SATELLITE TIME-TRANSFER: RECENT DEVELOPMENTS AND PROJECTS

W. LEWANDOWSKI [1] and J. NAWROCKI [2]
[1] Bureau International des Poids et Mesures, Sèvres, France
e-mail: wlewandowski@bipm.org
[2] Astrogeodynamical Observatory, Space Research Centre, Borowiec, Poland
e-mail: nawrocki@cbk.poznan.pl

ABSTRACT. Global Navigation Satellite Systems (GNSS) keep a central role in the international timekeeping. American Global Positioning System (GPS) is a navigation system that has proven itself to be a reliable source of positioning for both the military community and the civilian community. But, little known by many, is the fact that GPS has proven itself to be an important and valuable utility to the timekeeping community (Lewandowski et al. 1999). GPS is a versatile and global tool which can be used to both *distribute time* to an arbitrary number of users and *synchronise clocks* over large distances with a high degree of precision and accuracy. Similar performance can be obtained with Russian Global Navigation Satellite System (GLONASS). It is expected in the near future satellites of a new European navigation system GALILEO might bring some important opportunities for international timekeeping. This paper after a brief introduction to international timekeeping focuses on the description of recent progress in time transfer techniques using GNSS satellites.

1. INTRODUCTION

Construction of International Atomic Time (TAI) and Coordinated Universal Time (UTC) relies on a network of satellite time links encircling the Earth. For a quarter of century the American Global Positioning System (GPS) has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks. From about ten years Two-Way Satellite Time and Frequency transfer (TWSTFT) through telecommunication satellites plays an increasing role. Russian GLONASS P-code shows an outstanding performance, although is not yet used operationally. A possible common use of GPS+GLONASS has also been demonstrated. GPS and GLONASS augmentation satellites such as WAAS, EGNOS, MSAS and GAGAN appear to be convenient for time transfer. It is expected that the European project Galileo will provide new opportunities. The timing community is developing time transfer standards for all available and upcoming global navigation satellite systems (GNSS). The interoperability of all GNSS is a major issue, implying coordination of time scales and reference frames.

Until now the major research work focused on GPS time transfer. This resulted in improvement of GPS time transfer reaching now accuracy of 1ns when using multichannel and P3 techniques. A major part of this progress is due to new generations of satellite receivers, often geodetic. However the TWSTFT technique has the best performance approaching right now 0.2 ns and having a great potential of further improvements.

The Bureau International des Poids et Mesures (BIPM), located in Sèvres near Paris, is on charge of computing and publishing international reference time scale. A practical scale of time for world-wide use has two essential elements: a realization of the unit of time and a continuous temporal reference. The reference used is International Atomic Time (TAI), a time scale calculated at the BIPM using data from some two hundred atomic clocks in over fifty national laboratories. The long-term stability of TAI is assured by a judicious way of weighting the participating clocks. The scale unit of TAI is kept as close as possible to the SI second by using data from those national laboratories which maintain the best primary caesium standards. TAI is a uniform and stable scale which does not, therefore, keep in step with the slightly irregular rotation of the Earth. For public and practical purposes it is necessary to have a scale that, in the long term, does. Such a scale is Coordinated Universal Time (UTC), which is identical with TAI except that from time to time a leap second is added to ensure that, when averaged over a year, the Sun crosses the Greenwich meridian at noon UTC to within 0.9 s. The dates of application of the leap second are decided by the International Earth Rotation Service (IERS). At present TAI is 32 s ahead of UTC (see Figure 1 and http://www.bipm.org/en/scientific/tai/tai.html).

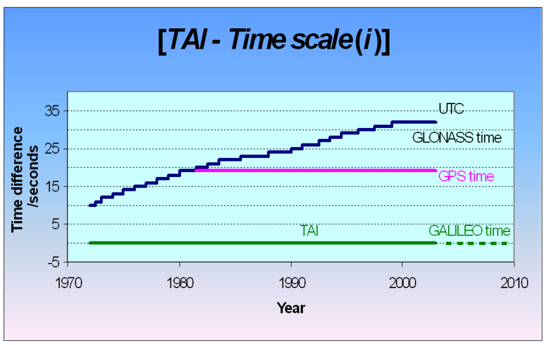

Figure 1: Differences between TAI, UTC, 'GPS time', 'GLONASS time', 'Galileo time' (project).

