A Clock Ensemble Using Only Active Hydrogen Masers

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BIOGRAPHIES

Thomas E. Parker received his B.S. in Physics from Allegheny College in 1967. He received his M.S. in 1969 and his Ph.D. in 1973, both in Physics, from Purdue University. In August 1973, Dr. Parker joined the Professional Staff of the Raytheon Research Division, Lexington, Massachusetts, USA. Initially, his work was primarily related to the development of improved temperature stable surface acoustic wave materials. From 1977, Dr. Parker contributed to the development of high performance surface acoustic wave (SAW) oscillator technology at the Research Division. His primary interest was frequency stability, with an emphasis on 1/*f* noise, vibration sensitivity, and long-term frequency stability. In June of 1994 Dr. Parker joined the Time and Frequency Division of the National Institute of Standards and Technology (NIST) in Boulder, Colorado, USA. He was the leader of the Atomic Frequency Standards Group until October 2007 and his interests include primary frequency standards, timescales, and time transfer technology. Since 2007 Dr. Parker has worked as a contractor for the Time and Frequency Division.

Stefania Römisch is originally from Torino, Italy. She received her Ph.D. in Electronic Instrumentation in 1998, from Politecnico di Torino, Italy. She was a Guest Researcher at NIST (National Institute for Standards and Technology) in Boulder, CO and then joined the Department of Electrical and Computer Engineering of University of Colorado at Boulder. After a few years of work as an independent contractor at Spectral Research, LLC, she joined the Time and Frequency Division of NIST in Boulder, CO. She now leads the Atomic Standards Group whose activities include the generation of UTC(NIST), and the use of GPS and TWSTFT to contribute to Universal Coordinated Time. Her research interests span from timescale generation to the calibration of time transfer links and the application of time synchronization to fundamental physics experiments.

ABSTRACT

The current real-time timescale at NIST, AT1, as well as the post-processed scale TP162, both contain hydrogen masers and commercial cesium frequency standards. The cesium standards are much nosier in the short term than the hydrogen masers and consequently have very little short-term weight. However, they may have better long-term stability than the masers and therefore contribute to some extent to the long-term performance of the scales. Nevertheless, the cesium standards are expensive to maintain and require attention from the staff. A test has been performed using the post-processed AT1 timescale algorithm for two cases to investigate the impact of commercial cesium frequency standards on the clock ensemble at NIST. In the first case both hydrogen masers and cesium standards were used, and in the second case only hydrogen masers were used. The ensemble using both masers and cesium standards is identified as TP162, and the ensemble using only hydrogen masers is identified as TP165. Over the 500-day test interval the number of hydrogen masers in TP162 and TP165 was exactly the same. Over the test interval the two scales diverged by only 6.6 ns, with an average fractional frequency difference of $1.5\text{x}10^{-16}$. Allan deviation plots of the two scales relative to TAI are nearly identical.

INTRODUCTION

The real-time timescales at NIST, AT1 and TSC (the backup scale), as well as the post-processed scale TP162, all currently contain a clock ensemble of both active, cavity tuned, hydrogen masers and high performance commercial cesium frequency standards. The cesium standards are much nosier in the short term than the hydrogen masers and consequently have very little short-term (less than a few days) weight. However, they may have better long-term stability than the masers (at time intervals of tens to hundreds of days) and therefore contribute to the long-term performance of the scales to a small extent. The overall long-term weight of all of the cesium standards is comparable to one average hydrogen maser. Nevertheless, the cesium standards are expensive to maintain (tubes need to be replaced every seven to ten years) and require attention from the staff. In theory the presence of cesium standards should improve the stability of a time scale no matter how noisy they are, but it is worth quantifying the long-term benefit (time and frequency offsets and frequency stability) of having cesium standards in the scales with real data.

TEST CONDITIONS

A test was performed using a post-processed version of the AT1 timescale algorithm [1] for two cases to investigate the impact of commercial cesium frequency standards on the performance of the clock ensemble at NIST. In the first case both active hydrogen masers and cesium standards were used, and in the second case only hydrogen masers were used. The ensemble using both masers and cesium standards is identified as TP162, and the ensemble using only hydrogen masers is identified as TP165. TP162, or its equivalent, [2] has been maintained for over 19 years as a stable frequency reference for the primary standards NIST-F1 and NIST-F2. Frequency drift of the hydrogen masers is modeled using data from primary frequency standards, while the drift in the cesium standards is not modeled. Small frequency steps of +/- $5x10^{-16}$ are occasionally inserted in TP162 in order to keep its frequency within +/- $2x10^{-15}$ of International Atomic Time (TAI). Identical steps were applied to TP165.

