Metrologia **40** (2003) 184–188 PII: S0026-1394(03)64150-2

# Time transfer to TAI using geodetic receivers

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Received 29 November 2002
Published 25 June 2003
Online at stacks.iop.org/Met/40/184

**Abstract**
The classical time transfer method used to realize International Atomic Time (TAI) is based on the common view technique, with GPS observations collected by C/A code receivers. The resulting clock offsets between the laboratory clock and GPS time are obtained from a fixed procedure defined by the Consultative Committee for Time and Frequency (CCTF). A similar procedure can be applied to the Receiver INdependent EXchange (RINEX) observation files produced by geodetic receivers driven by a stable external frequency. If the link between the receiver clock and the external clock is stable and precisely determined, the geodetic receivers can then be used for time transfer to TAI. In that case, we propose some modifications to the CCTF procedure to adapt it for the links between geodetic receivers, in order to take advantage of the P codes available on L1 and L2. This new procedure forms the ionosphere-free combination of the P1 and P2 codes as given by the 30 s RINEX observation files, the standard of the International GPS Service. The procedure is tested using the Ashtech Z-XII3T geodetic receivers and the results are compared with those obtained with the classical CCTF procedure based on the C/A code by computing the fractional frequency stability (Allan deviation) of the time links. Over short baselines, the two techniques are equivalent, while the new technique provides a factor 2 improvement for a transatlantic time link. For time links between a time receiver and a geodetic receiver, the differential satellite delays (P1-C/A or P2-C/A) must additionally be introduced. We show here that these biases do not, however, alter the long-term (>3 days) stability of the time transfer results. The corrections associated with tidal station displacement are also investigated, and the results indicate that they do not significantly improve the results at the present level of precision.

## 1. Introduction

In order to compare remote clocks for the computation of International Atomic Time (TAI), the Bureau International des Poids et Mesures (BIPM) uses the common view method [1] based on GPS C/A code observations from time receivers installed in the time laboratories. These time receivers are connected to the 1 pps (pulse per second) signal delivered by UTC($k$), the local realization of UTC at time lab '$k$'. Internal software computes, following a given procedure [2] as recommended by the CCTF, the clock offsets between UTC($k$) and GPS time as realized by each satellite for conventional 13 min tracks appearing in the International BIPM tracking schedules. This procedure was later extended to multi-channel receivers [3]. The clock offsets are collected in a fixed format, called Common GPS GLONASS Time Transfer Standard (CGGTTS). The CCTF procedure is based on broadcast satellite orbit and clock parameters and uses the broadcast Klobuchar model for ionospheric corrections. For the computation of TAI, the BIPM then improves the CGGTTS results using the International GPS Service (IGS) precise orbits, and replacing the ionospheric corrections computed by the time receiver from the broadcast Klobuchar model with the value computed from IGS Ionex maps [4].

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We recently developed software providing CGGTTS files from the Receiver INdependent EXchange files (RINEX, the standard used by the IGS) of geodetic receivers [5]. This software applies the CCTF procedure to the code pseudo-ranges collected in the RINEX observation files. The method was validated by collocation of time and geodetic receivers [6]. Geodetic GPS receivers have the advantage of additionally providing the P code observations on L1 and L2, and with a noise level smaller than the noise on the C/A code. However, most of these receivers do not allow a direct link between their internal clock signal and the external clock used to steer the receiver frequency. In fact, these receivers resynchronize their internal clock on GPS time after each tracking interruption, with an uncertainty of 1 ms, which induces a clock discontinuity at each tracking interruption. To overcome this drawback, some geodetic receivers, like the Ashtech Z-XII3T, have been especially designed to be suitable also for time transfer. This involves two modifications: first the receiver does not phase-lock to the external oscillator, but instead uses that oscillator directly; second, the 1 pps input signal is used to define one particular cycle of the external 20 MHz frequency to form an internal reference for the receiver. In this way, there are no clock discontinuities associated with tracking interruptions, as is the case with classical geodetic receivers. The receiver internal clock is therefore directly, with a constant offset, a mirror of the external clock which can be chosen as UTC($k$). This is, of course, only valid if the phase lag between the input 1 pps and the input 20 MHz frequency remains constant. Introducing CGGTTS files from RINEX observations files gathered by geodetic receivers such as the Ashtech Z-XII3T into the realization of TAI fits one of the main goals of the IGS–BIPM pilot project [7], which is to establish a link between the IGS clock combination [8] or the new IGS timescale [9], and TAI.

