TIME TRANSFER WITHIN THE IGS AND LINKS TO TAI

P. Defraigne[(1)], K. Senior[(2)], J. Ray[(3)], G. Petit[(4)]

[(1)] *Royal Observatory of Belgium, Avenue Circulaire, 3 – B-1180 Brussel- Belgium – e-mail: p.defraigne@oma.be*
[(2)] *US Naval Observatory, 3450 Mass. Ave. NW, Washington, DC, USA – e-mail: senior.ken@usno.navy.mil*
[(3)] *As (2) -- e-mail: jimr@maia.usno.navy.mil*
[(4)] *BIPM, Pavillon de Breteuil, 92312 Sèvres Cedex – France- e-mail: gpetit@bipm.org*

ABSTRACT

The computation of the International Atomic Time (TAI) scale is based primarily on classical GPS common view time transfers between remote clocks using dedicated timing receivers. We show that this technique can be improved significantly using geodetic receivers and methods. The potential is being demonstrated by the International GPS Service (IGS), which maintains a global network of permanent GPS stations equipped with geodetic receivers using atomic clocks. The IGS routinely computes clock solutions, providing station and satellite clock behavior with respect to a reference IGS time scale. We investigate methods to improve the link between the IGS time scale and TAI.

INTRODUCTION

The International Atomic Time (TAI) scale is computed by the Bureau International des Poids et Mesures (BIPM) from a set of atomic clocks distributed in about 50 time laboratories around the world. The weighted mean is combined with a set of primary frequency standards[1] operating by a few laboratories in order to ensure that the TAI second is as close as possible to the official SI second. The legal time scale, Coordinated Universal Time (UTC), is then obtained by adding the number of accumulated leap seconds to TAI. As UTC is determined with a delay of several weeks, each time laboratory 'k' maintains a local realization of UTC, UTC(k). To compare remote clocks for the computation of TAI, the BIPM uses the common view method [1]. The principle is to connect each clock to a GPS receiver and to observe simultaneously the same satellite ('common view'). Knowing the station and satellite positions, one can deduce the synchronization error between each station clock and the satellite clock. Simultaneous observation of the same satellite by two remote labs allows, by simple subtraction of the independent results, a determination of the clock difference between those two labs (see Figure 1). For TAI, the common view data are based on GPS single-frequency C/A-code observations collected by dedicated timing receivers, which, until recently, observed only one satellite at a time. These receivers are connected to a 1 pps (pulse per second) signal delivered by UTC(k), which permits an internal comparison to be made of the clock offset between UTC(k) and GPS time as broadcast by each satellite. In order to ensure simultaneous tracking of common satellites, the BIPM distributes international tracking schedules consisting of conventional 13-minute observations of specified satellites. The procedure uses broadcast satellite orbit and clock parameters, as well as the broadcast Klobuchar model for ionospheric corrections (needed because of the single-frequency data). In the computation of TAI, the BIPM improves the raw observational results by using precise orbits and ionospheric total electron maps distributed by the IGS. When comparing clocks located several thousands km apart, the precision of the common view technique is a few nanoseconds for integrations of several days. In a parallel development, the IGS produces similar satellite and station clock comparisons using dual-frequency geodetic receivers and techniques, which rely heavily on the very precise GPS carrier phase data. The IGS clocks are referenced to a new time scale, IGST, formed using a weighted ensemble algorithm from the available atomic frequency standards in the IGS network and in the GPS satellites. In this paper, we discuss this new time scale and present a method to improve its link to TAI.

FREQUENCY TRANSFER USING GPS CARRIER PHASES

As the noise level of the GPS phase observable is about 100 times smaller than that of code observables, this quantity has long been used for geodetic applications requiring very high precision. In recent years, carrier phase methods have

[1] Primary frequency standards are operated by only a few laboratories and provide practical realizations of the SI second.

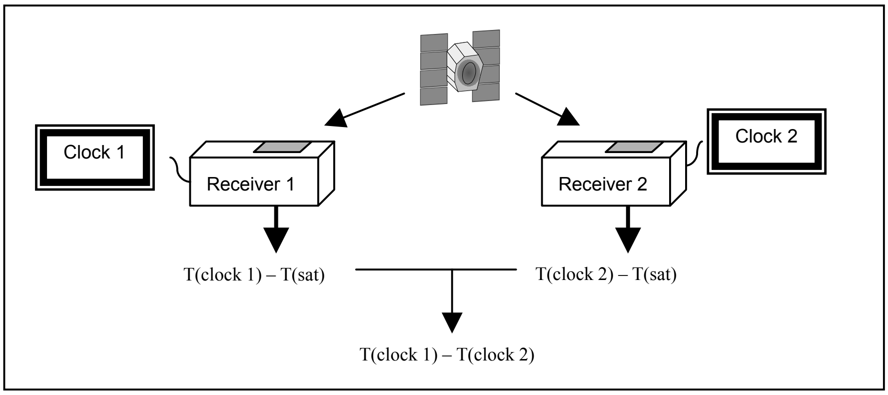

Fig. 1. Principle of common view.

