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ORIGINAL ARTICLE

Use of IGS products in TAI applications

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Abstract The Bureau International des Poids et Mesures (BIPM) is in charge of producing International Atomic Time TAI. In this aim, it uses clock data from more than 60 laboratories spread worldwide. For two decades, GPS has been an essential tool to link these clocks, and products from the International GNSS Service (IGS) have been used to improve the quality of these time links since its creation in the early 1990s. This paper reviews the various interactions between the IGS and time activities at the BIPM, and shows that TAI has greatly benefited from IGS products so that their availability is now an essential need for the quality of TAI links. On the other hand, IGS has also benefited from introducing time laboratories equipped with highly stable clocks in its network of stations. In the future, similar products will be needed for an ensemble of satellite systems, starting with GLONASS and GALILEO. It will be a major challenge to the IGS to obtain a consistent set of products, particularly for what concerns satellite clocks and inter-system bias values.

Keywords Time tranfer · GNSS · TAI

1 Introduction

The international timescales TAI and Coordinated Universal Time UTC are calculated at the Bureau International des Poids et Mesures. They are the result of the worldwide cooperation of more than 60 national metrology laboratories and astronomical observatories that operate commercial atomic clocks. In addition, about ten of them develop and maintain primary frequency standards that provide TAI accuracy. The algorithm used for the calculation of TAI has been designed to guarantee the reliability, the long-term stability, the frequency accuracy and the accessibility of the scale. Nevertheless, the quality of TAI rests critically on the methods of clock comparison which may bring significant instability mostly at short averaging time (5–10 days). Local representations of UTC, named UTC(k) are maintained in laboratories “k” contributing clock data to the BIPM. The BIPM organizes the international network of time links to compare local realizations of UTC in contributing laboratories and uses them in the formation of TAI. The network of time links presently used by the BIPM is non-redundant and relies on the observation of GPS satellites and on two-way satellite time and frequency transfer (TWSTFT).

The International GNSS Service (Dow et al. 2005) is an voluntary federation of institutions which operate, on a voluntary basis, a network of several hundred permanent GPS and GLONASS stations, many analysis centres, and data centres that distribute its products. GPS and GLONASS observation data sets coming from GNSS stations are analysed and combined to form the IGS products which support many Earth science applications. Some of these products have been used in the process of calculation of TAI since the IGS inception; e.g. maps of the ionosphere total electronic content (TEC) have allowed obtaining high-quality time transfer using existing single-frequency receivers; post-processed precise satellite ephemerides from the IGS have been used for correcting satellite positions.

The cooperation between the IGS and the BIPM has therefore contributed to significant improvement in time transfer. An example of this successful association is the pilot project conducted jointly by the BIPM and the IGS between 1998 and 2002, focusing on the feasibility of accurate time and frequency comparisons using GPS phase and code measurements (Ray and Senior 2003). As a conclusion of some

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studies conducted during this project, precise-code data from GPS geodetic-type, multi-channel, dual-frequency receivers have been introduced since June 2004 in the calculation of TAI (Defraigne and Petit 2003). These so-called GPS P3 links provide ionosphere-free data and allow clock comparisons with sub-nanosecond uncertainty. The most recent improvement in TAI, which is the routine calculation of GPS time links by the method of "GPS all-in-view" (Petit and Jiang 2008a) has been made possible by the IGS products. On the other hand, several time laboratories have become IGS stations and have contributed to the development of the IGS clock products.

In this paper, we review the various interactions between the IGS and TAI. In Sect. 2, we summarize the past history of clock comparisons in TAI and the role of the IGS. In Sect. 3, we recall the basis of GPS time transfer that will be applied to the different analysis techniques used for TAI: Common-view is presented in Sect. 4. All-in-view in Sect. 5 and Precise point positioning in Sect. 6. Section 7 reviews the question of code biases and their link to the receiver calibration.