The original CCTF procedure is based on the pseudo-ranges collected on the C/A code observations and at a 1 s sampling rate. In section 2 we describe how to adapt this procedure for the links between geodetic receivers as was proposed to the CGGTTS Working Group [10], in order to take advantage of the P codes available on L1 and L2. In section 3, we investigate the correction for satellite differential biases that must be applied to perform time links between a geodetic and a time receiver. The tidal station displacement effects on long baseline time links are studied in section 4, and section 5 presents a summary and conclusions.

## 2. Modifications to the CCTF procedure

The procedure used to compute the CGGTTS results [2] can be summarized as follows. For each individual GPS satellite track, the time receiver uses raw 1 s C/A code pseudo-range data collected over 13 min (leading to 780 data points). These pseudo-range data are measurements of the clock offset between the receiver and the satellite, resulting from an integration of the received signal over a time interval shorter than 1 s. Simultaneously during the track, an internal counter determines the clock offset between the receiver 1 pps and the laboratory reference UTC($k$) 1 pps signal input to the receiver. The difference between the two quantities so obtained gives access to the clock offset between UTC($k$) and the satellite clock. The 780 pseudo-range data points are then separated into 52 blocks of 15 data points. In each of the blocks, the 1 s data are smoothed using a quadratic polynomial. The following procedure is applied to the 52 points corresponding to the values of the quadratic fits at the midpoints of the blocks. These 52 points are then corrected for: geometric delay (computed with antenna coordinates and broadcast ephemerides), ionospheric delay (computed with broadcast Klobuchar model), tropospheric delay (computed with Hopfield's model with standard atmosphere values), Sagnac effect, periodic relativistic effect associated with the satellite orbit, L1–L2 group delay (from broadcast parameter TGD), receiver delay, antenna and local clock cable delays.

The final CCTF results for this satellite track are obtained after performing two linear fits. The first one is applied on the 52 corrected data points, and the value of this fit at the midpoint of the track is given as 'UTC($k$)-Tsat' (column REFSV in the CGGTTS files). A second linear fit is applied to the 52 points additionally corrected for the satellite clock offset using the broadcast polynomial parameters. The final result of the track for 'UTC($k$) − GPS time' (column REFGPS in the CGGTTS files) is the value of this second linear fit at the midpoint of the track.

In the classical CCTF procedure described earlier, the values of 'UTC($k$) − GPS time' given in the CGGTTS files are computed from the raw GPS C/A code data taken at a 1 s sampling rate. However, within the IGS, the standard sampling interval is 30 s. We therefore proposed the following modifications in order to use directly the 30 s RINEX files [6]. First, we chose to apply directly a linear fit to the 26 points corresponding to the 13 min track (after having corrected for the effects mentioned above and given in the CCTF conventions). The difference between the pseudo-CCTF results so obtained and those obtained from the 1 s RINEX files following strictly the CCTF conventions is smaller than 0.1 ns [6], well below the standard uncertainty of one common view measurement with the CGGTTS convention, which is about 4 ns [11]. Note that because the BIPM tracking schedules are dated in UTC and the RINEX files are dated in GPS time, we have to take this difference into account to choose the 26 data points which are inside the 13 min tracks.

