REQUIREMENTS ON GNSS RECEIVERS FROM THE PERSPECTIVE OF TIMING APPLICATIONS

P. Defraigne[1], G. Petit[2], P. Uhrich[3], W. Aerts[1]

[1]**Royal Observatory of Belgium,**
3 avenue Circulaire,
B-1180 Brussels, Belgium,
p.defraigne@oma.be
w.aerts@oma.be

[2]***Bureau International des Poids et Mesures,***
Pavillon de Breteuil,
92312 Sèvres, France
gpetit@bipm.org

[3]***LNE-SYRTE, Observatoire de Paris, LNE, CNRS, UPMC,***
61 avenue de l'Observatoire,
75014 Paris, France
Pierre.Uhrich@obspm.fr

ABSTRACT

This paper reviews the requirements on GNSS receiver setups for precise time and frequency transfer; these concern the receiver itself, the GNSS measurements, the antenna and cables used in the full setup. Concerning the receiver, we show that for a high level scientific use of a GNSS receiver within the frame of timing applications, it is essential that certain time delay related parameters be described in detail by the manufacturer.

INTRODUCTION

GPS is used for time and frequency transfer since the eighties [1]. Following the improvements of atomic frequency standards in terms of precision and accuracy, GPS (or more generally GNSS) time and frequency transfer underwent major evolutions both at the algorithmic levels and at the hardware level. Starting with one-channel C/A code receivers, a first improvement was found in the use of a multi-channel approach (e.g. [2]), increasing the number of satellites which reduces correspondingly the noise of clock solutions. The need for dual-frequency receivers measuring codes on both frequencies was then shown, as the combination of dual-frequency measurements enables to remove the ionosphere delays at the first order (i.e. 99.9 percent of the effect), leading to a factor 2 improvement in the precision of the intercontinental time links (e.g. [3]). The time community also started during the past ten years with combined analysis of code and carrier phase GPS data for Time and Frequency Transfer (TFT), also called "geodetic time transfer" (see e.g. [4-6]) as it uses the same modelling of GPS observations as used by geodesists long before. The precision of TFT using this technique is below 100 picoseconds (ps) for each observation epoch [e.g. 7,8], allowing frequency transfer with an uncertainty of order 1×10^{-15} for averaging time of one day. The accuracy is determined by both the pseudorange noise and the calibration capabilities [9], and is estimated to be at a few nanoseconds (ns); e.g. the uB uncertainty for one link is set to 5 ns in the BIPM circular T.

The Consultative Committee for Time and Frequency (CCTF) advocated in its Recommendation S 5 (2001) that the manufacturers of receivers used for timing with global navigation satellite systems (GNSS) implement the technical guidelines for receiver hardware compiled by the CCTF Group on GNSS Time Transfer Standards (CGGTTS). These guidelines have been compiled with the aim of achieving a system that can transfer time with an accuracy of 1 ns or better. They can be applied to all available global navigation satellite systems, such as GPS, GLONASS, WAAS, EGNOS, MSAS, COMPASS and Galileo. In the following, we review and in some cases update the major points of these guidelines, following developments that occurred since they were established.

RECEIVER OPERATION

The receiver system consists of a GNSS antenna and receiver, a microprocessor-controller, an input provided for an external frequency reference (typically 5 MHz or 10 MHz) to be used in all internal oscillator functions, an input provided for an external pulsed signal related to the external frequency standard (1 pulse per second, abbreviated 1 pps), and possibly an internal time-interval counter. The components may be integrated into a single package or may be separate and connected together by appropriate cables. During operation the internal oscillator must remain locked to the external frequency reference. The epoch of the receiver clock can be either (1) set based on the GNSS signals themselves and continuously monitored against the external pulsed signal using a time-interval counter, or (2) locked directly to the 1 PPS signal.