2 Clock comparisons in TAI

TAI and UTC are post-processed time scales obtained at the BIPM from a combination of data from some 350 atomic clocks kept by more than 60 laboratories spread worldwide. The data are regularly reported to the BIPM by timing centres which maintain a local realization of UTC. Results are calculated on the basis of data acquired in the previous month and are published in monthly *BIPM Circular T* (http://www.bipm.org/jsp/en/TimeFtp.jsp?TypePub=publication).

The calculation of a time scale on the basis of the readings of clocks located in different laboratories requires the use of methods of comparison of distant clocks. A prime requisite is that the methods of time transfer do not contaminate the frequency stability of the clocks, and this often was a major limitation in the construction of a time scale before the advent of GPS. The use of GPS satellites in time comparisons in the 1980s introduced a major improvement in the construction and dissemination of time scales. The Consultative Committee for Time and Frequency (CCTF) soon set up a working group to establish a common format, standard formulae and parameters to facilitate the data exchange for time dissemination and transfer (CCTF Working Group on GNSS time transfer standards, CGGTTS). GPS (and later GPS/GLONASS) receivers installed in national time laboratories started providing in an automated way time transfer data according to the CGGTTS directives (Allan and Thomas 1994), where GPS transfer data is provided in the form of the time difference between the laboratory reference clock and the GPS time.

2.1 GNSS equipment for time transfer

For nearly two decades, GPS C/A-code observations provided the best tool for clock comparisons in TAI, thus no test of its performance with respect to other methods was possible. In 2000, the situation became quite different with the introduction of the independent TWSTFT technique, and having two techniques resulted in a more robust system. For the links where the two techniques are available, both GPS and TWSTFT links are computed; the best being used in the calculation of TAI, the other being kept as a backup. The GPS links using geodetic-type, dual frequency code receivers (so-called "P3") have further increased the reliability of the system of time links, providing a method of assessing the performance of the TWSTFT technique. Comparisons of results obtained on the same baselines with the different techniques show equivalent performances for GPS geodetic-type dual-frequency receivers and TWSTFT equipment, at long averaging times, with RMS difference at or below 1 ns (Petit and Jiang 2004).

The first generation of receivers used for time comparison was single-channel, single-frequency C/A code receivers, which use only the code that modulates the L1 frequency. The manufacturers later developed multi-channel receivers, operating also at one frequency, but allowing simultaneous observations of all satellites in view. The increasing number of this kind of receiver in laboratories improved the quality of time comparisons. As the propagation of the microwave signal is affected by the ionosphere, which is a dispersive medium, single-frequency receivers suffer from significant errors, much bigger during periods of high solar activity. Dual-frequency reception nearly eliminates the ionospheric delays, thereby improving the accuracy of time transfer. Multi-channel, dual-frequency receivers are increasing in number in laboratories participating in the calculation of TAI. These are geodetic-type receivers that provide the P-code (precise) observations on the two L1 and L2 frequencies.

At the moment, most of the links in TAI are obtained by using GPS equipment (70% with GPS single-frequency receivers; 16% with GPS dual-frequency receivers), and about 14% of the links are provided by TWSTFT observations. Nevertheless, it should be noted that the best techniques (GPS dual frequency and TWSTFT), although used at only 30% of time laboratories, account for between 70 and 75% of the clock weight in TAI.

2.2 IGS products

Since the early 1990s, the IGS has provided precise orbits of the GPS satellites, later expanded to GLONASS satellites, and will incorporate new GNSS systems as they appear. Since 2000, the IGS has also provided high precision clock products, which consist of the precise determination of the satellite clock offsets with respect to a time reference (the offsets of a selection of station clocks are also provided). Since May 2004, the reference used is a very stable ensemble time scale (IGST) computed at the IGS (Senior et al. 2003). In recent years, the instability of the reference time has been significantly reduced, while broadcast GPS Time has a relative frequency instability of about 2×10^{-14} for an averaging time of one day, the latest realization of IGS Time has an instability of 10^{-15} at one-day averaging. Satellite positions are now provided with an uncertainty of order a few cm, and clock products with an uncertainty better than 100 ps (modulo calibration biases), allowing new, highly accurate positioning and timing applications (Kouba and Héroux 2001).

