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POSITIONING OF GPS ANTENNAS IN TIME-KEEPING LABORATORIES OF NORTH AMERICA

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ABSTRACT

One of the problems with the use of the Global Positioning System (GPS) for time transfer is that it is a one-way system. In addition, most of the time-keeping laboratories of the world use only the L1 frequency. However, the use of GPS in the common view approach diminishes the impact of some of the errors such as orbit error, GPS clock error and ionospheric error, in the one-way system. But the common view approach does not cancel the antenna coordinate error.

The Bureau International des Poids et Mesures (International Bureau of Weights and Measures, BIPM) has developed a method of differential positioning using the data of time comparisons themselves. The consistency of the coordinates is within 30 cm for distances up to 1000 km. The agreement with space geodesy positioning for such distances has been verified within involved uncertainties. The method was applied to the European laboratories one year ago. Since then the obtained coordinate corrections have been used for the current BIPM computations of time comparisons in Europe. The consistency of time comparison improved from about 10 ns to about 2 ns.

The principles of this technique and the results of its application to the North American time laboratories are presented in this paper. Work on differential positioning by geodetic double-frequency receivers, between U.S. Naval Observatory and Maryland Very Long Baseline Interferometry (VLBI) point, are reported.

1. INTRODUCTION

The Global Positioning System (GPS) now in general use for regional and intercontinental atomic clock comparisons is a one-way system of time transfer. This means that the errors of satellite clock, satellite position, ionospheric delays, and ground antenna coordinates have a direct impact on the accuracy of time transfer between satellites and earth stations.

However, the simultaneous observations of GPS satellites (called the "GPS common-view technique") cancel or diminish some of these one-way system errors [1]. But the common-view approach does not cancel or diminish the ground-antenna coordinate errors. Thus the adoption of good ground-antenna coordinates appears to be an important factor in the accuracy of time comparisons by GPS satellites.

With the present state of the art of atomic clocks it is desirable that their comparisons be at the level of few nanoseconds of accuracy. In order to achieve such accuracy, the error due to antenna coordinates should not exceed 1 to 2 ns in the global budget of errors of the common-view technique.

To attain this goal the antenna coordinates must fulfill the following requirements:

(a) They must be accurately determined in a common homogeneous geodetic reference system. Uncertainties should be of the order of 30 cm or less.

(b) In order to reduce the residual errors of the common view method, the satellite and antenna coordinates should be expressed in the same geodetic reference system; for example WGS 84 is currently used for the broadcast ephemerides of GPS satellites. But this requirement is less strong than (a): WGS 84 is known with an accuracy of only about two meters with respect to the GPS monitor station network.

To realize the positioning at such a level between antennas located on different continents, the most accurate geodetic technologies, such as Very Long Baseline Interferometry (VLBI) or Satellite Laser Ranging (SLR), are required. The TRANSIT positioning is not sufficiently accurate. Inside the continents or regions a less expensive differential positioning, giving desired uncertainty, can be applied.

We can imagine the following approach for access of time laboratories to accurate coordinates:

(a) realizations of differential positionings between the antennas of the principle timing centers within a given area and

(b) realizations of differential positioning between those principal timing centers of a continent or a region and a VLBI site or SLR site located in the concerned area.

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*) Acronym meanings are listed at the end of the text.

In practice however, the time-keeping laboratories are often using TRANSIT positioning (± 1 m) or a navigation solution provided by GPS time receivers (± several meters) or other types of coordinates not accurate enough.

Recent studies [5,6] have shown that over distances of about 1000 km or less, a main source of biases in the GPS time comparisons is the adoption of wrong geodetic coordinates of the antennas. In BIPM a method of differential positioning over the distances of 1000 km or less has been developed by using data of time comparisons themselves. This method was applied to the European time laboratories one year ago. Since then, the obtained coordinate corrections have been used for the current BIPM computations of time comparisons in Europe, improving their consistency from about 10 ns to about 2 ns.

To examine and eventually establish the homogeneity of antennas' coordinates of North American time-keeping laboratories, several actions have been undertaken:

(a) An analysis of the antennas' coordinates of these laboratories by the BIPM method has been realized; the resulting coordinate corrections are reported here.

(b) A differential positioning by geodetic dual frequency receivers between the U.S. Naval Observatory and, the Maryland Point VLBI site, 20 km away, has been realized by NGS; final reductions of the data should be completed by mid-June 1989.

