FORMATION OF A GPS-LINKED GLOBAL ENSEMBLE OF HYDROGEN MASERS, AN1) COMPARISON TO JPL'S LINEAR ION TRAP

1,.11. Young, D.C. Jefferson, S. M. Lichten, R.L. Tjoelker and L. Maleki

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, M/S 238-600
Pasadena, CA 91109

Abstract

This paper will describe the usc of precision GPS time transfer to form an ensemble of hydrogen mast.r clocks. The performance of this ensemble, including the GPS time-transfer system, was measured relative to a stable Linear Ion Trap Standard,

Very high-precision techniques have recently been developed in support of efforts to achieve crn-level accuracy in tbc usc of GPS for geodesy. A global network of tracking stations, equipped with precision dual-frequency GPS receivers, has been in operation for several years. The post-processing software developed for cm-level geodesy has been used to demonstrate sub-nanosecond (ns) time synchronization, as reported in the 1'"1"1'1 conferences of 1991 and 1993. The global network of GPS stations includes 25 which arc run coherently from hydrogen masers. 'l'his paper explores the usc of high precision GPS estimation techniques to transfer time globally in conjunction with ensembles of atomic time stand ards, which in principle should be superior in performance to a single clock. Together, the.sc techniques have potential to provide a means of directly assessing performance of individual clocks for which statistical information about stability is desired,

GPS System Performance

Advanced TurboRogue GPS receivers, which produce dual-frequency pseudorange and carrier phase observables, have been developed to fill NASA's require.ments for high-accuracy GPS measurements. [1] When anti spoofing is on, this receiver uscs P-codeless processing to generate pseudorange observables with sub-decimeter precision, and mm precision carrier phase observables. A sophisticated multi-parameter estimation package, GIPSY-OASIS 11, has been developed to take advantage of the mrn-level precision inherent in tbc carrier phase observable to obtain cm-level baseline estimation accuracy. [2] The combination of a global network of advanced receivers and highly-accurate post-processing software have demonstrated sub-nanosecond time-(ransfer capability at intercontinental distances. [3,4] The. JPL-developed Linear Ion Trap Standard (LITS) which this experiment uscs as a standard to compare with the long-term stability of the maser ensemble, including errors due. to the GPS time transfer, is described elsewhere in these proceedings.[5] The errors in the Jet Propulsion Laboratory's GPS time transfer technique arc described in reference 6,

Ensemble Clock

Ensemble Concept: As the number of ncw generation clocks such as mercury trapped ion standards and laser cooled cesium standards continues to grow, remote comparisons of their stability performance will be highly desirable, Until GPS receivers to compare these new clocks arc in place, and as a first step in characterizing tbc limitations of current time transfer techniques, wc have attempted to build an ensemble of hydrogen masers that arc currently collocated with several high precision GPS receivers.

About **24** of the high-precision GPS receivers whose data arc used in JPL's geodetic solutions have their internal clocks driven from masers. If GPS can transfer the. timing information among these masers with enough accuracy, if the drifts of the maser clocks arc independent, and if no clock is vastly more stable than the rest, then an ensemble clock formed from these 24 masers would have significantly better performance than any single maser.

The conditions described above were not fully met for the experiment described here; yet the concept dots offer hope for formation of global clock ensembles with superior stability, especially for longer time periods when ncw high stability and accuracy frequency standards are included.

~'ir~~e-transfer Accuracy: The accuracy of the GPS time transfer system was described in reference 6 to be 2×10^{-15} over about 1 day. This error is dominated by 15 cm lorlg-term errors in the GPS satellite ephemeris determined in the geodetic processing, which translates to 0.15 ns relative clock synchronization error over intercontinental baselines. The accuracies that arc discussed in this paper, and in reference 6, do not include instrumental biases that are constant, and so the absolute offsets between clocks arc not measure.ci with these

