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PRECISE GPS EPHEMERIDES FROM DMA AND NGS TESTED BY TIME TRANSFER

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Abstract

It has already been shown that the use of DMA precise ephemerides brings a significant improvement to the accuracy of GPS time transfer. At present a new set of precise ephemerides produced by the NGS has been made available to the timing community. This study demonstrates that both types of precise ephemerides improve long-distance GPS time transfer and remove the effects of SA degradation of broadcast ephemerides. The issue of overcoming SA is also discussed in terms of the routine availability of precise ephemerides.

INTRODUCTION

Among the many challenges faced by the timing metrology community two of immediate concern are:

- improving the accuracy of routine intercontinental GPS time transfer from the 10-20ns level (a large part of which is due to broadcast ephemerides) to a few nanoseconds,
- overcoming the SA degradation of GPS broadcast ephemerides.

It appears that the best way to progress is to tackle both problems by correcting raw GPS data with post-processed precise ephemerides. Other improvements of GPS common-view time transfer [1], such as adoption of more accurate antenna coordinates, introduction of double-frequency ionospheric measurement systems, differential calibrations of receivers are progressively being introduced [2,3,4].

Previous papers showed the improvements brought about by use of the post-processed precise ephemerides produced by Defense Mapping Agency (DMA) [5,3]. At present the National Geodetic Survey (NGS) provides publicly available precise ephemerides. The purpose of this study is to test both types of ephemerides by long-distance GPS time transfer. Also removal of the effects of degradation of broadcast ephemerides, in case of Selective Availability (SA), is investigated. The issue of overcoming SA is also discussed in terms of the routine availability of precise ephemerides. We present here an experiment of 38 days duration in which three long-distance time links are computed using both types of ephemerides. The precision of time links is estimated from the residuals of the smoothed common-view values. In addition we use the accuracy test of the closure around the world [3], which is the combination of these time links: the three independent time links should add to zero. The laboratories involved are the Paris Observatory (Paris, France), the National Institute of Standards and Technology (Boulder, Colorado, USA) and the Communications Research Laboratory (Tokyo, Japan). First we present briefly DMA and NGS precise ephemerides.

DMA PRECISE EPHEMERIDES

The United States Defense Mapping Agency (DMA) produces GPS precise ephemerides in support of its operational geodesy requirements [6]. From the beginning of 1986 until July 29, 1989 precise ephemerides were provided to the DMA by the Naval Surface Warfare Center (NSWC). Since July 30, 1989 they have been computed at the DMA. Since January 1990 Block II satellites have been included in the computations.

The pseudo-range measurements used for the computations of DMA precise ephemerides are performed at ten tracking stations. Five of the stations are operated by the United States Air Force and five by the DMA. The ten stations are quite evenly spread on the Earth surface.

The software system currently used, called OMNIS, includes a multisatellite Kalman filter/smoother that estimates a set of parameters including satellite orbits, satellite clocks, station clocks, and Earth orientation. Each precise ephemeris consists of the Earth-fixed position and velocity of the satellite center of mass at 15-minute intervals given in the WGS 84 reference frame. Estimates of the offsets between each satellite clock and GPS time and frequency at one-hour intervals are also generated. Over the years improvements have been made both to processing procedures and to the OMNIS software system with a view of improving the accuracy of the products and making them more compatible with the IERS standards within the framework of the WGS 84. Estimated uncertainty of the DMA precise ephemerides ranges from 1m to 5m. The DMA precise ephemerides are available for some research purposes with a delay of about 2 months.

NGS PRECISE EPHEMERIDES

The National Geodetic Survey (NGS) independently generates precise ephemerides for all available GPS satellites [7]. Beginning in 1991, these ephemerides have been produced from double-differenced phase observations solely from the Cooperative International GPS Network (CIGNET) tracking sites. The double-difference technique combines simultaneous observations of two satellites from two ground stations effectively eliminating satellite and ground receiver clock errors, and the Selective Availability signal degradation currently in effect.

CIGNET is a global GPS tracking network whose primary purpose is to provide orbit parameters. At present there are twenty- two CIGNET sites which are located mainly in the northern hemisphere. In addition, time and physical limitations allow only sub-networks in the United States, Europe, and Australia to be processed for orbit determination. Planned software and hardware improvements, and the continued growth of CIGNET will allow other sites to be included in the near future.

