USE OF THE GPS TIME TRANSFER
AT THE BUREAU INTERNATIONAL DES POIDS ET MESURES

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ABSTRACT

The majority of the laboratories contributing to the establishment of the International Atomic Time TAI are now equipped with GPS time receivers. The BIPM coordinates the international time comparisons by GPS and evaluates most of the time links that are needed for the International Atomic Time TAI. The BIPM also participates to the calibration of instrumental delays by transportation of a receiver.

In the practice of GPS time comparisons, it appears that one is often rather far from reaching the potential accuracy. We have made a study of some of the limiting factors. Among them are the errors of the antenna coordinates: we show that they can be improved from the time measurements so that an accuracy of about 2 ns can be reached over short distances. An other source of difficulties is the lack of stability of some local time scales, which restricts the possibility of improving the precision by filtering; this difficulty appears mainly with the clocks which are too sharply steered.

The tracking schedules in use aim at providing links between the greatest possible number of laboratories. One of our conclusion, which should be discussed with the cooperating laboratories, is that one should organize a worldwide network of links which should be optimized not for the number of links, but for the accuracy of the necessary links.

1. INTRODUCTION

Among the 40 laboratories (or national centers federating several laboratories), which participate in the establishment of the International Atomic Time, TAI, by the Bureau International des Poids et Mesures (BIPM), 21 are equipped with GPS time receivers. These laboratories follow the common view approach devised by NBS [the meaning of the acronyms is given at the end] (Allan and Weiss, 1980). The responsibility of establishing the tracking schedules, initially at NBS, was transferred to BIPM in 1986; for this task, BIPM uses techniques developped at NBS.

The common view schedules offer the possibility of connecting each laboratory with a maximum of other laboratories, so that the time links can be very redundant (but not independent). We use a selected non-redundant number of links. Let us define by an "observation" some particular simultaneous tracking of normally 13 minutes duration, linking laboratories i and j. The evaluation is based on 6 to 25 daily observations, which are repeated every sidereal day, with practically the same geometry, except for the position of the Sun.

When looking at the daily values of UTC(i) - UTC(j), obtained from the same all methods of smoothing more or less fail to give the right answer. The most accurate methods are those which, in fact, use the narrowest window for averaging, at the cost of a lesser precision.

We are experimenting on methods devised according to the following principles:

(a) determination of the biases between the various satellites over intervals of about 10 days, either empirically or by geometrical considerations (see 3.2);
(b) correction of each observation for the biases;
(c) use of a weak smoothing over the corrected observations.

For instance, values represented by 2 and 3 on figure 2 are obtained according to these principles. Point 3 (linear fit over 2 days) is probably the closest to reality; its computed uncertainty is 0.9 ns.

A similar problem arises about the comparisons of the local clocks of laboratory i with UTC(i), which are reported at BIPM for standard dates, 0 h UTC. The answers to a recent questionnaire reveal a great variety of procedures, ranging from the unique measurement to the linear fit for over 10 days. The latter procedure is widely employed. The clock comparisons used by BIPM either over long distances (by GPS or LORAN-C) or within the laboratories should be compatible. The BIPM will propose general rules for both, after consulting the cooperating laboratories.

3.2. Biases due to errors of antenna coordinates

Let S be, at some instant, the true position of a GPS satellite tracked by stations A and B. S' is the position which corresponds to the broadcast ephemeris; $\vec{u}_a$ and $\vec{u}_b$ are the unit vectors of AS and BS (fig. 3). The error of the time comparison due to the ephemeris error is

$$E_1 = c^{-1}\, \vec{SS'} \cdot (\vec{u}_A - \vec{u}_B).$$

Its maximum is proportional to $\vec{SS'}$ and approximately to the angle α under which the baseline AB is seen from the satellite. Note that this error is maximum for "good" common views at equal elevation from A and B.

Now, let us assume that the coordinates assigned to A and S are correctly expressed in a reference frame and that the coordinates assigned to B are erroneous in this frame: they define a point B'. Then the time comparison error is

$$E_2 = c^{-1}\, \vec{BB'} \cdot \vec{u}_B,$$

independent of the baseline AB.

Error E_1 decreases with the distance AB. With AB $\approx$ 6000 km (Washington Paris) one typically observes biases up to 30 ns between satellites. If these biases are entirely due to a SS' error, they should reduce to 3 ns for distances of 600 km, which are common between european laboratories. The smallness of these biases for short distances is usually confirmed (fig. 4), but in some cases larger biases are found (fig. 5a). They cannot be explained by an error of the differential ionospheric correction. They are mostly due to an E_2-type error.

