shows that one or more problems exist somewhere. Successful stability and comparison tests are necessary, but not sufficient, conditions for proper performance. It is very likely that you will not know for sure that a primary frequency standard is working properly until the next generation of standards comes along.

Performing the above tests generally requires making frequency comparisons over displacements in both time and space. Comparing frequency measurements made at different times requires a stable (but not necessarily accurate) frequency reference. Another primary frequency standard of

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comparable accuracy can serve this purpose, but there are also other possibilities. At the National Institute of Standards and Technology (NIST) an ensemble of five active, cavity-tuned, hydrogen masers is used for this purpose. Frequency stability in the mid 10^{-16} range over tens of days has been demonstrated [1]. Comparisons involving separation in space require different technologies. Frequency comparisons between two standards that are geographically widely separated require at least one, and preferably two or three independent, highly stable, long-distance techniques for time or frequency transfer.

In section 2 the techniques and performance levels for making comparisons over time will be discussed. Long-distance frequency-comparison techniques and performance characteristics will be discussed in section 3. In section 4 an example of the comparison of two cesium-fountain primary frequency standards is given. Section 5 contains some brief speculation about future performance of stable frequency standards and time/frequency transfer techniques.

2 Long-Term Frequency Stability and Dead Time

The characteristics of the post-processed, maser ensemble at NIST, AT1E, have been discussed in the literature, so these will not be repeated here [1]. The one-sigma uncertainty of a frequency comparison with dead time, or with an offset in the measurement intervals, can be estimated by using the known noise characteristics of AT1E along with the method of Douglas and Boulanger [2]. Detailed calculations have been presented in the literature [3, 4].

In the case of dead time the high stability of AT1E allows two standards to be meaningfully compared even if the operating intervals are not the same length. If the two standards operate at exactly the same time the stability of the intermediate reference is not important since both standards are measuring the same thing at the same time. However, when this is not the case, the instability of the reference contributes to the uncertainty of the comparison. For example, if one standard measures the average frequency of AT1E for 30 days, and the second standard operates for only 15 days (fully contained within the 30-day period), the uncertainty of the comparison process will be in the range of 3×10^{-16} to 5×10^{-16}, depending on where the 15-day interval is located within the 30-day period. The issue of dead time is also important in a formal fountain evaluation if the fountain does not run all the time.

The impact of an offset in the measurement intervals (some part of two equal measurement intervals doesn't overlap with the other) on the uncertainty of a frequency comparison is considerably larger than that for dead time. Again the procedure of [2] is used to make these calculations. Consider two 30-day measurements of AT1E that are offset in time as an example. The measurements may be made by two different primary frequency standards or may consist of two measurements with the same standard. With two standards the measurements may overlap either partially or completely. If the overlap is perfect (measurement offset is zero) there is no additional uncertainty since both standards are again measuring the same thing at the same time. However, if there is an offset between the measurement intervals, the instability of AT1E becomes an important factor in how well one frequency standard can be compared to the other. For the noise characteristics of AT1E the offset must be no greater than about 12 days to keep the comparison uncertainty under 5×10^{-16}. However, the uncertainty increases roughly as the square root of the offset time so it does not grow very rapidly. By 200 days of offset the uncertainty is just a little over $3x10^{-15}$. Thus the maser ensemble can be used to compare standards at the mid-to-low 10^{-15} level over intervals of hundreds of days.

In making frequency estimates with either dead time or measurement interval offsets the frequency drift of the reference must also be properly accounted for.

3 Long-Distance Frequency Comparison Techniques

There are four possible techniques for making long-distance frequency comparisons: these are Two-Way Satellite Time and Frequency Transfer (TWSTFT) [5], GPS carrier-phase [6], GPS common-view [7] and a transportable frequency standard. Of these four techniques only TWSTFT and GPS carrier-phase will be discussed here, since they are considerably more stable than GPS common-view, and also more convenient than a transportable standard. As a specific example we will examine the comparison of the NIST cesium-fountain NIST-F1 with the Physikalisch-Technische Bundesanstalt (PTB) fountain PTB-CSF1. The TWSTFT measurements that were used followed the standard three days per week (Monday, Wednesday and Friday) schedule of the Bureau International des Poids et Measures (BIPM) and were made at Ku-band by means of a commercial communications satellite. The two-way data used for this comparison were the same as those reported to the BIPM, except that data comparing UTC(NIST) to the maser H2 at PTB were extracted. The GPS carrier-phase data came from two dual-frequency, geodetic-quality receivers located at NIST and PTB [8]. 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 $1x10^{-16}$ at 15 days.