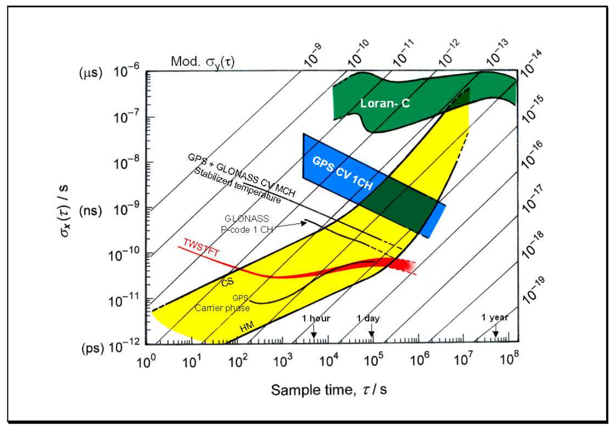

Figure 2: Comparison of some newer techniques with classical GPS single-channel common-view time transfer. Also indicated are typical clock performances.

This presentation reviews the above mentioned techniques as well as their potential impact on UTC and TAI.

UTC is computed and made available every month in the BIPM *Circular T* through the publication of [*UTC - UTC(k)*]. UTC is the reference time scale for world-wide time coordination. It serves as the basis of legal time in the different countries. Local realizations of UTC named UTC(k) are broadcast by time signals in some countries.

The GNSS are using 'internal' reference time scales. GPS uses 'GPS time', which was set in 1980 to have zero second difference with UTC, and to be 19 s behind TAI. 'GPS time' is, like TAI, a uniform time scale, it means that it does not follow leap seconds. GLONASS uses 'GLONASS time' which does follow leap seconds. According to the information available in September 2004, 'Galileo time' will be set to have zero second difference with TAI, and will be uniform time scale so not following leap seconds (see Figure 1). Each of these systems is programmed to broadcast a prediction of UTC, so a time scale using leap seconds. It happens, however, that for some applications it is suggested to use uniform time scales as TAI or 'GPS time', instead of UTC 'suffering' from leap seconds. Such proliferation of various time scales may cause major problems.

The utility of leap seconds is under discussion within International Astronomical Union (IAU) and International Telecommunications Union (ITU). A colloquium on future of UTC was organized by the ITU at the IEN Galileo Ferraris, Turin, Italy, in May 2003.

2. TIME TRANSFER TECHNIQUES

For the timekeeping community, GPS is today a significant contributor to solving the traditional problems of timekeeping; it is a reliable source of time and it is a reliable time transfer system. Russian global satellite navigation system GLONASS although not as well known as the GPS possesses comparable capabilities for navigation, precise geodetic positioning and time-transfer applications (Gouzhva et al. 1992).

Over the years, the clocks by which we have kept time have become not only more precise but also more accurate and the timekeeping community has sought more precise and more stable systems to help them with synchronisation. Time metrology began to use GPS signals about fifteen years ago at the National Bureau of Standards, NBS (now National Institute of Standards and Technology, NIST). A system using common-view observations of GPS satellites for accurate time and frequency transfer was suggested (Allan and Weiss 1980), and receivers especially designed for this purpose were built first at the NBS and then in several commercial companies. These were single-channel one-frequency C/A-code receivers capable of tracking only one satellite at a time. To operate them it was essential to issue periodic schedules of common-view observations. The common-view method was clever and far-reaching: it not only reduced some uncertainties of physical origin, but went on to cancel the deliberate degradation of GPS Time introduced in 1990 under the name of Selective Availability (SA).

The introduction of GPS brought about a significant improvement in time and frequency transfer. With uncertainties ranging from 10 ns to 20 ns for time comparisons during early stages of the use of GPS, it was possible, for the first time, to compare the best atomic standards in the world at their full level of performance using integration times of about 10 days. Since then a number of improvements have been introduced, including the use of ultra-accurate antenna coordinates, precise ephemerides and measurements of the ionosphere. These led at the beginning of 1990s to time comparison uncertainties of about 3 ns, which corresponds to a few parts in 10^{14} in frequency transfer. This paralleled improvements in atomic standards, which advanced by an order of magnitude, and made possible the comparison of the new clocks, e.g., HP5071A Cesium Beam Frequency Standards, at their full level of performances for averaging times of several days.

Today, in metrology, we are witnessing the birth of a number of new and innovative frequency standards. These devices have accuracy of about 1×10^{-15} and seem to have short term instability approaching 1×10^{-16}. This corresponds to a clock having the capability to maintain a level of performance corresponding to 10 picoseconds/day. Since the newest devices are not transportable and do not operate continuously, it is important to compare them in a reasonable time in order to determine the existence of systematic differences among them. A measurement with a precision of 1 nanosecond over a 24 hour period corresponds to 1×10^{-14} in frequency. Therefore, at today's present levels, it would take weeks to compare two such devices. That is why it is important to develop and improve time transfer methods to allow these comparisons to be made within a reasonable amount of time. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons. Among them are GNSS techniques based on multi-channel GPS C/A-code measurements, GPS carrier-phase (Schildknecht et al. 1990), GPS P3 (Defraigne and Petit 2003) and GLONASS P-code measurements (Azoubib and Lewandowski 2000; Lewandowski et al. 2000), temperature-stabilised antennas and standardisation of receiver software.

