COMPARISONS OF CLOCKS BY GPS AND TWSTFT

J. Azoubib[(1)] and W. Lewandowski[(2)]

[(1)]Bureau International des Poids et Mesures, Pavillon de Breteuil, 92310 Sèvres, France
jazoubib@bipm.org

[(2)]As above, but E-mail: wlewandowski@bipm.org

ABSTRACT

The GPS has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks for the last two decades. GPS common-view time transfer is, however, barely sufficient for comparison of today's atomic clocks within a few days. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons, among them is the two-way satellite time and frequency transfer (TWSTFT). This paper describes impact of time transfer on the computation of International Atomic Time and a comparison of single-channel GPS C/A-code common-view time transfer and TWSTFT.

INTRODUCTION

For a decade and half the American Global Positioning System (GPS) has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks [1]. In the pre-GPS era the technology of atomic clocks was always ahead of that of time transfer. The uncertainties of the long-distance time comparisons, by LORAN-C, were some hundreds of nanoseconds and large areas of the earth were not covered. This resulted in an annual term in International Atomic Time (TAI). The introduction of GPS has led to a major improvement of world-wide time metrology in precision, accuracy and coverage. With GPS operated in single-channel common-view C/A-code mode, time comparisons are performed with an uncertainty of a few nanoseconds which corresponds to one part in 10^{14} for averaging times of a few days. For the periods of about one month when the noise of GPS is completely removed the stability of TAI currently reaches two parts in 10^{15}.

A single-channel GPS C/A-code common-view time transfer is, however, barely sufficient for the comparison of today's atomic clocks for periods of several days and needs to be improved rapidly to meet the challenge of clocks currently being designed. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons. Among them are techniques based on multi-channel GPS and GLONASS C/A-code measurements, GLONASS P-code measurements, GPS carrier-phase measurements, temperature-stabilized antennas (TSA), standardization of receiver software and two-way satellite time and frequency transfer (TWSTFT) through telecommunication satellites.

The GPS carrier-phase technique allows frequency comparisons at a level of one part in 10^{15} and should soon be a useful tool for the comparison of primary frequency standards. However, the persistent difficulties in the calibration of GPS carrier-phase equipment seems to preclude the use of this technique for TAI during the coming few years. On the contrary, the TWSTFT technique, which has a similar performance to carrier phase, is at present operational and used in TAI for several links.

This paper emphasizes the impact of time transfer on the computation of TAI and provides a comparison of single-channel GPS C/A-code common-view time transfer and TWSTFT.

EVOLUTION OF CLOCKS AND TIME LINKS CONTRIBUTING TO TAI

The international time scales computed at the Bureau International des Poids et Mesures (BIPM) – TAI and UTC – are based on data from some 220 atomic clocks located in about 50 time laboratories around the world. The number of clocks fluctuates a little but remains roughly constant. The quality of the clocks, however, has been improving dramatically. In 1992 the first Hewlett-Packard (HP) 5071A caesium clocks with high-performance tubes were introduced into the TAI computation, and the number of hydrogen masers has also been increasing steadily. In 1999 about 65 % of the participating clocks were HP 50701A with a high-performance tube and about 17 % were hydrogen masers [2]. Other commercial caesium clocks (including HP 5071A clocks with a low-performance tube, and continuously operating primary frequency standards) account for only 18 %. This progress has of course contributed to a significant improvement in the stability of TAI.

The quality of the clocks, although an important issue, is not the only factor contributing to the stability of TAI. Another important factor is the quality of the time links used to compare the clocks. Prior to 1981 only LORAN-C and TV links were used to compare clocks contributing to TAI. In 1981 the first GPS common-view single-channel C/A-code links were introduced. These allowed, for the first time, comparison of the stability of remote atomic clocks within an averaging time of several days. The proportion of GPS common-view links has increased steadily over the years and reached almost 100% in 1999. A new technique was then entered into TAI: that of Two-Way Satellite Time and Frequency Transfer (TWSTFT). As of June 2000 five TWSTFT links are used for TAI, and several others are in preparation.