By differencing the data from TWSTFT and carrier-phase transfer techniques the clock noise can be removed, giving a clearer picture of the stability of the frequency-transfer processes, particularly in the long term. Figure 1 shows the time difference between the TWSTFT and carrier-phase data for the UTC(NIST) - H2 link over a 430-day period. The horizontal axis is the Modified Julian Date (MJD). The data are spaced at the two-way interval and the large transients near MJD 51830 and 51975 are from known causes and don't represent typical data. Even though clock noise is not present in this data, there are still some relatively large and slow fluctuations in the time difference. It is not clear whether these variations come from two-way, carrier-phase, or both: but in any case, the regions of high slope constitute real frequency errors (rate offsets) of up to $1x10^{-15}$ in frequency measurement made over tens of days 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 to corrections for jumps and gaps in the data. This could be a possible cause of the variations in the time difference. Other possibilities are seasonal environmental fluctuations affecting either system, although the period appears to be on the order of only 200 days.

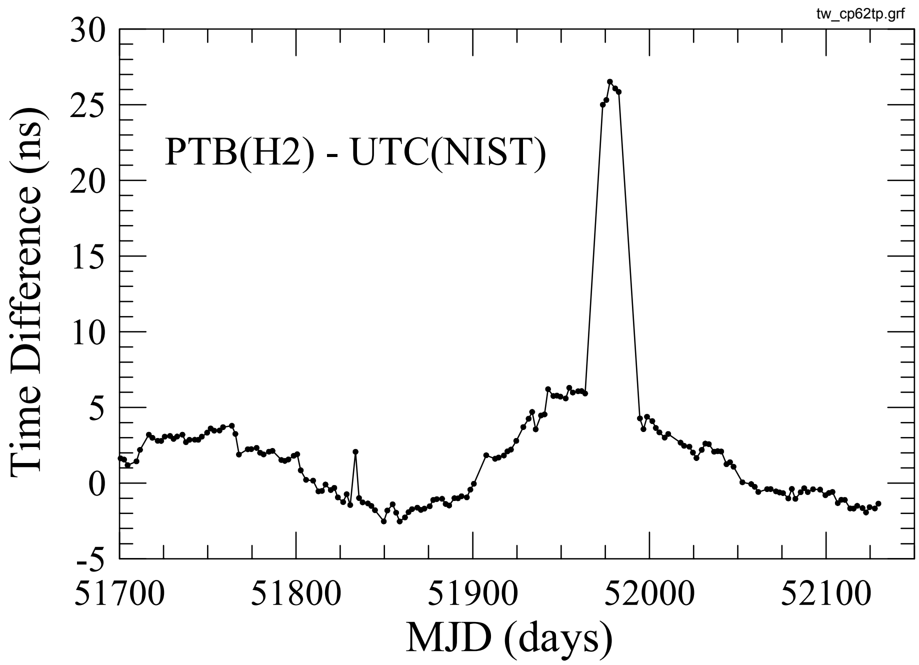

Figure 1. Time difference between two-way and carrier-phase for the PTB(H2)-UTC(NIST) link.

Time deviation values, $\sigma_x(\tau)$, are on the order of 200 to 300 ps in the range of $\tau = 3$ to 15 days (after the transients have been removed). The Allan deviation values, $\sigma_y(\tau)$, indicate 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 constant rate (frequency) offset.

A better approach is to use a first-difference statistic that is the RMS fractional frequency of the time-series data [9]. Use of this approach for the 430 day period of TWSTFT minus carrier-phase data gives an uncertainty of $8.4x10^{-16}$ for a 15-day interval, and $7.2x10^{-16}$ for a 30-day interval (again, transients removed). This is more consistent with the observed slopes in the data. For the purposes of this comparison we assume that the instabilities of TWSTFT and carrier phase are independent and that they contribute equally to the combined instability of $8.4x10^{-16}$. This gives a frequency-transfer uncertainty of $5.9x10^{-16}$ at 15 days and $5.1x10^{-16}$ at 30 days for each of the two techniques individually.