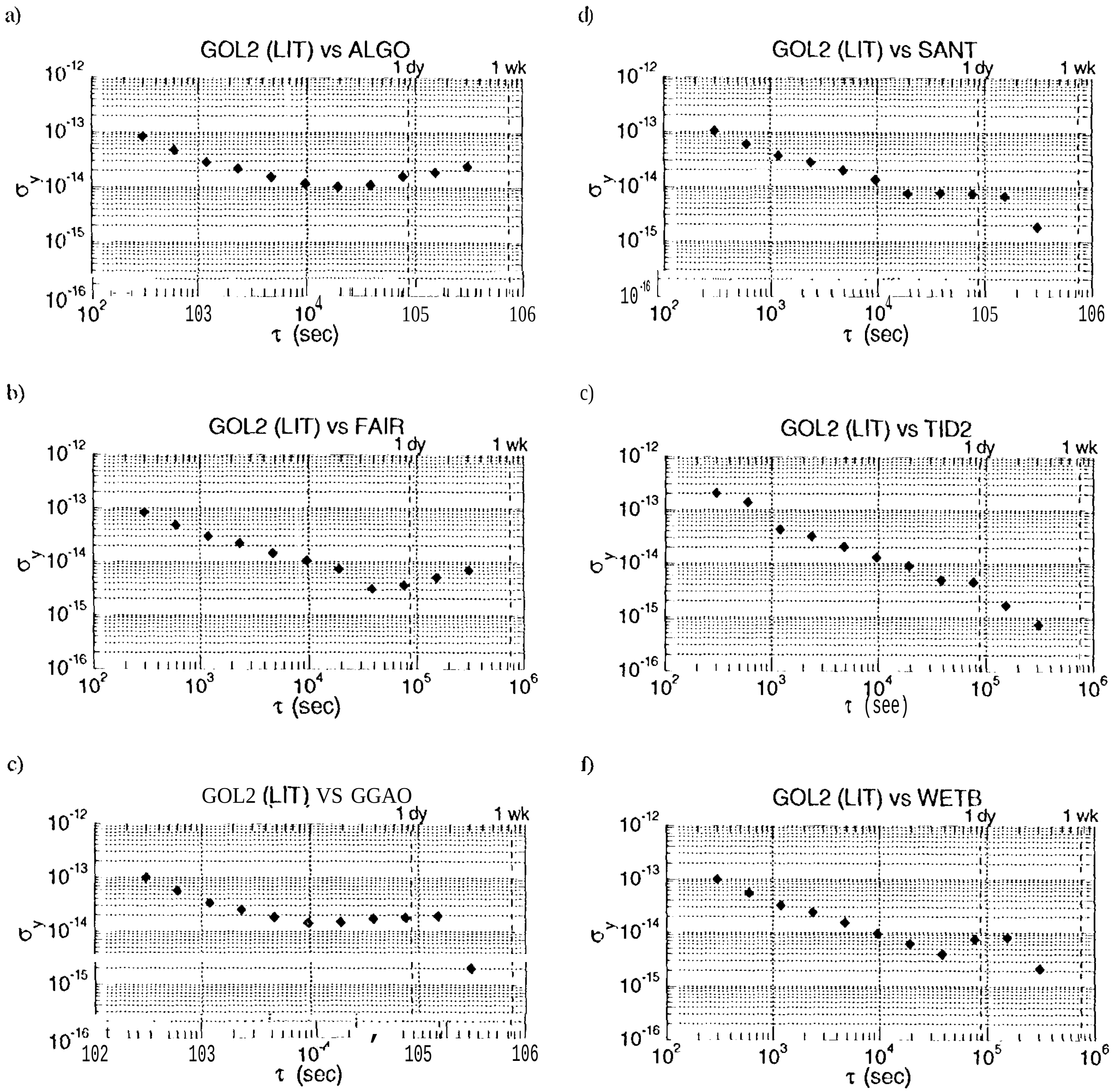

Figure 1: Allan deviation taken from 10 days of data for each of the six hydrogen masers relative to the 1.1'1'S. Linear frequency drifts have been removed. The performance shown includes GPS time transfer errors.

accuracies. Rather, the variations of the offsets between clocks arc measured. The desired GPS accuracy for formation of an ensemble clock is that the GPS errors be comparable to, or less than, the best clock stability at the time intervals of interest. The GPS time transfer stability of 2 x 10^{-15} over 10^5 seconds is similar to what laboratory tests indicate for hydrogen mast.rs.