COMPARISON OF GPS AND TWSTFT TIME LINKS

TWSTFT is a technique that utilizes geostationary telecommunications satellites to provide time transfer with a theoretical precision of several hundred picoseconds [3]. At present the TWSTFT technique is operational in eight European, three US and two Japanese time laboratories. Some other laboratories have reached pre-operational status. The technique has been contributed to TAI since July 1999, following recommendations of the Consultative Committee for Time and Frequency (CCTF). The number of such links used for TAI is likely to increase from the present five.

In May 1999 the BIPM started publishing Monthly TWSTFT Reports. Some selected TWSTFT links through INTELSAT 307° E are computed and compared with GPS at the time of preparation of *Circular T*. An example of such a comparison between National Physical Laboratory (NPL) and National Institute of Standards and Technology (NIST) is given in Fig. 1. This TWSTFT link was calibrated by a portable GPS receiver.

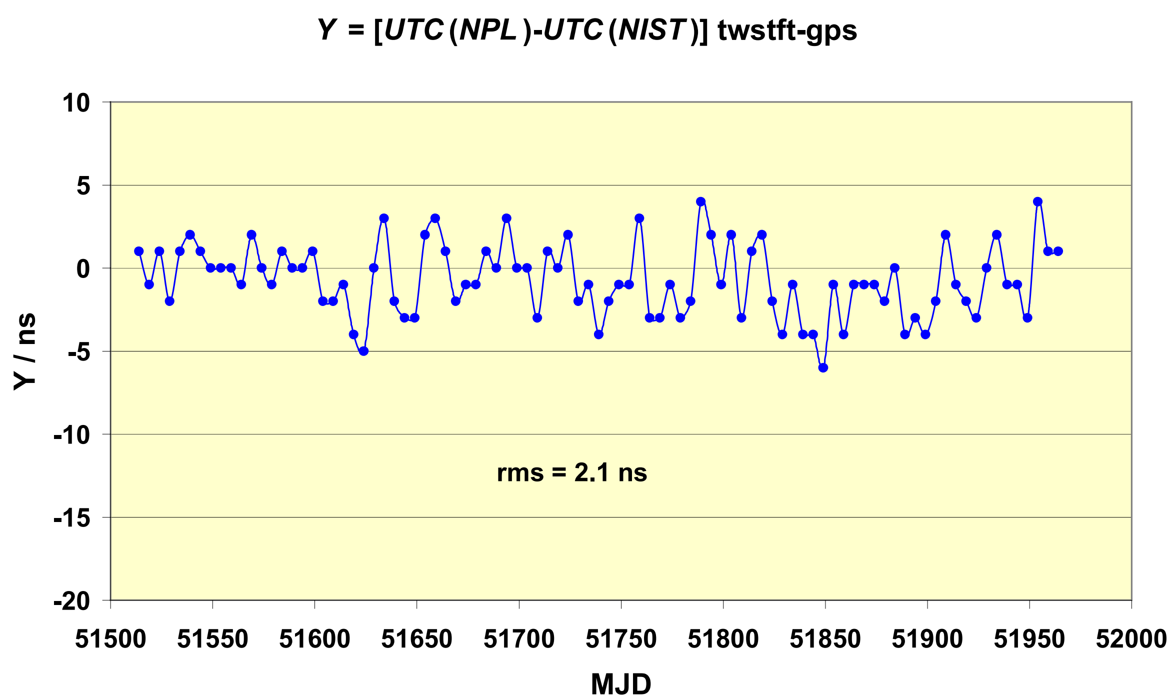

Fig. 1. Differences between TWSTFT and GPS common-view for NPL/NIST link.

Modified Allan variance analysis of TWSTFT and GPS links shows better behaviour of TWSTFT for almost all analysed links up to 20 days. This is particularly striking for the NPL/NIST link where TWSTFT is showing the behaviour of clocks already for averaging time of 5 days (see Fig. 2). Using a GPS link we have to wait 20 days to smooth out white-phase noise due to time transfer.