Several IGS analysis centres provide ionosphere products in the form of TEC maps. Since May 2000 the ionosphere products of the Centre for Orbit Determination in Europe (CODE, Bern) are used for the ionospheric corrections of all TAI links obtained with data from single-frequency GPS receivers. Rapid global ionosphere maps are available daily from CODE analysis centre with a latency of one day, a delay that is quite sufficient for the post-real time calculation of TAI at the BIPM.

It is to be noted that, although station clock solutions have been available from the IGS for several years, they are currently not used in the TAI computation for several reasons. First, the IGS aims at an automated and efficient processing of a large number of stations and cannot ensure that a small number of them (the time laboratories) have a complete data set. This is specially the case for the Rapid products that should be used for TAI, because of the latency of the IGS Final products. The BIPM, on the other hand, works in deferred time every month and tries to ensure that data sets are as complete as possible. Also the IGS clock products are referenced to the clock driving the receiver and would need to be transferred to the local realization UTC(k).

2.3 Analysis techniques for GNSS time transfer

The common-view (CV) method proposed by Allan and Weiss (1980) has been mostly used for comparing distant clocks since that time. It consists of the simultaneous reception at two Earth laboratories of the same emitted signal. This method has been developed to remove or attenuate the main errors in the GPS measurements, which are completely or partly common to the two receptions: errors in the satellite position, instabilities of the satellite clocks, errors in the transmission of the signal between the satellite and the receiver, effects of the intentional degradation (known as Selective Availability) that was applied to the GPS signal until May 2000.

In CV, the number of satellites used in a comparison is limited by the need of common-view, resulting in an inhomogeneous sky distribution of satellite that tend to bias the comparison. Also, in order to compare clocks between laboratories at long distances where common-views are not possible, one or two intermediate laboratories are necessary which further degrades the result. Thanks to the IGS, some of the most important error sources of clock comparison with GPS have been substantially reduced, making the CV method less advantageous, and promoting a different strategy, named All-in-view (AV), where each laboratory reference is compared with a realization of the GPS time by averaging all available measurements. Since September 2006, the generation of TAI at the BIPM makes use of the AV method using the GPS time as the reference. As mentioned earlier, some TWSTFT links are also used and the time laboratory at the Physikalisch-Technischen Bundesanstalt (PTB, Braunschweig, Germany) serves as a crossover site between techniques. As a consequence of using AV, clock comparison by GPS can be achieved directly between any two laboratories with improved stability due to the increase in the number of measurements used to compute the link.

The uncertainty of clock comparison is today at or below 1 ns for the best links, sufficient to compare the clocks over integration times of a few days (commercial Cs) to a few weeks (best primary standards). This assertion is strictly valid for frequency comparisons, where only the denominated type-A (statistical) uncertainty affects the process. In the case of time comparisons, the type-B (systematic) uncertainty, coming from the calibration, should be considered in addition. In the present situation, calibration of the hardware electrical delays contributes to an uncertainty that surpasses the statistical component. For non calibrated equipment delays, values typical for similar equipment are taken and the type B uncertainty is set to 20 ns. Repeated equipment calibrations are indispensable for the long-term stability of clock comparisons, and the BIPM makes a great effort to carry this out through calibration campaigns with travelling receivers.

The Russian satellite system of global navigation GLONASS is not yet used for time comparison in TAI on a routine basis since the satellite constellation is in the process of completion and it should become rapidly more stable. Studies conducted at the BIPM and in other laboratories prove that the system is potentially useful for accurate time transfer, when used in common-view mode (Lewandowski et al. 2005).