Independence of Drifts: The long-term frequency drifts of the hydrogen masers, particularly those of similar construction, may be corl-elated, This experiment did not attempt to independently deter-mine this correlation, but masers of various types were included in the ensemble. The types of masers used at cacb of the six sites chosen for our comparison arc shown in l'able 1.

I'able 1: Frequency standards used in the ensemble clock.

STATION	MASER TYPE	CAVITY TUNED?
ALGO	NR-9	NO
FAIR	NR-5	PRE-PROG
GGAO	NR-10	NO
SANT	NR-4	PRE-PROG
TID2	SAO	NO
WTZB	EFOS 13	NO

Similarity of Clock Stabilities: For the purpose of this experiment, the. ensemble was constructed of both fixed-tune masers and those with prc-programmed cavity tuning, but none with active cavity tuning,. Our approach to forming this experimental ensemble from these clocks is to apply unequal weight to each standard, based on its apparent stability relative to the 1,1'1'S, as measured with GPS. Wc used the squared inverse of the AlIan deviation at 10S seconds as the ensemble weighting factor.

Ensemble Results

Operational Problems: During this experiment it was discovered that the masers were occasionally manually retuned to a different frequency; these masers were excluded from the ensemble. In addition, others had significant periods where their data were not available for various reasons, and so had to be excluded on those grounds. The result of these problems was that only data from six masers over a 10-day time span were analyzed for this paper, and only two of these masers attempted to compensate for drift. To characterize the long term capability of the time transfer technique, exclusive usc of cavity compensated masers would be preferred for any future ensemble

Maser Performance: Figure 1 shows the Allan deviation of cacb of the masers relative to the 1.1"1'S, as measured by the precision GPS technique. The.sc measurements were made with the masers running operationally in the field, at the observatories where they are used for astronomical and spacecraft tracking timing applications. The performance at a tau of onc day ranges from a few parts in 10^{15} for a pre-programmed cavity-tuned maser, to over a part in 10^{14} for onc of the non-tuned masers. It is emphasized that while these numbers reflect the entire system stability, including the errors duc to GPS time transfer, the differences between the performance seen at onc day and longer times arc probably duc to the masers themselves. For example, the GPS errors would be expected to be largest for the GOL2 (CA, USA) vs. TID2 (Tidbinbilla, Australia) comparison, because this was the longest baseline, but this pair shows one of the. most stable AlIan deviation measurements at onc day,

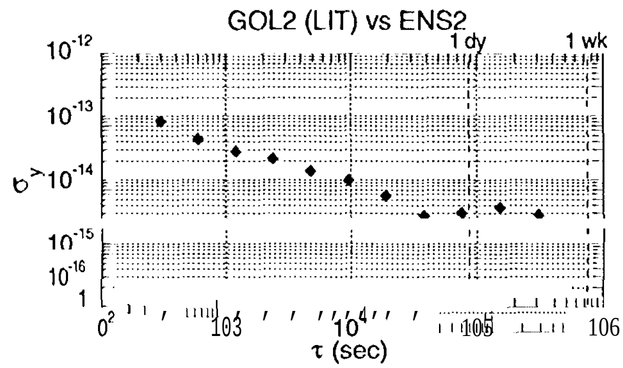

Figure 2: AlIan deviation taken from 10 days of data for the weighted ensemble of six hydrogen masers relative to the 1,1'1'S. Linear frequency drift has been removed. Tbc performance shown includes GPS time transfer errors.