The second modification consists of using the ionosphere-free combination P3 instead of the C/A code as used by classical time receivers. The ionospheric delay is usually modelled as proportional to TEC/$f^2$ where TEC is the Total Electron Content over the path of the signal and $f$ is the transmitted frequency. Therefore, it can be cancelled by forming, from the observations P1 and P2 at frequencies $f_1$ and $f_2$, the linear combination P3: $\mathrm{P3} = (f_1^2 * \mathrm{P1} - f_2^2 * \mathrm{P2})/(f_1^2 - f_2^2)$. This requires the knowledge of the receiver hardware delays on both P1 and P2, presently determined by a calibration campaign for Ashtech Z-XII3T receivers [12]. When using the P3 combinations, there are mainly two differences in the computation procedure with respect to what is performed with the C/A code. First, the ionospheric correction is already accounted for in P3, and the broadcast polynomial parameters must not be used. Second, the L1–L2 group delay correction must not be introduced. All the other corrections must be applied when using C/A codes.

## 3. Results on time links

In order to test this new procedure, two time links have been investigated, one on a short baseline (about 500 km) and the other on a transatlantic baseline. The stations used are NPLD (Teddington, UK), BRUS (Brussels, Belgium) and USNO (Washington, DC, USA). The receivers used in these stations, as well as the external frequencies used to drive the receivers, are given in table 1. They are all equipped with an Ashtech Z-XII3T receiver. Concerning the data of NPLD, we corrected for a frequency step of 1 ns day$^{-1}$ performed by NPL to steer their H-maser to UTC on mjd 52397.89.

Figure 1 shows the time links obtained (after removing a linear drift of 1.5 ns day$^{-1}$) for the short baseline (NPLD–BRUS) using either the classical CCTF procedure, used by the BIPM for the realization of TAI, i.e. based on the 1 s C/A code observations, IGS orbits and the IGS ionex maps, or with the modified procedure explained earlier, using the ionosphere-free combination P3 based on the 30 s observations of the P1 and P2 codes. To allow the comparison, the satellite positions are deduced from IGS rapid orbits in both cases. Each point of the figure corresponds to the average of the results for all the satellites in common view at the epoch given by the horizontal axis. The corresponding Allan deviations are given in figure 2. It appears clearly that the use of the ionosphere-free combination P3 gives results equivalent to (or even slightly worse than) those given by the use of C/A code with the IGS ionex maps. This is expected for short baselines because the advantage of measuring the ionospheric delay may not compensate for the noise level, which is about three times larger on the observable P3 than on the observable C/A, due to the combination of the two codes P1 and P2. Indeed, the ionosphere-free combination eliminates both the short and long wavelength behaviour of the ionosphere as well as short- and long-term variations, while the ionex maps only allow correction for the long wavelength and long-term variations (above 2 h). Close stations observe a similar ionosphere, with the same variations, so that the ionospheric delays mostly cancel out in the time transfer. Therefore, we expect an improvement by using the measured ionospheric delay only when the ionosphere at the two stations is markedly different, e.g. for long baselines or when the horizontal TEC gradients can be important such as in tropical regions.

The corresponding quantities for the transatlantic time link (NPLD–USNO) are presented in figure 3 (after removing a linear drift of −0.5 ns day$^{-1}$) and the Allan deviation is shown in figure 4. In that case, the improvement associated with the use of the ionosphere-free combination P3 is clear. The Allan deviations up to 10 days obtained using P3 are a factor 2 better than using the classical method used by BIPM for TAI (with ionex maps). Note that the RINEX observation files of USNO do not give the C/A code observations at the time period analysed, so that we only tested with the P1 code for the classical CCTF procedure. The only difference between the use of C/A or P1 code is the noise level, which is about 0.6 times

**Table 1.** Description of the IGS stations used.

| Station | Receiver | External frequency |
|---|---|---|
| NPLD | Ashtech Z-XII3T | Sigma Tau H-maser = UTC(NPL) |
| BRUS | Ashtech Z-XII3T | Kvarz H-maser = UTC(ORB) |
| USNO | Ashtech Z-XII3T | Sigma Tau H-maser<br>MC3 steered to UTC(USNO) |