3 Basics of GNSS time transfer

The observation equations for the carrier phases $L_{k,j}$ at each the two GPS frequencies (f_j, $j = 1, 2$) and the pseudoranges ($P_{k,j}$) measured at a station k, here both expressed in meters, can be written as (Petit and Jiang 2008a):

$$L_{k,j}/c = T_{pk} + \tau_{tk} - \tau_{ik,j} - \tau_s + \tau_{rk} + N_{k,j}\lambda_j/c + \tau_{\phi k,j} + \varepsilon_{\phi k,j} \tag{1}$$

$$P_{k,j}/c = T_{pk} + \tau_{tk} + \tau_{ik,j} - \tau_s + \tau_{rk} + \tau_{Ck,j} + \varepsilon_{Ck,j} \tag{2}$$

where c is the velocity of light, T_{pk} is the coordinate time of propagation of the signal from the satellite to the receiver k in empty space (between the instantaneous positions of the antenna phase centres), and τ_{tk} and τ_{ik} are the propagation delays due to the troposphere and the ionosphere, respectively. τ_s is the satellite clock term, τ_{rk} the receiver clock term, λ_j the carrier wavelength, $N_{k,j}$ the phase ambiguity, τ_{Ck} the instrumental code delay, $\tau_{\phi k}$ is the instrumental phase shift on the carrier, and ε_ϕ and ε_C represent the phase and code errors, respectively.

Time transfer techniques discussed below use either code only (Eq. 2) or code and phase (Eqs. 1 and 2) to determine the receiver clock term τ_{rk}. The IGS is a fundamental tool in this determination as it provides essential information to solve this problem: IGS satellite ephemerides provide the satellite positions used to compute T_{pk} and the satellite clock terms τ_s with respect to a given time reference, IGS Time (Senior et al. 2003), both with uncertainties below 100 ps. In time transfer receivers, measurements at the two frequencies are often available, then the ionosphere-free linear combinations $[L_3 = (f_1^2 L_1 - f_2^2 L_2)/(f_1^2 - f_2^2)$, $P_3 = (f_1^2 P_1 - f_2^2 P_2)/(f_1^2 - f_2^2)]$ are used so that τ_{ik} disappears. However, when only one frequency is available, IGS ionospheric maps allow to compute $\tau_{ik,j}$ with an uncertainty of order 1–2 ns (Schaer 1999). IGS also provides information on some satellite and receiver code delays which are part of the instrumental delay τ_{Ck} (see Sect. 7).

To quantify uncertainties, we recall here the magnitudes for different effects that affect GPS code measurements (2), considering 0.1 ns as a significance threshold, consistent with the precision with which TAI results are reported. When using IGS products and appropriate modelling of motion of the Earth crust (mostly the solid Earth tides), the effects from the geometry (satellite orbits and station real-time position) have negligible effect on time transfer, i.e. the residual error from this source is at most of order 0.1 ns. The same is true for the effect of satellite clock error, which is determined by the IGS in the same global processing that provides the orbits. The transmission delay through the ionosphere may also be determined to a similar level of accuracy with some averaging, using dual-frequency receivers (with the possible exception of a few periods of high ionosphere activity). Remaining effects which are significant at the 0.1 ns level are the code multipath resulting from reflected signals (mostly a short-term effect of magnitude possibly reaching 1 ns or more, also with possible long-term biases) and the tropospheric delay (mostly short-term noise plus biases of a few 0.1 ns slowly varying from day to day with the weather conditions). These two remaining effects are now the dominant effects contributing to the time transfer statistical uncertainty, along with the measurement noise itself. It should be noted that, while the measurement noise should average out to the 0.1 ns level with some averaging, errors from the other two effects (multipath and, to a lower level, troposphere) are not expected to have zero mean and are still significant at the 0.1 ns level at any averaging time.