Ensemble Performance: Figure 2 shows the AlIan deviation of the experimental ensemble clock relative to the 1.11'S. The ensemble was weighted to optimize its performance at onc day. The stability of tbc ensemble clock, including GPS time-transfer errors, was about 3 parts in 10^{15} for onc day, which is slightly better than tbc best individual I.IT-vs-maser pair (GOL2/FAIR). In this limited ensemble, only the GOL2/TID2 pair was within a factor of two of the Allan deviation of GOL2/FAIR, which explains why there was only a slight improvement.

Conclusions

The errors introduced by GPS time transfer, when combined with the sparse set of masers used in tbc formation of the experimental clock ensemble shown in fig. 2, and a relatively short time span, do not allow stability measurements comparable to the 10^{-16} stability expected from the LITS. [5] Formation of the ensemble clock using the c.avity-compensated masers in the GPS global network, over a much longer time than the ten days reported in this paper, together with the GPS-system improvements mentioned below, are expected to allow significant future improvements in the GPS-connected ensemble clock.

This paper described the first attempt to use the geodetic-quality GPS data to form a global ensemble of high-perfor[nance clocks for comparison with a 1,1'1'S. Improvements in operational control of the experiment to obtain long unbroken segments of data from each standard, and the inclusion of active cavity-tuned masers, is expected to allow improved long-term ensemble performance. Another area needing improvement is the algorithm used to weight the masers in the ensemble. Because the current GPS parameter estimation process is tuned for daily determination of geodetic parameters and GPS orbits, in which receiver clocks are regarded as nuisance parameters, the process is not optimal for continuous estimation of relative clocks over intervals of more than one day. We plan to revise this process as necessary, if there are future applications of JPL's GPS estimation software to precision clock transfer. We hope to include other high-stability standards, such as a Cesium-fountain clock, to increase the performance of any future intercontinental clock ensemble, Other future work will focus on the GPS error budget for clock estimation over intervals of 1 day or longer. Since the dominant GPS error over those intervals appears to be from GPS orbits, we anticipate that alternative orbit estimation strategies can be developed to better optimize the precision CiPS process for long-term time standard monitoring.

Acknowledgment

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

[1] '1. K. Meehan, J. M. Srinivasan, D. J. Spitzmesser, C. E. Dunn, J. Y. Tien, J. B. Thomas, '1'. N. Munson, and C. B. Duncan, "The TurboRogue GPS Receiver, " Proceedings of the 6th International Geodetic Symposium On Satellite Positioning, Columbus, Ohio, Mar 18, 1992.

[2] S.M. Lichten, Y. Ii. Rar-Sever, W.]. Bertiger, M. Heflin, K, Hurst, R.J. Muellerschoen, S.C. Wu, '1'. P. Yunck, anti J. Zumberge, "GIPSY-OASIS 11: A High Precision GPS Data Processing System and General Satellite Orbit Analysis Tool," *Technology 2005*, NASA Technology Transfer Conference, Chicago, IL., Oct. 24-26, 1995.

[3] C. Dunn, S. Lichten, 1). Jefferson, and J. Border, "Sub-Nanosecond Clock Synchronization and Precision Deep Space Tracking," proceedings of the 23rd Annual Precise Time. and Time Interval (PTTI) Conference, 199 1. NASA Conf. Pub. 31 59.

[4] C. Dunn, D. Jefferson, S. M. Lichten, J. B. Thomas and Y. Vigue, "Time and Position Accuracy using Codeless GPS," Prodccdings of the 25th Precise Time and Time Interval (1''1"1"1) Conference, Marina Del Rey, CA, NASA Con ference Publication, December 1993.

[5] R, L. Tjoelker, C. Bricker, W. Diener, R. L. Hamel, A. Kirk, P. Kuhnle, L. Maleki, J. D, Prestage, D. Santiago, D. Seidel, D. A. Stowers, R. L. Sydnor, T. Tucker, "A Mercury Ion Frequency Standard Engineering Prototype for the NASA Deep Space Network," these proceedings.

[6] David C. Jefferson, Stephen M. Lichten, anti Larry E. Young, "A Test of Precision GPS Clock Synchronization," these proceedings.