(c) In order to realize a differential positioning by the BIPM method between NIST in Boulder and the Platteville VLBI site 50 km away, NIST located an atomic cesium clock and GPS time receiver in Platteville in April 1989; the results of this positioning will be available later this year.

We hope these actions will reduce to 1 to 2 ns the impact of errors of antenna coordinates on the accuracy of time comparisons within North America. In addition the links with VLBI sites are a step toward improved accuracy of GPS time links with other continents.

The planned degradation of the GPS system, especially the degradation of the broadcast ephemerides, raises the question of the use, for time comparisons, of post-computed corrections to the broadcast ephemerides. One of the possible ways to resolve this problem is to compute the corrections to the broadcast ephemerides by time comparisons themselves. This approach is facilitated by the use of accurate coordinates of ground stations.

2. DIFFERENTIAL POSITIONING BY BIPM APPROACH

2.1. Biases due to Errors of Antenna Coordinates

For the comparisons of remote clocks by GPS satellites, the time laboratories apply a program of simultaneous trackings, called "common-views," which cancels the role of the satellite clocks and diminishes the errors of satellite position and ionospheric delay.

Let A and B be the positions of the GPS antennas of two laboratories (also designated by A and B) and S_k the position of a satellite they track. The unit vectors of AS_k and BS_k are $\vec{a}_k$ and $\vec{b}_k$ (fig. 1). The true value of the clock comparison at the instant of tracking is designated by

$$\text{clock reading of A} - \text{clock reading of B} = U_{ab}.$$

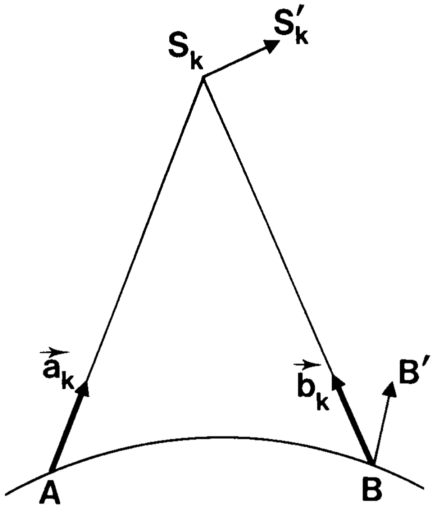

Fig. 1. Errors in the positions of satellite and antenna.

It is assumed throughout section 2 that the relativistic conversion in geocentric coordinate time has been made.

If the broadcast ephemerides correspond to the erroneous position S'_k, the measured time comparison $(U_{ab})_k$ is erroneous, and we define

$$E_k = U_{ab} - (U_{ab})_k. \qquad (1)$$

E_k is given by

$$E_k = -c^{-1}\ \overrightarrow{S'_kS_k} \bullet (\vec{a}_k - \vec{b}_k), \qquad (2)$$

where c is the velocity of light. For a given $\overrightarrow{S'_kS_k}$, E_k is roughly proportional to the chord $|AB|$.
If the adopted coordinates for B correspond not to B, but to B', the measured time comparison requires a correction F_k defined as in (1)

$$F_k = -c^{-1} \bullet \overrightarrow{B'B} \bullet \vec{b}, \qquad (3)$$

independent of the location of A.

It is possible by a theoretical approach to estimate the amount of E-type errors over short distances by considering their amount over long distances.

The laboratories of the U.S. Naval Observatory (USNO) and the Paris Observatory (OP) are 6000 km apart. One may compute the differences between the clocks of these laboratories for the same day as given by different common-views (different satellites, or the same satellite at different locations in the sky). The standard deviation of these computations with respect to the mean is of the order of 10 ns (15 ns in 1985, 7 ns in 1987). If we assume that this standard deviation is entirely due to the satellite ephemerides, which would be the worst case for our study, the influence of the E-type errors theoretically should reduce to 1 ns (one sigma) over distances of 600 km. Averaging over the usual 15 to 20 scheduled common-views leads to a quite negligible contribution.

Let us comment on another aspect of time comparisons by GPS satellites: the repeatability of the same geometry of observations from day to day for periods of several months. The scheduled common-views (SCV) are repeated every 23 h 56 m, so that on account of the sidereal orbits of the GPS satellites, the satellites are observed every sidereal day at nearly the same location on the sky. The common-view schedule is kept without change for about 6 months; then a new schedule is issued.

Repeated time comparisons, each usually averaged over a duration of 13 min, by the same satellite at the same sidereal time typically have standard deviations of 3 ns. But systematic differences reaching 30 to 40 ns appear between the results of measurements using different satellites, or the same satellite at different times. These differences are revealing sources of systematic errors.