also been introduced in time transfer studies [2-6]. They provide a very powerful tool for frequency comparisons between remote clocks, but, since the carrier frequency cycles are not time-tagged, the phase data cannot provide any information about the absolute offset between clocks. Thus, the carrier phase measurements by themselves can only be used for frequency transfer; i.e., to determine the evolution of the differences between remote clocks. The absolute value of the clock offset must be determined using the code information, with an accuracy limited by the code noise (some nanoseconds instantaneously, or less if averaged over a finite interval).

Comparing very stable frequency standards (or clocks) over a short time interval, the code information does not give sufficiently precise results, so that the observed stability is limited by the comparison technique rather than by the standards. Recent studies have shown that using carrier phase data allows global frequency comparisons with a stability approaching one part in 10^{15} for a period of 1 day. The improvement obtained using carrier phase, rather than code, data is illustrated in Figure 2 where we have performed the frequency transfer between two hydrogen masers located in Brussels and Westerbork (about 290 km apart). The observed frequency stability obtained from carrier phase analysis agrees exactly with the known frequency stability of the two masers. This shows how carrier phase data can be used as a very powerful tool for frequency transfers between stable atomic standards, thanks to its low noise level.

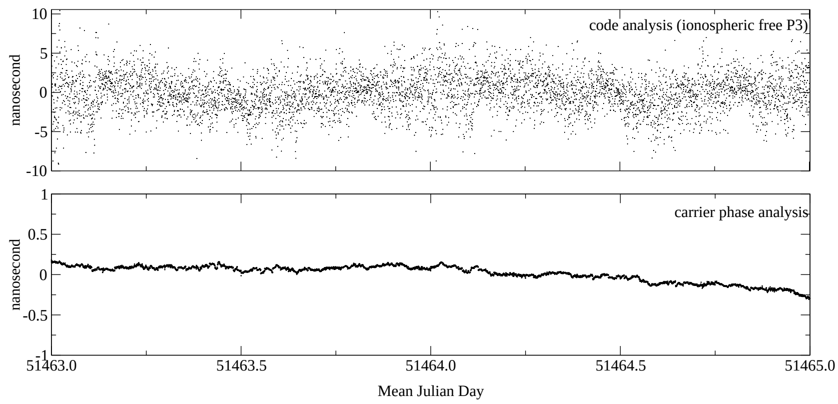

Figure 2. Frequency transfer between the two hydrogen masers located in Brussels and Westerbork, computed from separate code (top) and carrier phase (bottom) analyses.

IGS TIME SCALE

The main goals of the "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements" [7], initiated by the time community (through the BIPM) and the geodetic community (through the IGS) are, first, to improve the comparison of remote frequency standards with respect to the classical common view based on the C/A code. This is possible using the carrier phase observations, as shown above. A second objective is to use GPS in order to make accurate time and frequency comparisons available in near real time. This objective addresses the fact that TAI, while having very good long-term stability, is available only after several weeks.

The IGS uses its observed clock differences, for both satellites and stable receiver clocks, to form an internal reference time scale [8-9], the IGS time scale (IGST). A first realization, called IGRT (R denotes rapid), is available within a day, while the final series, IGST, follows about two weeks later. These time scales are steered to GPS time, which, in turn, is steered to a prediction of UTC, thus ensuring the long-term stability. The short-term stability relies on the use of carrier phase data and the stability of the available atomic standards, especially hydrogen masers used at about 40 IGS stations. The IGS publishes the offsets between each receiver and satellite clock and IGST (see the website at http://clockdev.usno.navy.mil/igst). Using information on UTC minus GPS time differences given by the BIPM's Circular T and IGST minus GPS time obtained from the steering algorithm, the link between IGST and UTC can be established to the few-ns level. The steering strategy used by the IGS maintains this link within ±60 nanoseconds (Figure 3).