The comparison started on Modified Julian Date (MJD) 57233 and ran through MJD 57733, for a duration of 500 days. TP165 was started on MJD 57233 from the existing state of TP162 and all but one of the cesium standards were immediately given a weight of zero. One cesium clock had to be left at normal weight (~ 4 % long-term weight) until MJD 57300 due to a technical issue with the measurement system, at which time its weight was also set to zero. Over the test interval the number of hydrogen masers in TP162 and TP165 was exactly the same and ranged from five to eight. The number of cesium standards in TP162 also ranged from five to eight. All timescale commands pertaining to the hydrogen masers were identical in both scales. Thus the only difference between the two scales was the absence of the cesium standards in TP165.

TEST RESULTS

Figure 1 shows the time difference between the two scales from MJD 57233 to MJD 57733. The difference is zero at the beginning (as expected) and then it changes monotonically to -6.6 ns. Figure 2 shows the fractional frequency difference (one day averages) between the two scales which reaches a maximum of about $-3.2x10^{-16}$ near MJD 57500. The average frequency difference is $-1.53x10^{-16}$. The average frequency drift rates of the two scales differ by $0.4x10^{-18}$/day.

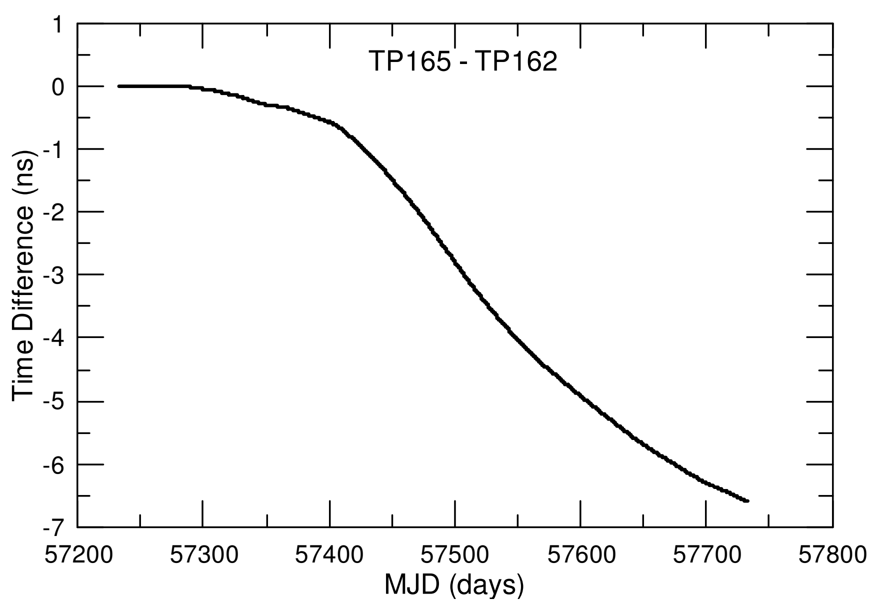

Figure 1. Time difference between TP165 (only masers) and TP162 (masers and cesium standards).

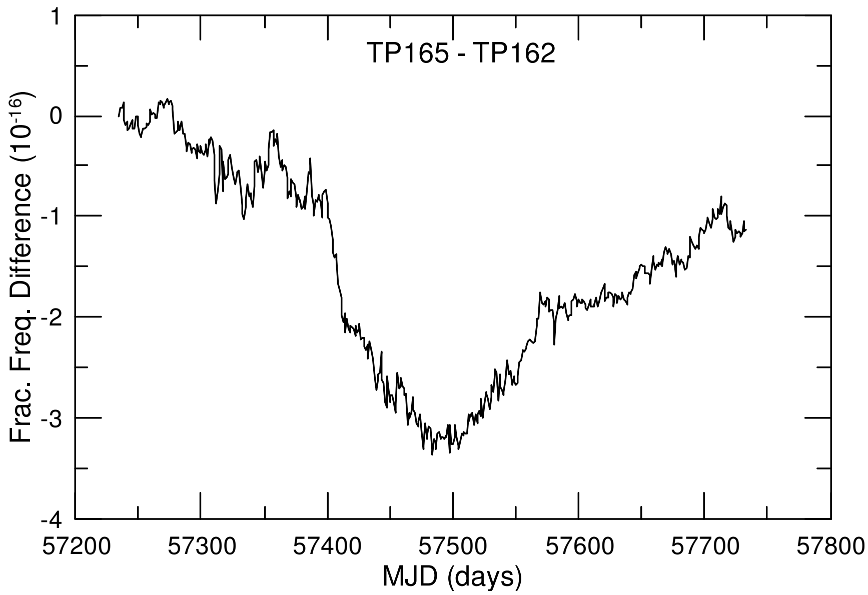

Figure 2. Frequency difference (one-day averages) between TP165 and TP162.

It is also useful to compare the frequency stabilities of the two scales to an outside reference, specifically TAI. Figure 3 shows the Total version of the Allan deviations of TP165 - TAI and TP162 - TAI. The data interval covers only MJD 57234 to MJD 57719 since TAI is only calculated once a month on a 5-day grid. The two plots are virtually identical except at the largest tau value, where TP165 has a slightly smaller value. This is somewhat surprising since there are fewer clocks in TP165.