Using phase measurements (1) allows reducing these two remaining error sources in time transfer. Indeed, the effects of phase multipath are considerably smaller than the code multipath (Misra and Enge 2001) and the phase measurements allow determining an average tropospheric delay from an adjustment to the measurements at different elevations. However, phase measurements only cannot provide time transfer, and so some information from code measurements has to be used and multipath noise still remains (Defraigne and Bruyninx 2007). In addition, variations in the electric hardware delays affect time transfer and will probably be the most important error source at long averaging times (weeks to months). Finally, if care is not taken, diurnal and temperature-dependent effects can be significant at up to the ns level. It is also to be noted that code measurements are sometimes smoothed by phases, which blurs the distinction between code-only and code+phase time transfer.

4 Common-view GNSS time transfer

In GNSS time transfer based on code measurements, Eq. (2) is rewritten as

$$\tau_{rk} = P_{k,j}/c - T_{pk} - \tau_{tk} - \tau_{ik,j} + \tau_s - \tau_{Ck,j} - \varepsilon_{Ck,j} \tag{3}$$

When applied to two stations (indexed by k and l) observing the same satellite at the same time, the two equations of type (3) are differenced to obtain

$$\tau_{rk} - \tau_{rl} = (P_{k,j} - P_{k,j})/c - (T_{pk} - T_{pl}) - (\tau_{tk} - \tau_{tl}) - (\tau_{ik,j} - \tau_{il,j}) \tag{4}$$

where we have suppressed the instrumental delay and error terms for clarity. The advantages of the CV method come from the disappearance of τ_s in Eq. (4), and from the fact that for the tropospheric and ionospheric terms, the uncertainty may be smaller in the difference in (4) than in the corresponding terms in (3), especially for stations not too far apart. In addition, the uncertainty originating from the satellite position in T_p is smaller in the difference in (4) than in the corresponding term in (3).

Since the 1990s, the BIPM has used this method to compute time links, and IGS precise satellite orbits have allowed decreasing the uncertainty originating from the satellite position to a level well below other sources of uncertainty. Maps of the ionospheric electron content from the IGS have allowed obtaining high-quality time transfer using existing single-frequency receivers. In such conditions, the dominant source of uncertainty in CV is the measurement noise, mostly the part originating in multipath, and the uncertainty in modelling the tropospheric term.

5 All-in-view GNSS time transfer

The CV technique requires simultaneous observing of the same satellites from two Earth points, so that the number of observable satellites diminishes with the length of the link, especially the high-elevation satellites for which the signal has high signal to noise ratio and for which the propagation delay (troposphere, ionosphere) is better known. Thus, despite its advantages, CV has many drawbacks so that it has been considered to use another approach in which all available code measurements at the laboratory k, at time t, are used to obtain an estimate of $[\mathrm{UTC}(k) - \mathrm{REFT}](t)$ where REFT hereafter designates the reference time to which the satellite clocks are referred. In effect

$$[\mathrm{UTC}(k) - \mathrm{REFT}](t) = \langle \tau_{rk}(t) \rangle \tag{5}$$

where $\tau_{rk}(t)$ is given by Eq. (3) and where $\langle\ \rangle$ designates a weighted average of all available measurements.

In this All-in-view approach (Petit and Jiang 2008a), the time transfer between two laboratories can then be obtained by a simple difference of the quantities $[\mathrm{UTC}(k) - \mathrm{REFT}]$. Since 2006, the BIPM processes all GPS data used in TAI computation with the AV method instead of CV

The AV method relies on the quality of the IGS-computed satellite clocks and, to a lesser extent and in the presence of data gaps, on the quality of the IGS reference time scale. Unlike CV, AV does not cancel or greatly reduce the errors in satellite orbits, clocks and IGST, so that these errors have to be considered. However, as indicated in Sect. 3, the uncertainty in IGS satellite position and clock products is such as to yield an uncertainty of order 100 ps in AV time transfer, well below other uncertainty sources such as code multipath or errors in modelling the tropospheric delay. Thus dominant error sources are those originating from the receiver itself or its immediate vicinity and they affect both CV and AV approaches, but they can be reduced more significantly by averaging in AV, because more data can be used. Several authors in the time community evaluated the AV method see, e.g. Weiss et al. (2005), with all studies concluding on the advantages of AV. So the Working Group on TAI of the CCTF advised to introduce this new technique in TAI generation (Matsakis et al. 2006).