Fig. 1 shows three types of receivers satisfying these requirements. In this figure, "geodetic receiver" (R1) means a dual-frequency receiver providing both code and carrier phase measurements, while "time receiver" (R2) means a receiver providing the data in CGGTTS (Common GPS GLONASS Time Transfer Standard) as used within the time community for regular time transfer applications. The classical geodetic receiver (R1) can be used for timing applications only if the 1 pps output is related to the internal reference (or receiver clock), and if the relation between the internal reference and the 1 pps output is perfectly known: it must be provided by the manufacturer or measured by the user following a given procedure which is different for each receiver make. The main difference between the receiver types R1 and R2 is that the time interval counter (TIC) and the computation of the CGGTTS data are inside the time receivers R2 while they are external to the classical geodetic receivers R1 and based on a conversion from RINEX to CGGTTS (called R2CGGTTS in Fig. 1). The need for a TIC in both cases is due to the fact that in these receivers the internal clock is not synchronized with the external clock UTC(k). However, this TIC should measure time intervals (of up to 1 s if required) with an accuracy approaching 100 ps or better, and a noise level below this accuracy specification, and the TIC measurements should be reported separately from the GPS measurements.

In order to overcome the possible noise introduced by the TIC, some geodetic–time receivers directly synchronize their internal clock (modulo one constant bias) on the external clock to be compared. The user must in that case ensure that the 1 PPS epoch is coherent with the frequency reference and maintained sufficiently close to the GNSS time scale to assure proper operation This is illustrated by R3 in Fig.1. This kind of receiver cancels the need for a time interval counter and hence provides a final solution UTC(k)-T GPS which is less noisy than the solutions obtained with R1 or R2.

In receiver type R3, the internal reference is obtained either by locking the internal oscillation on the external frequency, or by using directly the external frequency for the internal reference. If the internal oscillator is locked on the external frequency with an enslavement system, then the system should be described in full details by the manufacturer. This system should furthermore be designed to introduce no noise on the frequency; adding noise would make impossible the study of frequency stabilities of the best frequency standards via GNSS frequency transfer.
Furthermore, the way the internal reference clock is obtained from the external 1 pps must also be described by the manufacturer; this is mandatory to have access to the delay between the external clock and the GNSS measurements, and hence to correctly transfer time.

The trigger level of the 1 PPS reference input should lie between 0.25 V and 1 V and its value should be known. Stability is improved if the trigger level is low relative to the maximum voltage of the 1 PPS pulses. The amplitudes of the pulses should be between 2 V and 5 V, and the triggering should take place at the leading (rising) edge of the pulse. To reach the goal of a 1 ns system, the trigger jitter should be less than 100 ps or better for rise times of the 1 PPS pulses of up to 10 ns.

Concerning the external frequency to be delivered to the receiver, a standard reference frequency of 5 MHz or 10 MHz, as commonly used in the laboratories, is encouraged. In case of higher frequency requested by the receiver, the laboratories must therefore use an external device for converting one of the standard frequencies to this higher frequency. The phase instability of such a device (particularly with respect to temperature) can add a significant contribution to the overall uncertainty budget of the receiving equipment.