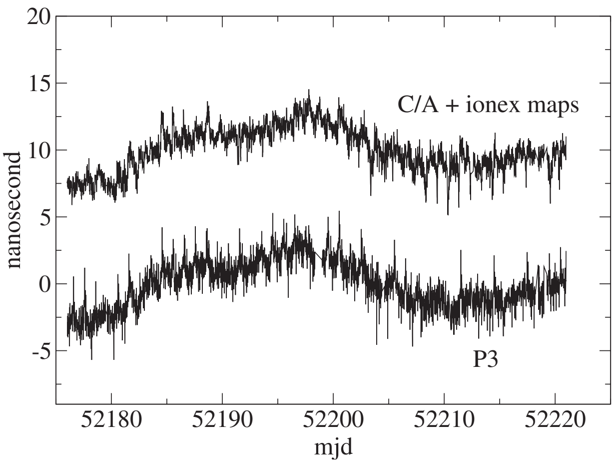


**Figure 1.** Time transfer between NPL and BRUS (short baseline) using different procedures. An arbitrary offset has been introduced between the two curves.

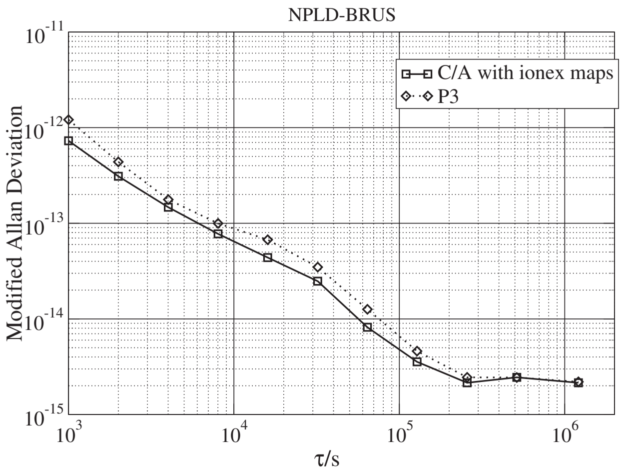


**Figure 2.** Frequency stability corresponding to figure 1.

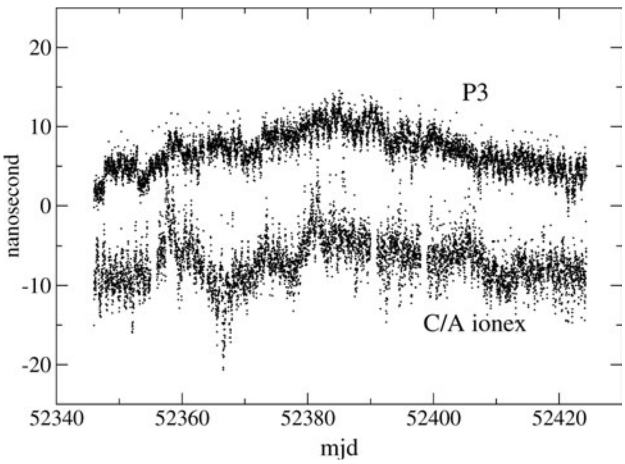


**Figure 3.** Time transfer between NPL and USNO (long baseline) using different procedures. An arbitrary offset has been introduced between the two curves.