4 Comparison Example

As an example, comparisons were made of the frequencies of NIST-F1 with PTB-CSF1 for two cases where the intervals of formal evaluations overlapped [10]. The results are shown in Table 1. These values were obtained using AT1E as the frequency reference (flywheel) and by averaging the two-way and carrier-phase results. The first comparison is for the period between MJD 51764 and 51794. NIST-F1 was operated in this 30 day interval, and PTB-CSF1 was operated in the 15 day interval 51764 to 51779. The stated systematic, statistical, and combined one sigma uncertainties (ub, ua, and u respectively) are shown for each standard. The additional statistical uncertainty introduced by the fact that the evaluation intervals were not the same length is given by ua(dead) and the long-distance time transfer uncertainty is ua(TT). The total uncertainty, u(total), is the root-sum-square of u(F1), u(CSF1), ua(dead) and ua(TT). The measured fractional frequency difference between the two standards is given by y(F1-CSF1).

Table 1. Comparison of two overlapping evaluations of NIST-F1 and PTB-CSF1.

First Comparison

NIST-F1	MJD 51764-51794	ub = 1.5×10^{-15}	ua = 0.8×10^{-15}	u = 1.7×10^{-15}
PTB-CSF1	MJD 51764-51779	ub = 1.5×10^{-15}	ua = 1.0×10^{-15}	u = 1.8×10^{-15}

ua(dead) = 0.46×10^{-15} ua(TT) = 0.59×10^{-15}

y(F1-CSF1) = -0.16×10^{-15} **u(total) = 2.6×10^{-15}**

Second Comparison

NIST-F1	MJD 52079-52119	ub = 1.0×10^{-15}	ua = 0.9×10^{-15}	u = 1.3×10^{-15}
PTB-CSF1	MJD 52109-52129	ub = 1.0×10^{-15}	ua = 1.0×10^{-15}	u = 1.4×10^{-15}

ua(dead) = 0.86×10^{-15} ua(TT) = 0.55×10^{-15}

y(F1-CSF1) = -2.80×10^{-15} **u(total) = 2.2×10^{-15}**

The results of the second comparison are also shown in Table 1. As can be seen, the uncertainties of both fountains have been reduced. The uncertainty ua(dead) is a little larger because there is less overlap, but the transfer uncertainty, ua(TT), is slightly smaller because the PTB-CSF1 interval is 5 days longer (20 days) than in the first comparison.

The agreement between the fountains is quite good. The result of the first comparison is well within the one-sigma total uncertainty, and the fractional frequency difference observed in the second comparison is only slightly larger than the total uncertainty for that comparison. A more qualitative comparison is shown in Fig. 2, which shows the fractional frequency difference between AT1E and NIST-F1 and PTB-CSF1 for the roughly 600-day period in which one or both standards have been performing formal evaluations for the BIPM. The results for two thermal beam standards, PTB-CS2 and NIST-7 are also shown. The long-term frequency fluctuations are from AT1E, and the general agreement between the two fountains is good.

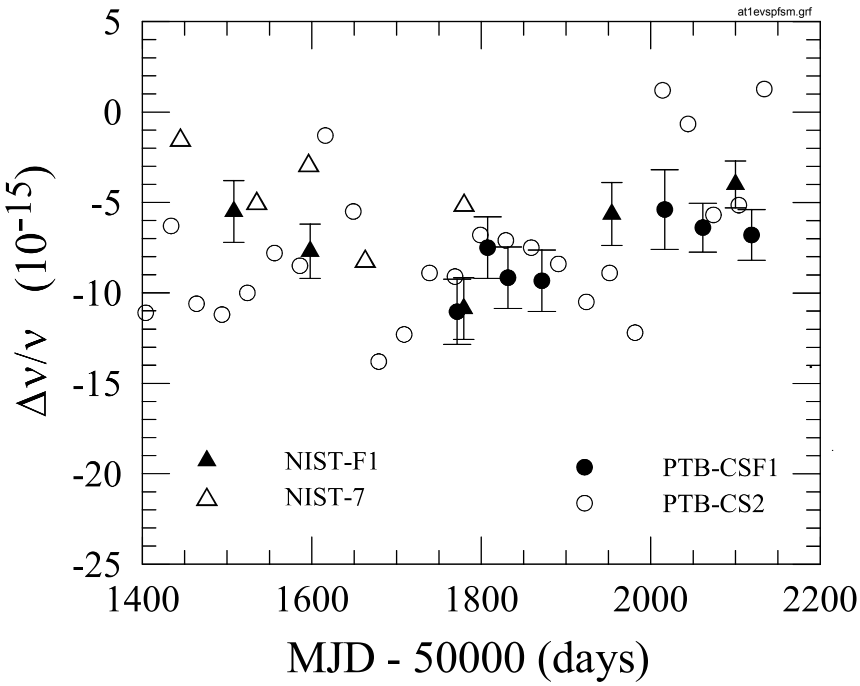

Figure 2. Fractional frequency difference between AT1E and four primary frequency standards.