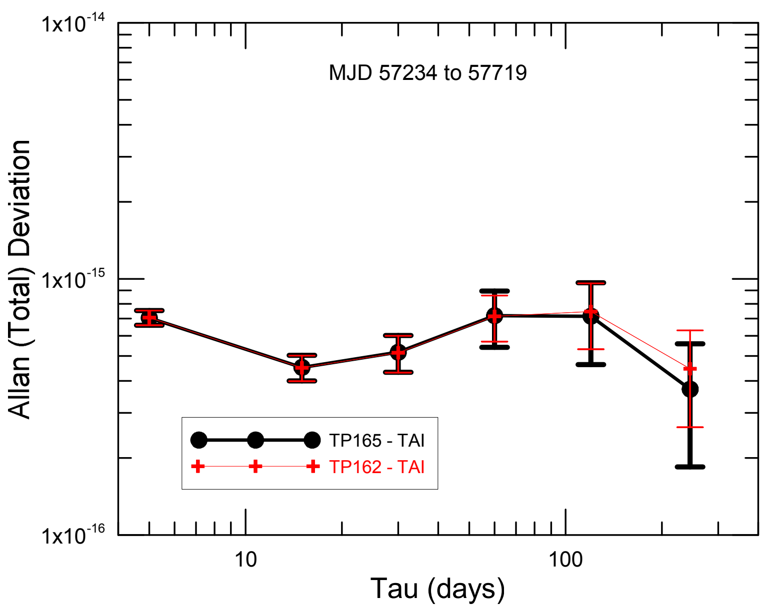

Figure 3. Allan (Total) deviations of TP165 – TAI and TP162 - TAI.

ANALYSIS

The primary functions of the real-time timescales AT1 and TSC (the backup scale) are to be stable frequency references for the generation of UTC(NIST). UTC(NIST) is steered via small frequency steps relative to AT1 (or TSC) to be as close a real-time realization of Coordinated Universal Time (UTC) as possible. The steers are based on data from rapid Coordinated Universal Time (UTCr) and UTC, as calculated by the Bureau International des Poids et Mesures (BIPM). Rate (frequency) steers to UTC(NIST) typically occur approximately every two to four weeks and range in magnitude from 0.1 ns/day to 0.5 ns/day. The average magnitude of a steer is ~ 0.3 ns/day. Given the frequency and magnitude of the steers, a difference of about 5 ns over a year due to not using the cesium standards should have a minimal impact on the performance of UTC(NIST). A typical steer would have to be adjusted by only 0.014 ns/day (or 5%) in order to compensate for the 5 ns change. Note that TP162 sometimes contains one or two more clocks than AT1 (or TSC), so the results given here are not exactly the same as what would be obtained with the real-time timescales.

The primary function of TP162 is to provide a stable paper frequency reference for the NIST primary frequency standards. It is a more stable frequency reference than AT1 (or TSC) since it is a post-processed scale and is periodically steered in frequency to match the frequency of TAI (but with a constant offset). AT1 and TSC are not steered. Fractional frequency steers of +/- $5x10^{-16}$ (or +/- 0.043 ns/day) are applied approximately once every other month to TP162. Obviously TP162 would also be impacted if there were no available cesium frequency standards. However, as TP165 has shown, the maximum and average frequency change over a full year due to not using cesium standards is only on the order of a few times 10^{-16}. This is not a significant perturbation.

One useful function of the cesium standards is that they are generally more reliable than the masers and therefore they are good clocks to be used as physical reference clocks on the measurement systems. Also, just having more clocks in the system makes the timescale less vulnerable to a catastrophic failure due to the loss of several clocks. Currently, our cesium standards are housed in temperature and humidity controlled chambers. Some resources could be saved by not using the environmental chambers. The stability of the cesium standards would be degraded and therefore their weights in the time scales would be reduced. However, since having zero weight in the scales has no significant impact, not using environmental chambers should also have no significant impact.

CONCLUSIONS

The robustness of a timescale increases with the number of clocks in the scale, but there are always practical limitations. Therefore, informed decisions must be made on where to place limited resources. The presence of commercial cesium standards in the NIST timescales has only a small impact on frequency stability and therefore, there would probably be no significant degradation to the scales if cesium standards were not used. The impact of fewer clocks on the robustness of the scales is more difficult to judge.

DISCLAIMER

ACKNOWLEDGMENTS

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REFERENCES

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[2} Thomas E. Parker, “Hydrogen Maser Ensemble Performance and Characterization of Frequency Standards,” *Proceedings of The Joint European Frequency and Time Forum and the IEEE International Frequency Control Symposium*, pp. 173-176, 1999.