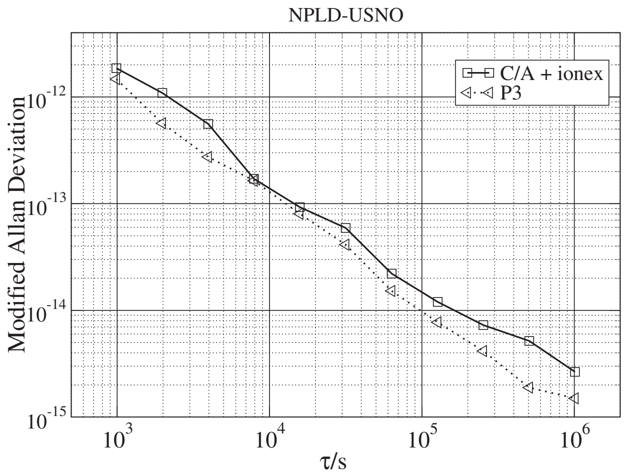


**Figure 4.** Frequency stability corresponding to figure 3.

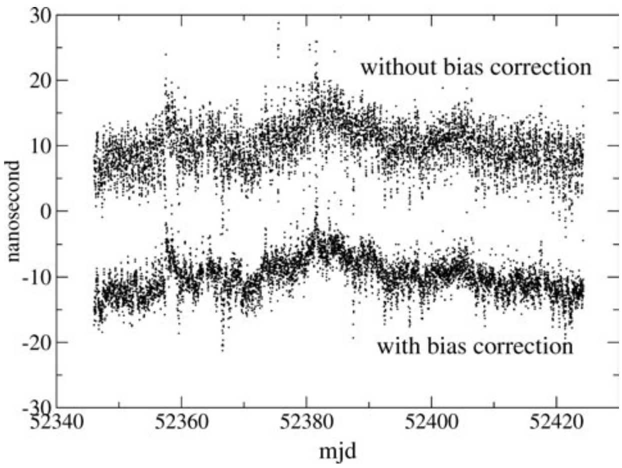


**Figure 5.** Effect of satellite differential biases on the time link USNO–NPLD using the C/A code in NPLD and the P3 combination in USNO. An arbitrary offset has been introduced between the two curves.

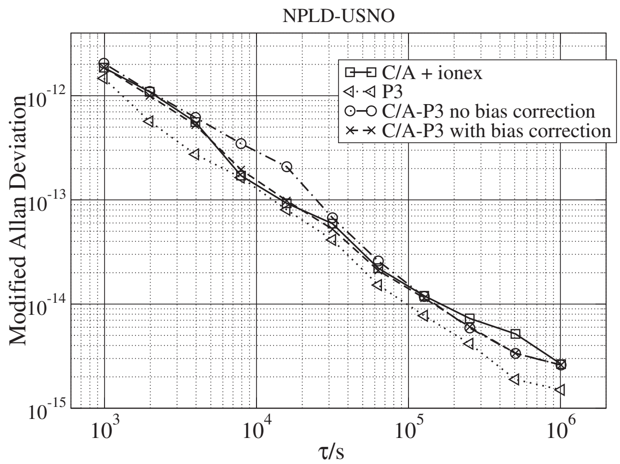


**Figure 6.** Frequency stability for the different computations of the time link USNO–NPLD.

better for P1 than for C/A, as indicated by the manufacturer Ashtech.

## 4. Satellite differential code biases

In a computation involving many receivers, it could be necessary to use results from time receivers and from geodetic receivers together. A first solution would be to use the same code observations in both cases, i.e. the C/A code, but this drops the advantage of the P3 combination available with the geodetic receiver. The other solution is to use the C/A code for the time receiver, and the P3 combination for the geodetic receiver, but that scheme necessitates the introduction of the differential code biases of the satellite. Indeed, the different codes have different hardware delays inside the satellite; if the same code observations are used by both stations, these delays cancel in the time link (single difference) but this is no longer the case if the stations use different code observations. We therefore tested the importance of such corrections in the time link between time and geodetic receivers. For this, we used the transatlantic time link presented before, NPLD–USNO. In NPLD we used the C/A code observations with ionosphere corrections deduced from ionex maps, and in USNO we used the P3 combination, with satellite positions obtained from IGS rapid ephemerides in both cases. We introduced the satellite differential P1–P2 and P1–C1 code biases (DCB) computed by the CODE analysis centre of IGS. The P1–P2 biases are estimated as constant values for each day, simultaneously with the 3072 parameters used to represent the global vertical TEC (TEC in the ionosphere) distribution; the values are given in the header of the ionex maps. The P1–C1 code bias computation is based on GPS tracking data from all types of receiver in the IGS network (see http://www.cx.unibe.ch/aiub/ionosphere.html). They are computed every day using the latest 30 daily solutions. Furthermore, monthly values are provided and archived. Because the variations of these biases with time are very small (the day-to-day reproducibility is of the order of 0.1 ns), we took a mean value for the whole period analysed, corresponding to the average for the three months investigated (March to May 2002). We present in figure 5 a comparison between the transatlantic time link results obtained without and with the correction related to the differential biases. We immediately see in that figure that the noise level is lower when the correction is applied. The Allan deviation (figure 6) shows that the effect is only important at averaging times below 1 day, and particularly at $\tau = 6\,\mathrm{h}$ due to the 12 h repeatability of the satellite visibility at each of the stations. For long-term stability (>3 days), the satellite differential bias correction has no effect. We also added in figure 6 the Allan deviations obtained with C/A with ionex maps in both stations, or with P3 in both stations. We see that the use of P3 if available in only one station gives slightly better stability than using C/A in both stations, but the difference is not very important.