As discussed above, over distances up to 1000 km the errors due to the uncertainties of the satellite position theoretically should not exceed 1 ns. Over such distances, the two paths of the signal through the refractive media are similar and we expect that the errors of the differential refraction are small. We assume also that the long series of repeated measurements further decrease the influence of the errors of the satellite ephemerides and differential refraction delays. They also should reduce somewhat the influence of multipath effects. It appears that the observed constant biases persisting during the months over short distances are entirely due to an error of differential antenna coordinates (F - type error).

2.2 Determination of Differential Coordinates

For the same day, we assume that the $(U_{ab})_k$ are all transferred at the same instant (0 h UTC, for instance). Usually the adopted time comparison is

$$\hat{U}_{ab} = \frac{1}{n}\sum_{k=1}^{n}(U_{ab})_k = U_{ab} - \Delta T, \qquad (4)$$

with the unknown ΔT defined by

$$\Delta T = \frac{1}{n}\sum_{k=1}^{n} F_k . \qquad (5)$$

From (4) and (3), we arrive at the equation

$$c^{-1} \bullet \overrightarrow{B'B} \bullet \vec{b} + \Delta T = (U_{ab})_k - \hat{U}_{ab} . \qquad (6)$$

The right side of (6) is obtained every day. On the left side, the unknowns are ΔT and the components DX, DY and DZ of $\overrightarrow{B'B}$ in the usual coordinate system: O at the geocenter, OZ toward the pole, OX in the prime meridian, and OY toward East. More precisely, DX, DY and DZ are corrections to add to the adopted coordinates of B in order to express them in the same frame as the coordinates of A (differential positioning).

The $\vec{b}$ in equation (6) are easily expressed in the OXYZ system, using the elevation and azimuth of S, which are included in the standard format for GPS data exchanges. However most of the GPS receivers give elevation and azimuth for instants which do not correspond to the center of tracking interval. Corrections are easily derived from these data themselves with the additional knowledge of rough values of the orbit inclination and of the terrestrial longitude of the ascending nodes. These corrections have been made.

We have also taken into account the displacement of stations A and B due to Earth tides, though this effect turns out to be negligible at the level of accuracy we are using here.

The system of equations (6) is solved by the minimum-least-squares method.

2.3. Comparison of BIPM Differential Solution with Space Geodesy Positioning

Four European time laboratories have recently established the local links between space geodesy sites and the center of phase of the GPS time receivers' antennas. These links have made it possible to check the results of the BIPM differential solution.

We give here, for an example, the differential positioning between two French laboratories, the OP and, located 635 km away (chord), OCA at Grasse.

At the OP a Doppler technique was used for absolute positioning by TRANSIT satellites (uncertainty ± 0.5 m), and in OCA laser ranging was used to LAGEOS satellite (uncertainty ± 0.1 m).

In both locations the local links between space geodesy points and GPS antennas have been realized with an uncertainty of ± 0.2 m.

The differences between geodetic coordinates and the coordinates introduced (adopted) into the receivers are following:

$$\text{OP(Doppler) - OP(adopted)} \quad \left\{ \begin{array}{ll} DX = -0.33 \text{ m} & \\ DY = 3.19 \text{ m} & (7) \\ DZ = 0.63 \text{ m} & \\ \text{uncertainty} \pm 0.5 \text{ m.} & \end{array} \right.$$

$$\text{OCA(laser)- OCA(adopted)} \quad \left\{ \begin{array}{ll} DX = -3.12 \text{ m} & \\ DY = 2.64 \text{ m} & (8) \\ DZ = 1.91 \text{ m} & \\ \text{uncertainty} \pm 0.1 \text{ m.} & \end{array} \right.$$

If the Doppler and laser positioning are perfectly accurate, the difference between the results in (7) and (8) represents the corrections which should be added to the relative coordinates of OP - OCA.

They are:

DX = -2.79 m
DY = -0.55 m
DZ = 1.28 m
total uncertainty ± 0.5 m.

The determination of these relative coordinate corrections, by the BIPM method realized over the period 18 July 1988 to 14 December 1988, is:

$$\begin{aligned} DX &= (-3.01 \pm 0.18)\ \mathrm{m} \\ DY &= (-0.09 \pm 0.07)\ \mathrm{m} \\ DZ &= (\ 0.52 \pm 0.17)\ \mathrm{m}, \end{aligned}$$

where the uncertainty stated here is the statistical deviation in the solution.