In applying the AV technique to TAI links we compute, for a station k and a series of instants t_i, the values $[\mathrm{UTC}(k) - \mathrm{REFT}](t_i)$ by averaging all measurements obtained at that time, each properly weighted according to the elevation of the satellite. In order to estimate the link values $[\mathrm{UTC}(k) - \mathrm{UTC}(l)](t)$ needed for TAI, we compute the series $[\mathrm{UTC}(k) - \mathrm{UTC}(l)](t_i)$ for all instants t_i by simple differences, then estimate $[\mathrm{UTC}(k) - \mathrm{UTC}(l)](t)$ by smoothing. All links are computed with respect to a single laboratory (PTB) that is chosen to provide a crossover site with the laboratories linked by TWSTFT, an approach termed the “physical pivot” approach. Note that it would be possible to directly compute $[\mathrm{UTC}(k) - \mathrm{REFT}](t)$ and introduce these values in the TAI computation. This “virtual pivot” approach has some specific advantages but is not considered in this study.

6 Precise point positioning

GPS carrier phase measurements are two orders of magnitude more precise than the GPS code data, much less sensitive to propagation multipath and allow a better estimate of the atmosphere effects. Receivers able to measure phase and code are becoming common place in time laboratories. For this reason, the CCTF, at its 17th meeting in September 2006 (CCTF, 2006) passed a recommendation “Concerning the use of Global Navigation Satellite System (GNSS) carrier phase techniques for time and frequency transfer in International Atomic Time (TAI)”, in which it asked that “the International Bureau of Weights and Measures (BIPM), in a highly cooperative manner, generate its own solutions, make them freely available to others, and add them to its time transfer comparison database,” and that “the BIPM begin preparing software and techniques for introduction of the data into the computation of Circular T,” (excerpts from Recommendation CCTF 4, 2006).

In Precise Point Positioning (PPP), dual frequency phase (1) and code (2) measurements are used without differencing between stations or satellites and it is necessary to use precise satellite position from the IGS and precise satellite clock value with respect to IGS Time as values fixed in the processing. In this case, T_p is a function of the receiver's position X_r only, and τ_s disappears from Eqs. (1) and (2), where $\tau_r(t)$ is now referenced to IGS Time. The ionosphere-free linear combinations (see Sect. 3) are used so that the ionospheric delay τ_i disappears from the equations. The tropospheric delay τ_t, which depends on time t and on the direction, is expressed as $\tau_z(t) M_f$, where τ_z is the delay at zenith and M_f is a given mapping function. Note that the actual tropospheric model distinguishes a hydrostatic and a wet component, but this distinction is not necessary in this short presentation. After the ionosphere-free linear combination, the phase ambiguities together with the unknown carrier phase shift are considered as a real-valued phase ambiguity for each satellite pass, here noted X_3. Equations (1) and (2) are then rewritten as

$$L_3/c = T_p(X_r) + \tau_z(t)M_f + \tau_r(t) + X_3 + \varepsilon_{\phi,3} \quad (6)$$

$$P_3/c = T_p(X_r) + \tau_z(t)M_f + \tau_r(t) + \varepsilon_{\mathrm{C},3} \quad (7)$$

which show explicitly the parameters which have to be determined by PPP: the receiver position X_r, the receiver clock $\tau_r(t)$, the zenith tropospheric delay $\tau_z(t)$, and the real-valued ambiguities. These parameters are obtained in an adjustment where a priori uncertainties are assigned to the observations, of order, a few ns for the codes (7) and, of order, tens of ps for the phase observations (6). The error terms $\varepsilon_{\mathrm{C},3}$ and $\varepsilon_{\phi,3}$ now include, in addition to measurement noise, residual errors from the IGS orbits and clocks, which are fixed and not adjusted, as well as errors from higher order ionospheric terms not removed by the linear combination.