We have devised a method for deriving differential geodetic coordinates by use of the current data of GPS time comparisons. In this method, the location of the satellites is calculated from the altitudes and azimuths which are provided by the GPS receivers and available in our files. It is thus possible to obtain the coordinates without extra trackings and extra data transmission.

have the means to homogenize the coordinates at the desired level of accuracy, using the GPS time comparisons themselves. This requires that the coordinates entered in the receivers are kept constant for sufficient spans of time and that their occasional changes be reported to BIPM.

We have undertaken a systematic check of relative coordinates from the data stored at BIPM.

3.3. Biases over long distances

Over distances of 5000 km, or more, even between stations having good coordinates, the UTC(i) - UTC(j) may differ by amounts up to 30 ns (fig. 7), depending on the satellite or the sideral time of observation of the same satellite. That can be due to an El-type error, or to the model for refraction.

We have tried, without success, to improve the satellite positions from the data we have. The causes of failure might be the errors of the ionospheric refraction model and/or a bad modelling of the SS' errors.

As long as these problems are not solved, an increase of the number of common views with different geometries might lead to a better accuracy by averaging. We have programmed our receiver in order to have 25 common views per day to link USNO-OP. In that case the time averaging might also help: in these long distance links the time scales should be stable enough to allow for a strong smoothing. This is in contrast with the short distance links where a weak smoothing is sufficient.

3.4. Other researches

We have started, jointly with IGN France, to analyze the data of dual frequency observation of TRANSIT satellites in order to map the total electron content of the ionosphere. But we doubt that it can lead to an operational method for correcting the GPS ionospheric delay. A scientist of the RRL (Japan), Mr. M. Imae, in stay at BIPM, is developing a dual frequency receiver of GPS signals, in order to measure the ionospheric refraction.

We pursue the differential calibration of instrumental delays by transportation of a receiver, that we have undertaken jointly with NBS (Lewandowski et al., 1986). We have visited Spain and Israel.

4. CONCLUSIONS

Substantial improvements are still possible in the practice of GPS comparisons.

(a) The need of an accurate and homogeneous network of antenna coordinates is often underestimated. But, at short distances ($\leqslant$ 1000 km) a good relative positioning with uncertainties smaller than 1 meter, can be derived from the time comparisons themselves, leading to an accuracy of 2 ns on daily averages. An important requirement is that the coordinates entered in the receivers be not altered without informing the cooperating laboratories. It is easy to take into account coordinate corrections in the processing of GPS time comparisons.

(b) The lack of stability of local time references limits sometimes the precision of time comparisons by reducing the duration of the interval on which individual measures may contribute to an averaged, or smoothed, or filtered value. According to the characteristics of local time references, different processings should be used.

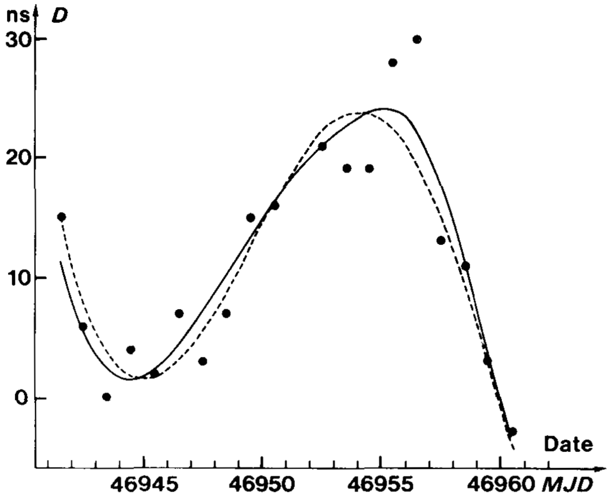

Fig. 1.- Measurements based on the same satellite (PRN 12) at daily interval. D is UTC(OP) - UTC(PTB) corrected for a linear function of time. The smoothed curves are Vondrak smoothings with different smoothing parameters. The standards deviations of observed values with respect to the smoothing are 3,3 and 3,6 ns. Other satellites give parallel curves and similar scattering.