Given the various uncertainties, the agreement between two determinations is quite satisfactory.

Similar agreements have been found for other pairs of laboratories having the links between GPS antennas and space geodesy sites. The self consistency of the BIPM method appears to be 30 cm. To determine accuracy, this method needs to be compared with a method that is more accurate.

2.4. Application to North American Laboratories

Proceeding with the above method, we have determined the relative coordinates between four time laboratories in North America. The analysis is based on the data of the common-view schedule No. 10, extending from 15 December 1987 to 22 June 1988.

The distances between laboratories are shown in Table I. We notice that the distances between NIST and the other laboratories are more than 2000 km. In this case, the results should be used with caution. They are nevertheless given because the stability of the biases seems to indicate a predominant contribution of coordinate errors.

TABLE I - Distances between the laboratories considered in this study in thousands of kilometers (chords).

	APL	NIST	NRC
NIST	2.41		
NRC	0.70	2.44	
USNO	0.03	0.73	0.73

The results of this differential positioning are given by Table II. Errors of up to 12 m are noted.

TABLE II - Results of the differential coordinates determination between laboratories considered in this study.

Unit: 1 meter.

	DX	σX	DY	σY	DZ	σZ
USNO - APL	1.02	0.11	0.99	0.23	-7.52	0.42
USNO - NRC	9.47	0.10	-2.96	0.24	4.05	0.41
USNO - NIST	-2.12	0.16	5.06	0.35	-3.39	0.61
NIST - APL	2.71	0.16	-3.60	0.40	-5.02	0.69
NIST - NRC	10.95	0.12	-7.84	0.30	6.59	0.51
APL - NRC	8.40	0.12	-4.60	0.24	11.91	0.49

Table III gives the closure by triangles of laboratories. A good consistency of differential solutions including NIST is observed.

TABLE III - Closures of differential coordinates given by Table II by triangles of laboratories.

Unit: 1 meter.

	DX	σX	DY	σY	DZ	σZ
USNO - APL	1.02	0.11	0.99	0.23	-7.52	0.42
USNO - NRC	9.47	0.10	-2.96	0.24	4.05	0.41
APL - NRC	8.40	0.12	-4.60	0.24	11.91	0.49
Closure	-0.05		-0.65		0.32	
USNO - NIST	-2.12	0.16	5.06	0.35	-3.39	0.61
NIST - NRC	10.95	0.12	-7.84	0.30	6.59	0.51
USNO - NRC	9.47	0.10	-2.96	0.24	4.05	0.41
Closure	-0.64		0.18		-0.85	
NIST - APL	2.71	0.16	-3.60	0.40	-5.02	0.69
NIST - NRC	10.95	0.12	-7.84	0.30	6.59	0.51
APL - NRC	8.40	0.12	-4.60	0.24	11.91	0.49
Closure	0.16		-0.36		0.30	
NIST - APL	2.71	0.16	-3.60	0.40	-5.02	0.69
USNO - APL	1.02	0.11	0.99	0.23	-7.52	0.42
USNO - NIST	-2.12	0.16	5.06	0.35	-3.39	0.61
Closure	-0.43		0.47		-0.89	

This analysis is based on a schedule which has not been optimized for the positioning. Only 14 SCV have been used. This explains the quite large uncertainties of differential positioning (up to 0.5 m). Using an optimized schedule (a good geometry and 24 SCV or more) has led to uncertainties below 0.2 m [6].

Special comments are needed for the USNO results. This laboratory is equipped with a receiver which is still using parameters of the WGS 72 coordinate system instead of WGS 84, the system adopted by GPS since January 1987. Thus antenna coordinates enterred in the receiver in the geodetic form ϕ, λ, h, are transformed into cartesian coordinates X, Y, Z using the wrong ellipsoid parameters. In December 1988, the cartesian coordinates X, Y, Z expressed in WGS 84, were directly introduced into the USNO receiver, thus avoiding the use of WGS 72 ellipsoid parameters. Before this date the USNO coordinates should be corrected by:

$$\begin{aligned} DX &= \ \ 0.36\ \mathrm{m} \\ DY &= -1.58\ \mathrm{m} \\ DZ &= \ \ 1.05\ \mathrm{m} \end{aligned}$$

These corrections have been applied to the results given by tables II and III.