PPP allows one to compute [UTC(k) − IGS Time] for any laboratory participating in TAI which is equipped with such a geodetic-type receiver. Then any link [UTC(k) − UTC(l)] can be computed by simple difference. This approach makes sense for computing TAI time links because it can be applied for any individual laboratory, properly equipped, without the need to participate in an organized network. Although participation in the IGS has other practical advantages such as improved experience return and reliability, it is unlikely that all laboratories in the TAI network will participate in the IGS so that the PPP approach is well adapted. The alternate network-type computation approach would not be well suited to the TAI network alone, because of its poor geometry. In addition, PPP is easy to put into operation using one of several existing software packages. It is, therefore, the natural follower of the All-in-view technique and has attracted in recent years a growing interest from the time community (Orgiazzi et al. 2005, Defraigne and Bruyninx 2007). PPP combines the precise GPS phase and the accurate code measurements and thus can provide excellent short-term stability from the phase and good accuracy.

For all these reasons, the BIPM plans, in the near future, to implement time transfer based on Precise Point Positioning computations for TAI links. A pilot experiment has been initiated and results of test computations and comparisons can be found at ftp://tai.bipm.org/TimeLink/LkC.

7 Code biases and calibration

The term τ_{Ck}, instrumental code delay, given in Eq. (2) for one particular satellite varies with the code concerned (e.g. for GPS C/A, P1, P2, now C2) and is composed of a part depending on the satellite hardware and a part depending on the receiver hardware. The instrumental delay actually depends on additional factors, such as the receiver filter bandwidth and transfer function and the correlator spacing (Hegarty et al. 2006). Assuming that these settings do not change and each delay component is stable over a sufficiently long time, it is possible (in principle) to determine each component from a global adjustment of all available Eqs. (1) and (2), except for one rank deficiency per station and per satellite. In practice however, the IGS does not consider individual code biases but differential code biases (DCB) between pairs of codes. The most important one is the bias between P1 and P2 which is necessary to generate accurate ionospheric map products and is determined in this process. Other differential code biases, between C/A and P codes, must also been taken into account when different types of observations are used but these biases are not further considered here (see, e.g. https://goby.nrl.navy.mil/IGStime/index.php#P1-C1). Therefore, in the rest of the section, DCB means the P1 − P2 differential code bias. Unlike code biases, differential code biases can be determined with only one global rank deficiency which is conventionally removed in the IGS determination by constraining the sum of all satellite DCBs to be zero.

Thus, in the IGS approach, instrumental code delays for each frequency at the receiver are not explicitly considered so that the clock solutions referred to IGS time obtained from ionosphere-free P3 combination implicitly contain the contribution for these code delays. As will be seen later, this allows monitoring the stability of these code delays, provided that the link can be established with some calibrated equipment.

When GNSS equipment is used to compute a time link, instrumental delays directly affect the accuracy of this link; therefore, equipment participating in the TAI network needs to be calibrated. This is usually performed with differential calibration, where one receiver travels to all sites to obtain the instrumental delays of the local equipment with respect to those of the travelling equipment. Assuming that the delays of the travelling equipment are stable, this procedure ensures accurate links. It is also possible to measure the absolute value of the instrumental delays and this exercise has been carried out for a limited number of equipments (Petit et al. 2001, Plumb et al. 2005). Accurate values can then be obtained for the instrumental delays of all equipments either by direct absolute calibration of the equipment or by differential calibration with absolutely calibrated travelling equipment. Such campaigns are regularly carried out by the BIPM (Petit et al. 2006), but these campaigns take time and calibrations are relatively rare and far apart for the same equipment.