5 Future Prospects

The demands on frequency flywheels and long-distance frequency-transfer techniques will increase as fountain performance improves and the uncertainties are reduced. Fortunately there are a number of potential improvements on the horizon that should yield better performance.

One possible approach to improved frequency stability for the frequency reference (flywheel) is the use of cold-atom standards designed for frequency stability [11] rather than accuracy. Such devices have the potential to deliver reliable signals with short-term frequency stability below 1×10^{-13} at 1 second, and long-term (up to hundreds of days) stability below 1×10^{-16}.

For long-distance transfer of time and frequency there are some areas where the stability of TWSTFT can be improved. For example, no attempt is currently made to correct for small ionospheric effects, and this could be incorporated. Higher chip rates for wider bandwidth spread spectrum would be useful, along with higher data rates (sessions more often than three times per week). Reduced multi-path and improved environmental controls on ground-based equipment would result in improved stability. Also, under some circumstances, the phase of the two-way carrier can be tracked, and this also significantly improves transfer stability [12].

Time and frequency transfer via GPS carrier-phase is still relatively new and it is reasonable to expect improvement in performance through improved software and hardware. Elimination of the slow time difference fluctuations in Fig. 1 (whether it comes from TWSTFT or carrier-phase) would be a significant improvement in itself.

Given that there are a number of known areas where improvements can be made it is not unreasonable to expect improvement by a factor of five to ten in the stability of time and frequency transfer techniques over the next decade or so. This would give a frequency-transfer uncertainty significantly better than 1×10^{-17} at 30 days. Unfortunately, this level of performance has to be achieved in at least two independent transfer techniques in order to be confident of the performance.

6 Summary

With current technologies frequency comparisons involving displacements in time or space can usually be made in a reasonable time with added uncertainties well under 1×10^{-15}. This is adequate for present-day cesium fountains, but as cold-atom technologies improve this will no longer be sufficient. More stable flywheels will be needed along with long-distance frequency-transfer techniques of higher stability. Fortunately, better comparison technologies are on the horizon.

References

1. Parker T. E., *Proc. 1999 Joint Meeting of the European Freq. and Time Forum and the IEEE International Freq. Control Symp.*, pp. 173-176, 1999.
2. Douglas R. J. and Boulanger J. S., *Proc. 11th European Freq. and Time Forum*, pp. 345-349, 1997.
3. Parker T. E. *et al*, *Proc. 15th European Freq. and Time Forum*, pp. 57-61, 2001.
4. Parker T. E., *Proc. IEEE International Freq. Control Symp*., pp 57-62, 2001.
5. Kirchner D., *Proc. of the IEEE*, vol. 79, pp. 983-990, 1991.
6. Larson K. M. and Levine J., *IEEE Trans. on Ultrason., Ferroelect., and Freq. Contr.*, vol. 46, no. 4, pp. 1001-1012, 1999.
7. Lewandowski W. and Thomas C., *Proc. of the IEEE*, vol. 79, pp. 991-1000, 1991.
8. Nelson L., Levine J. and Hetzel P., *Proc. 2000 IEEE International Freq. Control Symp.*, pp. 622-628, 2000.
9. Parker T. E., Howe D. A., and Weiss M., *Proc. 1998 IEEE International Freq. Control Symp.*, pp. 265-272, 1998.
10. Parker T. E. *et al, Proc. IEEE International Freq. Control Symp*., pp 63-68, 2001.
11. Jefferts S. R. *et al* , "Proposed laser-cooled 87 rubidium local oscillator at NIST", *in this proceedings*.
12. Schäfer W., Pawlitzki A. and Kuhn T. *Proc. 31st Annual Precise Time and Time Interval Meeting*, pp. 505-514, 1999.

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