## 5. Other effects

### *5.1. Tropospheric effect*

The tropospheric model used in the CCTF procedure is the standard Hopfield's model, with standard values for temperature, atmospheric pressure and vapour pressure coefficients. When varying these coefficients within possible

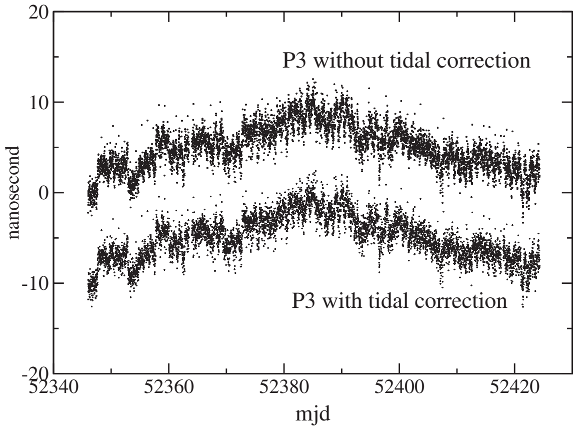


**Figure 7.** Effect of tidal station displacement on the time link USNO–NPLD using the P3 combination in both stations.

ranges, we get tropospheric delay variations of maximum 0.2 ns with respect to the value obtained with the standard parameters, so that it is still below the present precision level of our time transfer results.

### 5.2. *Tidal station displacement*

A last correction that we envisaged in this paper is the variations of the station position due to the tides, which can be very different for remote stations like NPLD and USNO. We therefore introduced in the code the vertical tidal displacement of both stations as a function of time. The results on the time link are shown in figure 7. Because the main tidal signal is on a diurnal period, the only visible, but not significant effect on the modified Allan deviation appears at $\tau = 0.5$ day, where it is $4.0 \times 10^{-14}$ without and $3.5 \times 10^{-14}$ with tidal correction, but the long-term stability as needed for TAI is not improved by this tidal correction.

## 6. Conclusions

This paper presents a new procedure that allows the inclusion of the time links using geodetic receivers in the computation of TAI. It is based on the standard 30 s RINEX files (with 26 observations inside the 13 min tracks), and on the ionosphere-free code P3. With respect to the classical procedure used at BIPM for time transfer within the TAI realization, i.e. C/A code with ionex maps, this new procedure has similar performance for short baselines, while for a transatlantic baseline, the improvement reaches a factor 2 on the Allan deviation up to $\tau = 10$ days. We also showed that if only long-term stability is needed, it is presently not necessary to take the tidal station displacement into account. Note that such time links need to be calibrated to be used for TAI. This is not considered in this paper (see e.g. [12]).

As a concluding remark, note also that if this application allows improvement of the time link stabilities for the TAI computation, it is also a starting point for improving the link between the IGS timescale and TAI presently realized from the data of UTC − GPS time (*Circular T*). Indeed, the IGS timescale is based on a stability algorithm using a weighted ensemble of clocks, which are both the satellite clocks and the stable receiver clocks of the IGS network [8, 9]. If the same clocks and receivers are used for both TAI and IGS timescales, they will allow us to determine, with a very high precision, the link between the IGS clock products and the TAI.

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