Each ephemeris covers a single week and is available within one month after the data were taken. Each is expressed in the ITRF reference frame. Checking is performed by baseline repeatability and direct comparison with other ephemerides. The estimated uncertainty of NGS ephemerides is 10m.

The NGS is actively investigating methods to improve the accuracy of its orbits and to reduce the delay in availability [8]. The ephemerides have been available to the public since July 1, 1991 through the Coast Guard GPS Information Center or directly from NGS through the Geodetic Information Service.

THE EXPERIMENT

The three long-distance time transfers UTC(OP)-UTC(NIST), UTC(NIST)-UTC(CRL) and UTC(CRL)-UTC(OP) were computed by the common-view method [1] using both types of ephemerides. At the time of processing, the DMA and NGS precise ephemerides, made available to the BIPM, covered a 42-day period, from June 2, 1991 (MJD=48409) to July 13, 1991 (MJD=48450).

The GPS data taken at the three sites corresponds to the international schedules No 16 and 17, issued by the BIPM. These schedules include Block I and Block II satellites. For one part of the period under study (July 1 to 4, 1991), the intentional degradation of GPS signals, known as Selective Availability (SA), was turned on for Block II satellites. This application of SA consisted of phase jitter degrading the readings of satellite clocks, which can be removed by strict common views [9], and of broadcast ephemerides degradation by a bias which changes frequently. It should be noted that one Block II satellite, PRN18, was removed from the tests for the period of SA: both types of precise ephemerides failed to correct it.

In our experiment only common views with the same starting time and the same track length were kept. Time comparison values UTC(Lab1)-UTC(Lab2) were obtained for each observed satellite at the time T_{mid}, of the midpoint of the track. About 7 common views were available daily for each of the three time links.

The GPS receivers used at the OP and the NIST come from the same maker and use the same software to treat the short-term data. This enhances the symmetry of the experiment for the time link OP-NIST. This is not the case for the the NIST-CRL and CRL-OP links, the GPS receiver in regular operation at CRL coming from another maker.

For this experiment the measurements of ionospheric delays were used. They were provided at the OP and the NIST by similar dual-frequency GPS receivers of the NIST type [10] (NIST Ionospheric Measurement System) and at the CRL by another type of dual-frequency GPS receiver designed by the CRL [11] (Realtime TECmeter). Detailed procedures for the application of ionospheric measurements to GPS time transfer can be found in [3].

The antenna coordinates of the three laboratories involved are expressed in the ITRF88 reference frame with an uncertainty of 50cm for OP, 30cm for NIST and 10cm for CRL.

APPLICATION OF PRECISE EPHEMERIDES TO TIME TRANSFER

In practice, computations with precise ephemerides require knowledge of the broadcast ephemerides used, during the observation, by the receiver software in order to apply differential corrections

[5,3]. For our three time links which encircle the Earth we needed access to recorded broadcast ephemerides on at least two correctly situated sites. We have used the broadcast ephemerides recorded at the BIPM (Sèvres near Paris, France) and recorded by the NGS in Mojave (California, USA).

The precise ephemerides, $\mathbf{PE}_i$, are provided in cartesian coordinates (expressed in WGS 84 reference frame for DMA and in ITRF88 reference frame for NGS) at time $\mathbf{T}_j$ corresponding to round quarters of hours: 0h00 UTC, 0h15 UTC, 0h30 UTC etc. It is then necessary to compute, from the broadcast Keplerian elements of the observed satellite, its positions $\mathbf{BE}_1$, $\mathbf{BE}_2$ and $\mathbf{BE}_3$ at three times $\mathbf{T}_1$, $\mathbf{T}_2$ and $\mathbf{T}_3$, such that:

$$T_1 < T_{\text{start}} < T_{\text{stop}} < T_3$$

where $\mathbf{T}_{\text{start}}$ and $\mathbf{T}_{\text{stop}}$ are the starting time and the stopping time of the usual 13-minute tracking. The ephemerides corrections $\mathbf{PE}_i - \mathbf{BE}_i$ for i = 1,2,3, are transformed in a frame linked to the satellite (On-track, Radial, Cross-track) and a quadratic polynomial in time is computed to represent each component. A quadratic representation is also computed in the same frame for the vector satellite-station. The inner product of these quadratic representations provides the corrections to the GPS measurements each 15 seconds. A linear fit over 13 minutes on these short-term corrections gives the corrections at the middle-time, $\mathbf{T}_{mid}$, of the track.