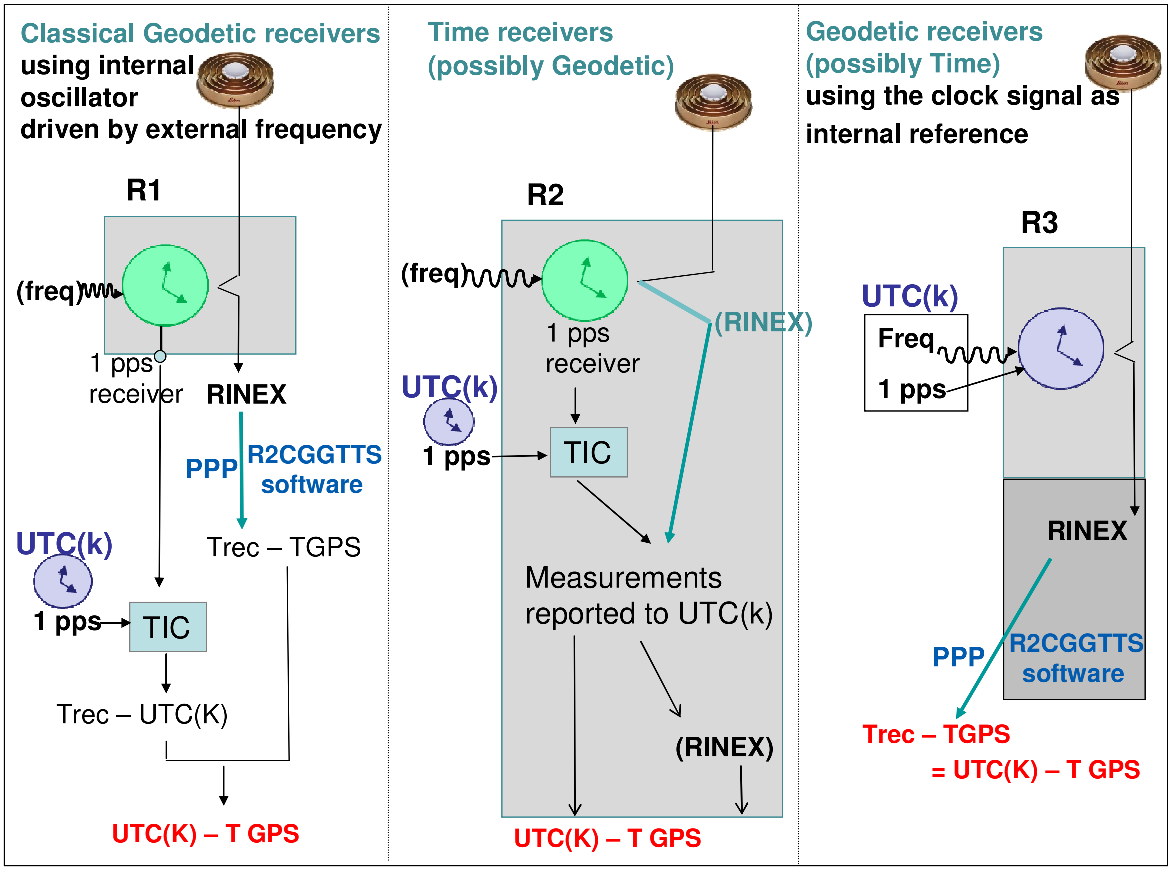

Fig. 1. Different kinds of receiver setups for GNSS time and frequency

CALIBRATION ISSUES

In a GNSS analysis dedicated to timing applications, a good understanding of the hardware-induced timing biases both in the satellites and in the ground equipment is important. These hardware delays will be different for all the different signals measured by the receiver and should be calibrated rigorously. Furthermore, the GNSS receivers used for timing applications are required to maintain constant their internal temperature, in order to assure the constancy of these hardware delays.

The recommendation CCTF 4(2001) recommends that

- absolute and differential calibration methods be continued to be developed and put into operation for all time transfer techniques used in TAI computation, with the aim of achieving 1 ns standard uncertainty,
- laboratories participating in TAI carry out regular calibration exercises and continuous monitoring of time-transfer equipment,
- techniques used for the time links of TAI be independently calibrated.

CCTF 5(2006) recommends that the timing laboratories work to improve the calibration of time transfer equipment, and to reduce the source of the type-B uncertainties of the receiving equipment including:

- equipment that minimizes the impact of fluctuations in the ambient temperature and humidity,
- antennae and cables which minimize the impact of multipath reflections and similar effects.