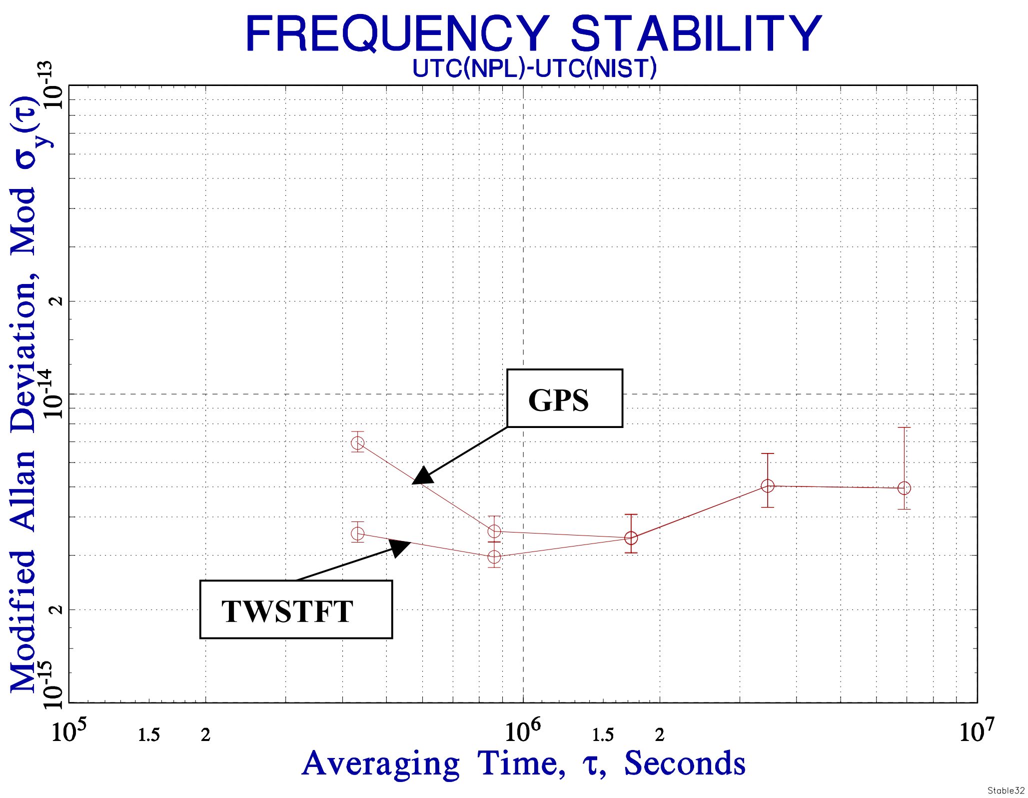

Fig. 2. Frequency stability of [*UTC*(*NPL*) – *UTC*(*NIST*)] by GPS and by TWSTFT.

SUMMARY

The construction of TAI requires time-transfer techniques that allow participating clocks to be compared at their full level of performance for intervals at which TAI is computed. In the pre-GPS era this was impossible because the technology of atomic clocks was always ahead of that of time transfer. This resulted in an annual term in TAI. The replacement of LORAN-C links by GPS C/A-code common-view links during the years 1981-1998 has progressively reduced the impact of white phase noise on TAI, improving its stability up to about 80 days. During the 1980s, GPS allowed for the first time the comparison of remote atomic clocks at their full level of performance for averaging times of just a few days, fully satisfying needs of TAI, computed at this epoch at intervals of 10 days.

However, with the improvements in clock technology made during the 1980s and the resulting dramatic increase in the quality of the clocks contributing to TAI in the 1990s, intercontinental GPS C/A-code common-view measurements now need to be averaged over up to 20 days in order to smooth out measurement noise. This is no longer sufficient for TAI, computed at five-day intervals from 1 January 1996.

The first analysis of the performance of TWSTFT, which is now in use for several TAI links, shows that clocks located on different continents can be compared by this technique at five-day intervals at their full level of performance, without being affected by time-transfer measurement noise. Thus, if TWSTFT were used for all TAI links, the stability of TAI would be improved for periods of up to 20 days.

The introduction of TWSTFT (see Fig. 3) into TAI has brought about another important change for the better; TAI is not longer reliant on a single technique, because TWSTFT links are backed-up by GPS links and vice versa. Also, for the first time, two transatlantic links are used for its construction, and each of these links is performed by two independent techniques. This very new situation increases the robustness of TAI construction.