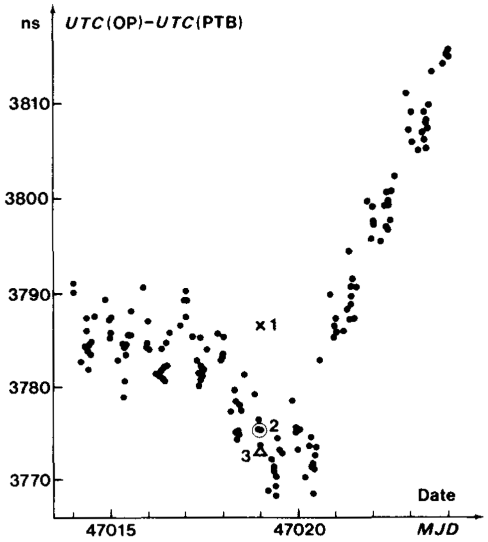

Fig. 2.- UTC(OP) - UTC(PTB) from all common views after removal of the biases. Evaluations at the standard date 47019:

1. by linear fit over 10 days,
2. by Vondrak smoothing with frequency cut-off of 1/9 days,
3. by linear fit over 2 days.

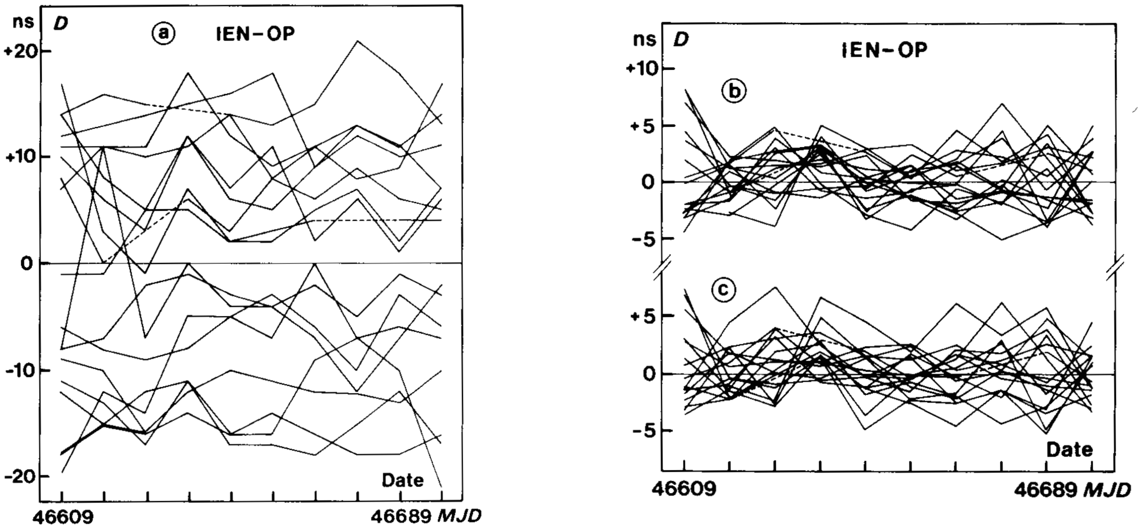

Fig. 6.- D is the difference between UTC(IEN) - UTC(OP) as given by each satellite and the mean value for all satellites,

(a) before coordinates corrections,
(b) with coordinates derived from TRANSIT positioning,
(c) with coordinates derived by BIPM from time comparisons.

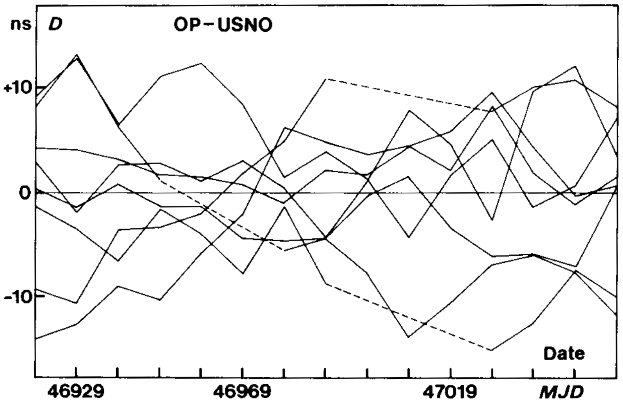

Fig. 7.- D is the difference between UTC(OP) - UTC(USNO) as given by each satellite and the mean value for all satellites.

Here a good positioning over long distance (≈ 6000 km) is used.