Fig. 2 presents the receiver setup with the different delays to be determined for a complete calibration.
X_O is the delay from the 1pps-input to the internal reference, and X_P is the delay from the laboratory reference to the 1pps-input. While X_C and X_P are determined from classical cable delay measurements, the determination of X_O and X_R (with X_R different for each GNSS frequency) depend on the receiver type (see [9]) and rely on the definition of the physical point where the GNSS measurements are made. These can be determined from absolute or relative calibrations procedures (see [10,11] for more details).

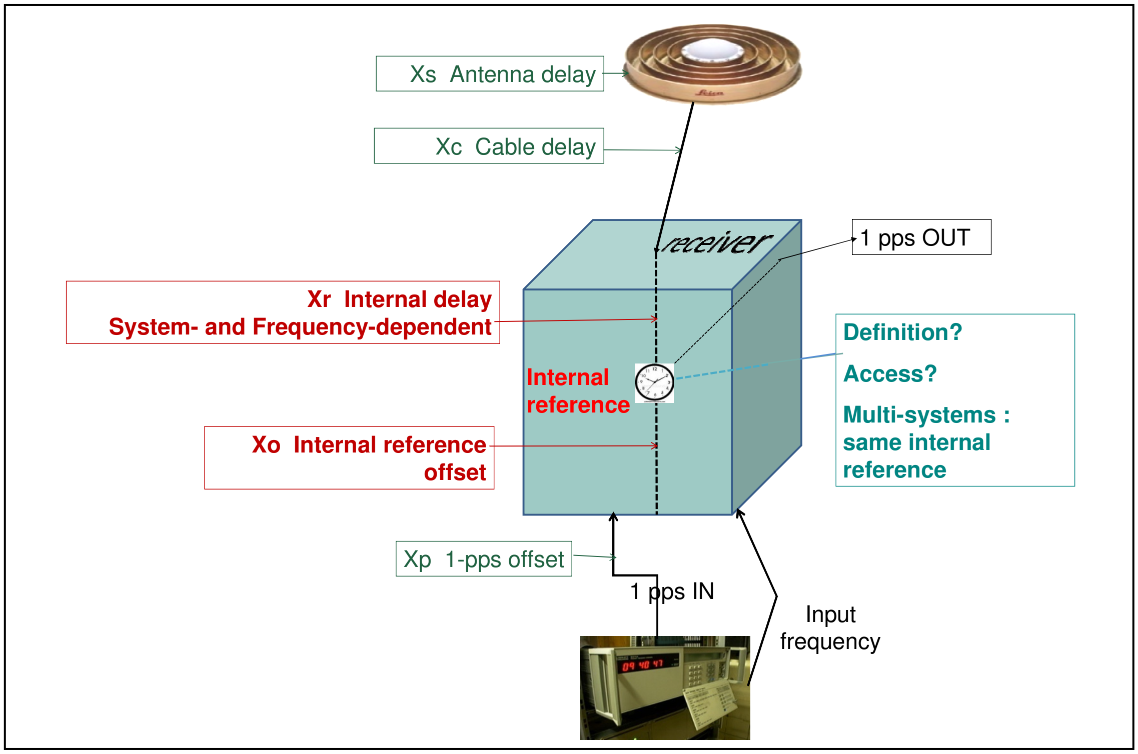

Fig. 2. Standard set-up of a receiver showing the definition of the different quantities those enter in the calibration.

It is therefore essential that the receiver manufacturer provides as information a correct definition of the physical point corresponding to the internal reference clock inside the receiver, i.e. the physical point where the GNSS measurements are made, and if the GNSS measurements are reported to another physical point than this internal clock, this should be reported too. The receiver must furthermore provide an access to its measurement point, either from the input 1 pps connector, or from an output 1pps connector. This access should also be fully detailed by the manufacturer. In parallel, the relation between the 1 pps reference input and the external frequency reference should be defined, as already stated in previous section. If this relationship is not important, or if the two signals must be coherent, this should be stated.

Note that an uncompensated change of the hardware delays in a time link may cause a significant instability in an ensemble time scale like TAI, so that the timing laboratories work to improve the calibration of time transfer equipment, and to use equipments that minimizes the impact of fluctuations in the ambient temperature and humidity.