Between such absolute determinations, it is useful to keep track of the stability of the equipment delays. With this purpose the BIPM regularly computes all its time links using all available techniques, compares the results of the different techniques and makes the results available on its web site (ftp://tai.bipm.org/TimeLink/LkC). As such comparisons concern only links between two stations, the behaviour of individual equipment has to be inferred by analysing multiple

Table 1 Some characteristics and equipment of laboratories participating to both IGS and TAI

IGS site	Time lab	Freq. std.	Location	Receiver	BIPM calibration	BIPM computation	Other techniques
BOR1	AOS	Cesium	Borowiec, Poland	Trimble	To be done	To be done	
BRUS	ORB	H-Maser	Brussels, Belgium	Z12T	Yes	Yes	
IENG	IT	Cesium	Torino, Italy	Z12T	Yes	Yes	TWSTFT
MIZU	NAO	Cesium	Misuzawa, Japan	PolaRx2	To be done	To be done	
NISU	NIST	H-Maser	Boulder, CO USA	Novatel	To be done	Yes	TWSTFT
NPLD	NPL	H-Maser	Teddington, UK	Z12T	Yes	Yes	TWSTFT
OPMT	OP	H-Maser	Paris, France	Z12T	Yes	Yes	TWSTFT
PTBB	PTB	H-Maser	Braunschweig, Germany	Z12T	Yes	Yes	TWSTFT (2 bands)
SPT0	SP	Cesium	Boras, Sweden	Javad	To be done	To be done	TWSTFT
TWTF	TL	Cesium	Taoyuan, Taiwan	Z12T	Yes	Yes	TWSTFT
USN3	USNO	H-Maser	Washington, DC USA	Z12T	Yes	Yes	TWSTFT (2 bands)
WAB2	CH	H-Maser	Bern, Switzerland	Z12T	Yes	Yes	TWSTFT
WTZA	IFAG	H-Maser	Wettzell, Germany	Z12T	Yes	Yes	

Expanded from a Table courtesy of K. Senior, US Naval Research Laboratory. List of laboratories regularly present in IGS clock solutions (Col.1) and TAI computations (Col.2), indicating the type of reference clock (Col.3), the location (Col.4), the type of receiver (Col.5), their situation with respect to: dual-frequency calibration by the BIPM (Col.6) and with regular TAI computation as a dual-frequency receiver (Col.7), and the presence of another time transfer technique (Col.8)

links. It is also limited to stations that maintain at least another independent time transfer technique of similar quality, in general two-way time transfer.

Because a number of laboratories participate in both the IGS and TAI network, it is also possible to use the IGS clock solutions for these common equipments, which are linked through the BIPM TAI computation, to estimate the stability of all equipments concerned for any averaging time larger than the time interval of the IGS analysis (typically 5 min). As the link between the IGS and TAI solutions is provided by the realization of GPS time in each solution, it is also possible to estimate the difference between both (Senior et al. 2004). This approach complements the BIPM stability analysis described above. As of end 2007, some 12 laboratories are regularly available in both IGS clock solutions and in TAI link computations: see more information in Table 1. However many more time-laboratories are equipped with similar equipment and such analysis could possibly be expanded to all of them.

As new modulations are added to the GPS signals and new systems added, it is expected that the determination of inter-signal biases will become a major task of the IGS. In addition, it is expected that the absolute calibration of delays will be developed to become regular contributions to time transfer accuracy.

8 Outlook and conclusions

The collaboration between IGS and the BIPM has extended over nearly two decades since the creation of the IGS. The products of the IGS have been critical in the improvements in GPS time transfer, used for TAI links, over these years. From the early days of common-view with a few satellites to PPP now, the statistical uncertainty of long distance time transfer has decreased by more than one order of magnitude, from 5 to 10 ns to less than 0.5 ns on a few hours averaging time. In to future, new satellite systems, starting with GLONASS and GALILEO, will become available and may provide significant improvement to time transfer if new code structures provide better multipath characteristics. GLONASS satellite ephemerides are already part of the routine IGS products, but it will be a major challenge to the IGS to produce a complete and consistent set of products for all systems, particularly for what concerns satellite clocks and differential code bias values. We are confident that the IGS will fulfil these expectations.

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