CONDITIONS OF TESTING

To test the precise ephemerides we have analyzed the precision and accuracy of three long-distance time links with each of two available sets of precise ephemerides. We have considered three different cases for each time link and for the closure, which is the sum of the three links:

- non-corrected values.
- values corrected by DMA ephemerides and ionospheric measurements.
- values corrected by NGS ephemerides and ionospheric measurements.

For each case, a Vondrak smoothing [12] is performed on the values UTC(Lab1)-UTC(Lab2). The smoothing used acts as a low-pass filter with a cut-off period of about 4 days. For the closure, the smoothed values are interpolated for 0h UTC of each day and the interpolated values are simply added.

PRECISE EPHEMERIDES TESTED BY PRECISION OF TIME LINKS

For the estimation of the precision of the time links we have used the standard deviations of the residuals to the smoothed values. These standard deviations for the complete period of the study are given in Table 1.

TABLE 1. Standard deviation, in nanoseconds, of the residuals to the smoothed values UTC(OP)-UTC(NIST), UTC(NIST)-UTC(CRL) and UTC(CRL)-UTC(OP) for the period of the study with application or not of the corrections.

	OP-NIST (7388km)	NIST-CRL (8522km)	CRL-OP (8816km)
non-corrected	19.5	19.6	26.3
DMA ephem.+iono.	2.9	4.2	4.2
NGS ephem.+iono.	6.7	9.0	7.4

We observe a clear improvement of the precision of the time links for both types of precise ephemerides with, however, a better performance for DMA ephemerides. This improvement is linked to the length of the baselines involved. For such long baselines, common-view observations are mostly at low elevations and so are more sensitive to ionospheric effects and to satellite positions.

The improvements brought by the corrections of ephemerides and ionosphere are also illustrated by Figures 1 to 3. The figures represent individual common views without smoothing. Both, DMA and NGS precise ephemerides, perform very well, in particularly for the removal of the effects of the SA ephemerides degradation.

PRECISE EPHEMERIDES TESTED BY THE ACCURACY OF TIME TRANSFER

A test of accuracy for GPS time transfer can be performed by computing the closure around the world via OP, NIST and CRL. Daily values of UTC(OP)-UTC(NIST), UTC(NIST)-UTC(CRL) and UTC(CRL)-UTC(OP) were estimated from the smoothed data points. The resulting daily values of the deviation from closure, for the period under study, are shown in Figure 4. This test shows an evident gain in accuracy brought by DMA ephemerides. One can see an improvement for the NGS ephemerides in the last part of the experiment, although the period is too short for a definitive conclusion. Detailed studies of the closure around the world with the DMA ephemerides are provided by **[3]** and **[13]**.

CONCLUSIONS

The DMA and NGS precise satellite ephemerides improve the precision and accuracy of long distance GPS time transfer. Further improvements of the quality of these ephemerides are expected, mainly for NGS after amelioration of the coverage of the globe by CIGNET stations.

Both types of precise ephemerides remove the SA degradation of GPS broadcast ephemerides.

Post-processed precise ephemerides can resolve the problem of SA degradation for TAI computation, provided that the BIPM has access to these ephemerides with a delay not exceeding two weeks.

ACKNOWLEDGMENTS

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ACRONYMS

BIPM	Bureau International des Poids et Mesures, Sèvres, France
CIGNET	Cooperative International GPS Network
CRL	Communications Research Laboratory, Tokyo, Japan
DMA	Defense Mapping Agency
GPS	Global Positioning SSystem
IERS	International Earth Rotation Service
ITRF	IERS Terrestrial Reference Frame
NGS	National Geodetic Survey
NIST	National Institute of Standards and Technology
NSWC	Naval Surface Warfare Center
OP	Paris Observatory, Paris, France
TAI	International Atomic Time
SA	Selective Availability of GPS
UTC	Coordinated Universal Time
UTC(CRL)	Coordinated Universal Time as realized by the CRL
UTC(NIST)	Coordinated Universal Time as realized by the NIST
UTC(OP)	Coordinated Universal Time as realized by the OP
WGS	World Geodetic System