OUTPUT DATA AND FORMATS

In order to get the highest precision, the GNSS measurements should be delivered on two frequencies, which give the possibility to cancel the first order ionosphere effects. No study is presently available to determine which frequencies will offer the best ionosphere-free combination for time transfer applications; this should be investigated in the future. Furthermore, in order to be able to make short term time and frequency comparisons with the highest precision, carrier phase measurements should be provided in addition to the code measurements.

Concerning the data format, the time community will be encouraged to follow the guidelines of the geodetic community using RINEX format, and to develop their own software to get 'CGGTTS-like' data from RINEX files. RINEX versions are updated as needed following the GNSS system deployments [12].

The future versions of the CGGTTS will certainly be based on a different computation procedure, different schedule of observations etc. Furthermore, as some systems will allow more than two frequency bands, different possible ionosphere-free combinations will be possible and could be included in the CGGTTS results. The GNSS time receivers will be encouraged to follow the evolutions of the CGGTTS to provide up-to-date results, but dedicated software will be distributed within the time community to get the new standard CGGTTS from RINEX files. The new standard should however assure some compatibility with the previous versions in order to enable the continuity of the computation of the time scales based on these data.

CABLES AND ANTENNA

Antenna and receiver electronics should be sufficiently stable with respect to environmental changes that the variation in delay through the system over the expected range of temperature and other environmental parameters is no more than 100 ps. While receivers can be installed in temperature-controlled rooms, the antenna and antenna cables should tolerate diurnal temperature changes of around 40 °C, as occur in certain parts of the world. Some experiments have been performed to test the sensitivity of the antenna, and showed maximum diurnal variations (for diurnal variations of 20 degrees) of 40 ps for the carrier phases [13], while up to 2 ns for the code measurements [14,15]. Antenna cables should be stable with respect to changes in temperature (the associated delay should vary less than 0.05 ps per degree per meter over the range –30 °C to +40 °C), and have low power loss. The impedance of the antenna cable and its terminations should be such that the power level of any extraneous signal reflected in the cable should be at least 40 dB below the direct signal at the receiver.
The antenna must be setup in a way that minimizes the reflections (multipath) and the near-field effects, as for example above a pillar, so that it is mounted away from close reflecting surface [16].

MULTI-SYSTEM RECEIVERS

Of course the timing applications will take advantage of the possibilities offered by a multi-system GNSS analysis. However, in order to be able to combine the measurements from different systems, it will be mandatory that the receiver internal reference be the same for all systems. Furthermore, for precise time comparisons, the receiver must be fully calibrated, i.e. the inter-frequency biases must be determined with the 100 ps accuracy. Indeed, in some cases the frequency bands used by different systems do not completely overlap, or the power spectrum inside the band is not the same. E.g. in GLONASS, several carrier frequencies are used in each frequency bands, yielding complex calibration procedures due to the need to calibrate one delay per carrier frequency.

CONCLUSIONS

This paper presented a review of the requirements for future GNSS receivers to be used for precise time and frequency transfer. These should be able to transfer time with an accuracy of 1 ns or better, and compare remote frequency standards without degradation of their frequency due to the receiver architecture. It comes out that it is essential that the receiver functions be described in detail by the manufacturer. This information must contain a correct definition of the physical point corresponding to the internal reference clock inside the receiver, i.e. the physical point where the GNSS measurements are made. The information should also contain all the relations between this physical point and the input/output signals, and between this physical point and the point to which the measurements are reported (if it is not the same). The receivers should also provide the measurements using the standard geodetic format RINEX, and if delivering the CGGTTS files, then the manufacturers should follow the future updates of this format. The timing community also will take advantage of multi-system receivers, but only if these use the same internal reference for the measurements of all the systems and if the inter-frequency biases can be precisely determined.

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