Another problem arises in the computation of the position of satellites by receivers using WGS 72 parameters. The cartesian coordinates X, Y, Z of the satellite are computed by the receiver software from the broadcast Keplerian elements using WGS 72 values of the universal gravitational parameter and the earth's rotation rate. The estimated error in the satellite position due to the use of wrong parameters is of the order of 2 to 3 m. If the error vector for each satellite has a constant value and direction, it could introduce an error of a similar amount to the differential coordinates computed by BIPM method. This possible error was not removed and could exist in the differential coordinates between

USNO and other laboratories, provided by Tables II and III.

2.5. Use of Coordinate Corrections for Accurate Time Comparisons

Let us consider again a pair of laboratories. We refer to the notation and equations in section 2.1. Instead of using ΔT from the coordinate solution to correct the $\hat{U}_{ab}$, it is better for time transfer to correct each $(U_{ab})_k$ by applying the coordinate corrections to, let us say, B by (3). This is easily done by computation, using the known elevation and azimuth of S_k.

Fig. 2 illustrates the improvement brought by application of coordinate corrections.

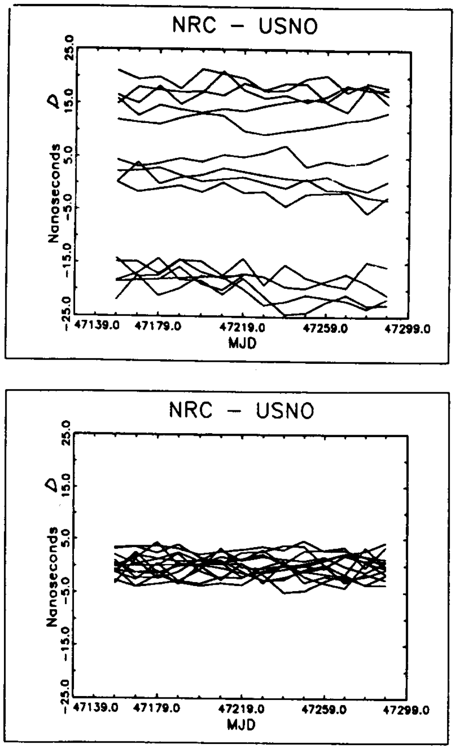

Fig. 2. D is $(Ua_b)_k - \hat{U}_{ab}$ of equation (6), averaged over 10-day intervals. One line is drawn for each k, above with the adopted coordinates, below after coordinate correction.

A bias could remain due to the remaining error of the differential coordinates of B with respect to A. It is maximum for $\overrightarrow{B'B}$ in the direction of $\overrightarrow{BS'_k}$.

A conservative estimate is: $c^{-1} \, |\overrightarrow{B'B}|/2$, corresponding to $\overrightarrow{B'B}$ vertical and uniform distribution of S_k on the sky. B'B is evaluated by

$$\overrightarrow{B'B} = (\sigma_x^2 + \sigma_y^2 + \sigma_z^2)^{\frac{1}{2}},$$

where the σ's are those of the differential positioning. If we take the portion of the error represented by the statistical deviations in Table II, we get a total uncertainty of 2 ns due to positioning for the pair laboratories in that list. This may be optimistic in that we have not fully established the accuracy of this method.

3. LINK OF NORTH AMERICAN LABORATORIES WITH VLBI SITES

The two principal time centers NIST and USNO can be linked to two VLBI primary sites of the BIH Terrestrial System (BTS).

BTS has been established by BIH, with the aim of providing the best possible world-wide reference frame by giving the coordinates of a small number of sites where the most accurate positioning are permanently used (very long baseline interferometry, lunar laser ranging, satellite laser ranging).

The uncertainties of BTS primary sites range from about 5 to 20 cm. The coordinates of sites are revised annually and referred to epoch 1984.0 with a model of tectonic plate motions. This model can be used also to bring the coordinates to date.

The 1987 issue of the BTS, designated BTS (1987), and the formulas for the transformation of BTS coordinates into WGS 84 are given in the BIH Annual Report for 1987 [2].

Since 1 January 1988, the maintenance of the BTS has become one of the tasks of the International Earth Rotation Service (IERS), and the name BTS changed to IERS Terrestrial Reference Frame (ITRF).

3.1. Link Between USNO and Maryland Point VLBI Site

In April 1985 the double-frequency geodetic GPS receivers were used to connect the Maryland Point VLBT Site (BTS site reference: VLBI 7277) to the time transfer antenna at the USNO located 20 km away. The geodetic GPS receivers located a point directly below the time transfer antenna relative to Maryland Point, with the height of the time transfer antenna above this point determined by direct measurement. This connection between the Maryland Point VLBI site and the USNO time transfer antenna is expected to be accurate to 2 to 5 cm. Final reductions of the GPS data should be completed by mid-June 1989.