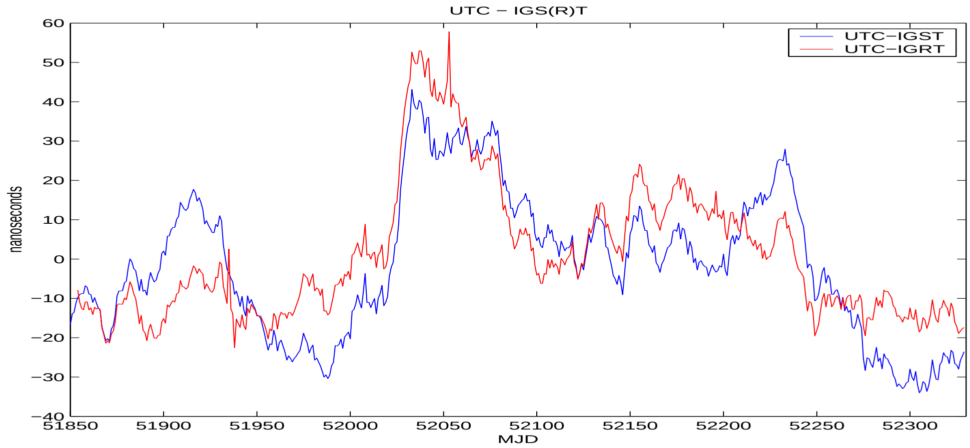

Figure 3. Plot of the IGS Final (IGST) and Rapid (IGRT) time scales referenced to UTC via GPS time. The alignment to UTC of each IGS time scale assumes that GPS time via the BIPM Circular T is equivalent to the IGS alignment to GPS time. This assumption can lead to errors at the 10-ns level or greater.

GEODETIC RECEIVERS WITHIN TAI

The link between the UTC and IGST can be improved using so-called collocated laboratories, which operate clocks that contribute to both the TAI and IGS time scales. If the same clock is involved with both scales, we have access to its offset with respect to each. Assuming collocations at several independent laboratories, we can determine the link between IGST and UTC with very high precision and redundancy. We develop here a strategy to exploit this idea. The main advantage of using a receiver that contributes to both TAI and IGST is that the receiver hardware delays are the same for both contributions.

Geodetic GPS receivers provide dual-frequency P-code and carrier phase data, with a noise level significantly smaller than that of the single-frequency C/A-code data tracked by timing receivers. However, most geodetic receivers do not allow a direct epoch offset comparison between their internal clock signal and the external clock used to steer the receiver synthesizer. These receivers resynchronize their internal clocks to GPS time after each tracking interruption, within a large uncertainty. Such resets induce a clock discontinuity at each tracking interruption. Some geodetic receivers, like the Ashtech Z-XII3T, are specially modified for time transfer applications. This receiver does not phase lock to the external oscillator, but instead uses that oscillator directly. A 1 pps input signal is supplied to define the 1-second points of the input frequency, so that the receiver internal clock is directly a mirror of the external clock which can be chosen as UTC(k). In this way, there are no clock discontinuities associated with tracking interruptions, as with classical geodetic receivers. Furthermore, the internal instrumental delays can be measured to the few-ns level. We have developed a software tool to reproduce the procedure applied inside time receivers, but using the RINEX observation files gathered by geodetic receivers (e.g., Ashtech Z-XII3T). This allows the use of geodetic receivers as contributors to TAI [10]. The method has been validated by collocation of time and geodetic receivers [11]. In addition, we proposed to modify the conventional common-view procedure for geodetic receivers in order to take advantage of the dual-frequency P-code data to compute observed ionospheric corrections rather than using model estimates. With this modification, the results for trans-Atlantic clock comparisons are improved by a factor of 2 [12], as shown in Figure 4.

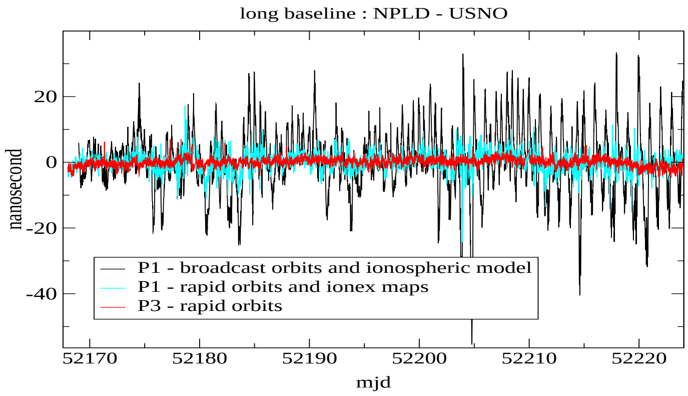

Fig. 4. Time transfer between NPL and USNO (long baseline) using different procedures

CONCLUDING REMARKS

These performances concerning time comparisons can only be reached if all the delays due to propagation of the signal inside the GPS antenna, cables, and receiver are precisely determined and are constant. This stresses the necessity of calibration [13] and of temperature stability of the receiver hardware [14]. Our results indicate that an absolute accuracy of 1 nanosecond can be reached in time comparisons, while the frequency comparisons obtained from carrier phase analyses reach a stability of about $2x10^{-15}$ averaged over one day.

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