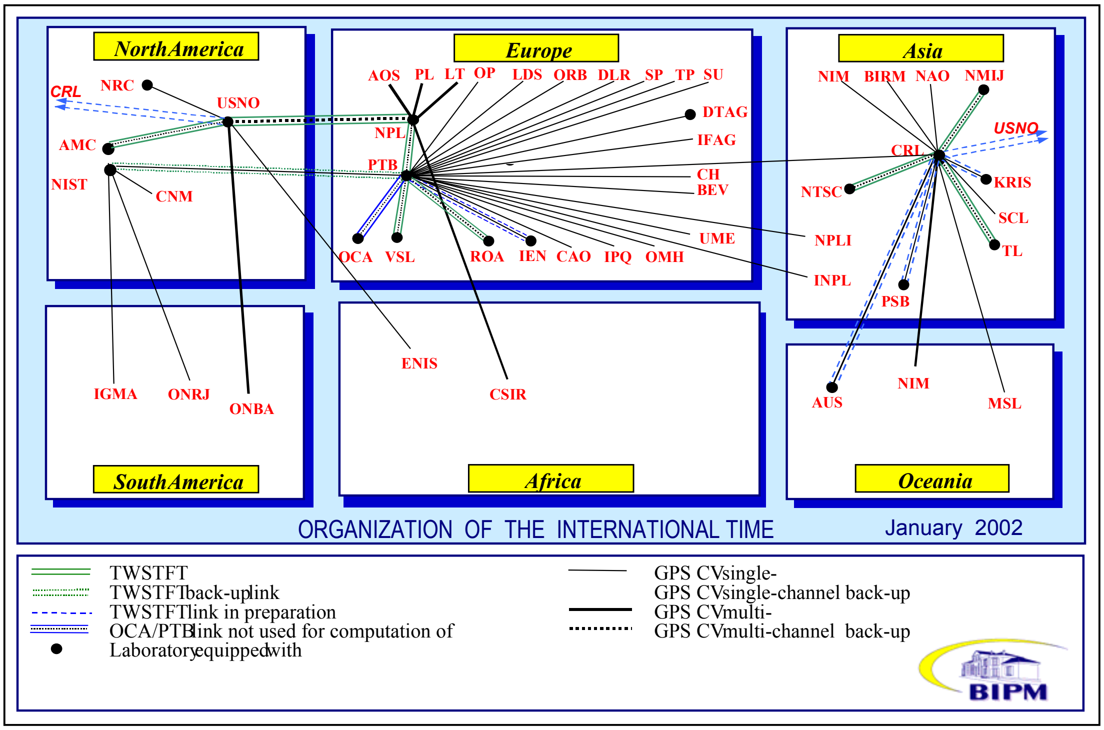

Fig. 3. Summary of the international time links as for January 2002.

Another important issue is the accuracy of TAI time links. These determine the accuracy with which laboratories have access to UTC. Significant proportion of GPS links were never calibrated and their accuracy is limited to several tens of nanoseconds. The other GPS links and all but one of the TWSTFT links have been calibrated by a differential technique using a portable GPS receiver. The uncertainty of such a calibration is limited to several nanoseconds, mainly due to the environmental instability of GPS time-receiving equipment. This could be reduced by using TSAs, keeping receivers in air-conditioned rooms, and, if possible, using GLONASS P-code observations.

One TWSTFT link, NPL/USNO (United States Naval observatory), has been calibrated by a portable TWSTFT station. The uncertainty of this calibration is believed to be 1 ns or better. Other TWSTFT calibrations are planned, and it is expected that use of TWSTFT will bring a substantial improvement to the accuracy of TAI time links.

For better monitoring of the accuracy of time links, repeated calibrations are required, either by GPS or by TWSTFT.

REFERENCES

[1] Allan D.W., Weiss M.A., "Accurate Time and Frequency Transfer During Common-View of a GPS Satellite", *Proc. 1980 Frequency Control Symposium*, pp. 334-336, 1980.
[2] W. Lewandowski, J. Azoubib, "Time Transfer and TAI", *Proc IEEE/EIA International Frequency Control Symposium*, Kansas City, pp. 586- 597, June 2000.
[3] Kirchner D., Ressler H., Grudler P., Baumont F., Veillet C., Lewandowski W., Hanson W., Klepczynski W.J., Uhrich P. "Comparison of GPS common-view and Two-Way Satellite Time Transfer over a baseline of 800 km", *Metrologia* 30, pp. 183-192, 1993.