3.2. Link Between NIST and Platteville VLBI Site

In order to realize the differential positioning by the BIPM approach between the NIST GPS time receiver and the VLBI site in Platteville, 50 km away (BTS site reference: VLBI 7258), NIST installed an atomic cesium clock and a GPS time receiver in Platteville in April 1989.

A specially conceived tracking schedule for the positioning, having 30 tracks has been introduced to both receivers in Boulder and Platteville. The GPS antenna in Platteville is located at the level of the ground without any obstacles around. This location seems to have reduced the noise due to multipath interference to 2 to 3 ns. The antenna in Boulder is shielded by an anti-reflecting plane, reducing noise of multipath to 3 to 5 ns.

The expected consistency of this differential positioning is about 30 cm.

Because the differential positioning by BIPM method requires several months of observations, the results will be available in the Fall, 1989.

4. UNCERTAINTIES OF GPS TIME COMPARISONS

Although it is not the purpose of this paper to discuss in detail other sources of uncertainties in GPS time comparisons [13], we will mention them briefly.

The differential receiver delays can be calibrated with uncertainties of the order of 1 ns [3,10,15,12]. However more recent studies have revealed systematic and random differences between different type of GPS time receivers [4,9].

For short distances, with observations spread in time and direction, we assume that the systematic component of the differential refraction, not corrected by the model, is below 1 ns. Nevertheless this assumption should be verified by measurements of ionospheric delay by dual frequency GPS receivers.

For long distances, a model to compute the ionospheric delay is insufficient, and the measurements of ionosphere by dual-frequency receivers are necessary [7,8].

Over short distances, the errors of satellites' positions are well cancelled by the common-view approach, and contribute less than 1 ns to the uncertainties of time comparisons. The use of post-processed ephemerides can reduce the impact of the ephemerides errors on long distance time comparisons [11].

Multipath propagation is another source of uncertainties. An appropriate location or shielding by anti-reflecting planes of GPS time receivers' antennas can significantly reduce this phenomenon.

5. CONCLUSIONS

(a) The uncertainties of GPS time comparisons due to the antenna positioning can be reduced to the level of 1 ns to 2 ns by the adoption of accurate coordinates (± 0.3 m).

(b) The TRANSIT Doppler positioning (± 1 m) is not sufficient. The navigation solution using the GPS time receiver positioning software (± 6 m) is worse.

(c) Inside a continent or a region (distances between laboratories up to 1000 km) a differential positioning by BIPM approach can be realized from the time comparisons themselves with a consistency of about 0.3 m or less.

(d) The GPS antennas of the principal timing centers of a continent or a region should be linked to VLBI or SLR sites by accurate local geodetic ties (± 0.05 m).

(e) Corrections to the adopted coordinates can be easily performed by software when computing the time differences between sites. We therefore recommend not changing adopted coordinates. All affected laboratories should be informed if any changes are made.

(f) The accurate coordinates of GPS time receivers located on different continents may permit the computations of the corrections to the broadcast ephemerides, assuming that the problems of ionospheric delay errors and multipath have been resolved.

The degradation of GPS system, planned for the near future, makes the improvement of deteriorated ephemerides a matter of urgent interest.

(g) It is important to investigate other sources of uncertainties of GPS time comparisons such as ionospheric delay, satellite position, multipath interference and anomalies of GPS time receivers' software.

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8. ACRONYMS USED IN THE TEXT

APL	Applied Physics Laboratory, Laurel, Maryland, USA.
BIH	Bureau International de l'Heure, Paris, France.
BTS	BIH Terrestrial System
BIPM	Bureau International des Poids et Mesures, Sevres, France.
GPS	Global Positioning System
IERS	International Earth Rotation System
ITRF	IERS Terrestrial Reference Frame
NGS	National Geodetic Survey, Rockville, Maryland, USA.
NIST	National Institute of Standards and Technology, Boulder, Colorado, USA.
NRC	National Research Council, Ottawa, Ontario, Canada.
OCA	Observatoire de la Cote d'Azure, Grasse, France.
OP	Onservatoire de Paris, Paris, France.
USNO	United States Naval Observatory, Washington D.C., USA.
WGS	World Geodetic System