The performances of various methods of time transfer are illustrated in Figure 2. It has been shown that the stability of time and frequency transfer is improved by a factor of about 3 when GPS common-view time transfer is carried out in multi-channel mode (Lewandowski et al. 1997). The use of GLONASS P-code shows a reduction in noise level by a factor of 5 in comparison with GPS C/A-code. It is now well documented that satellite-receiving equipment is subject to significant systematic effects due to environmental conditions; the use of TSA antennas and better cables reduces these effects and improves the accuracy of time transfer. The GPS carrier-phase technique allows frequency comparisons at a level of 1 part in 10^{15} and should soon be a useful tool for the comparison of primary frequency standards. Difficulties in calibration of GPS carrier-phase equipment remain unresolved, however, and this technique can not yet be used for operational time transfer. The Two-Way Satellite Time and Frequency Transfer (TWSTFT) technique (Kirchner 1999), which has a similar performance to that of carrier phase, is already operational and used in TAI for several time links.

3. EVOLUTION OF CLOCKS AND TIME LINKS AND TIME LINKS CONTRIBUTING TO TAI

The international time scales computed at the 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 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. 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 (see Figure 3). A new technique was then entered into TAI: that of TWSTFT. As of September 2004 nine TWSTFT links are used for TAI, and several others are in preparation.

To illustrate the impact of the improved quality of the time links on the frequency stability of TAI, we have analysed the period mid-1986-1993, during which the number of GPS links steadily increase but there was no dramatic change in the nature of the participating clocks. The frequency stability of EAL (the échelle atomic libre) against the primary frequency standard PTB CS2 is indicated in Figure 4 for the three periods mid-1986-mid-1988, 1988-1989 and 1992-1993. EAL is the free atomic time scale from which TAI is derived using steering corrections. We observe a significant improvement in the frequency stability of EAL for each consecutive period for averaging times up to a few tens of days (for these averaging times the white phase noise due to the time-transfer methods by which EAL was affected is drastically reduced). The evaluation of the frequency stability of EAL is here limited by the frequency stability of PTB CS2.

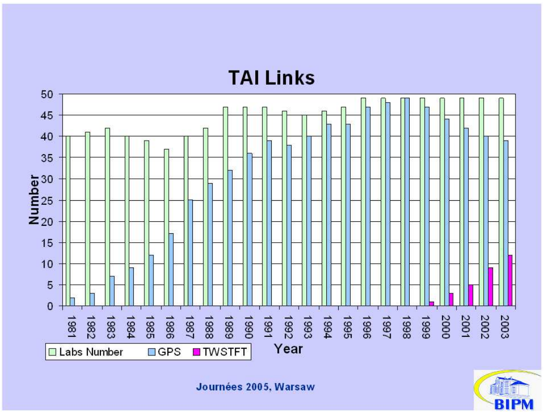

Figure 3: DTAI time links.

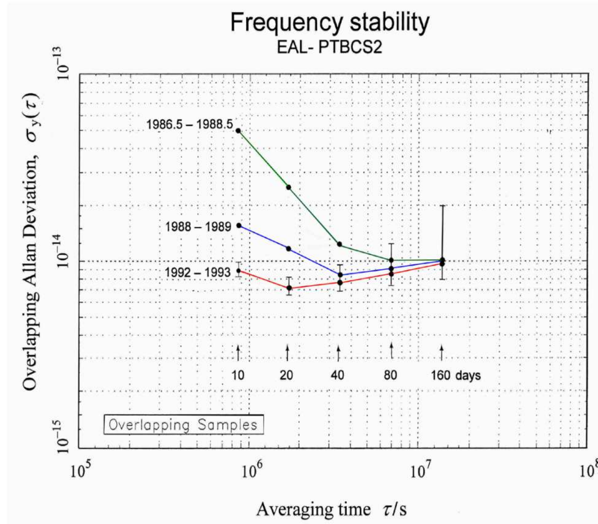

Figure 4: Frequency stability of [*EAL–PTB Cs2*].

4. 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 single-channel common-view measurements need to be averaged sometimes 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. However, the GPS multi-channel C/A-code and P3 measurements are showing better performance.

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 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.

The international timekeeping, despite using for some links TWSTFT, still relies heavily on the use of sole GPS satellites. The use of other GNSS satellites as GLONASS and GALILEO is expected to bring more reliability and some further improvements in the performance of time links. A particular problem is the uniformization of reference time scales used by different GNSS systems.

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