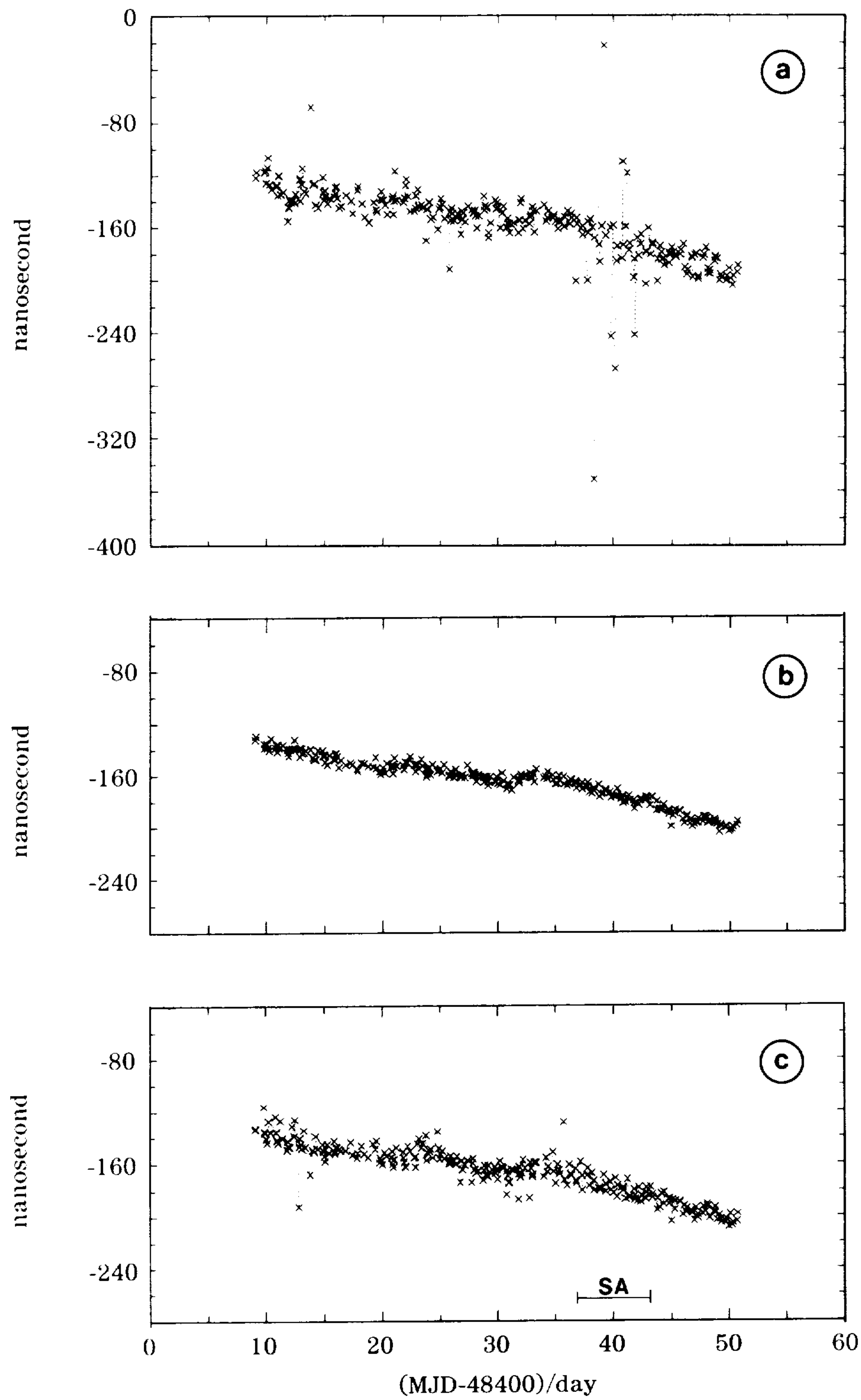

FIGURE 1. *GPS time link UTC(OP)-UTC(NIST) obtained with:*
1-a. non-corrected data,
1-b. data corrected for DMA ephemerides and measured ionospheric delays,
1-c. data corrected for NGS ephemerides and measured ionospheric delays.

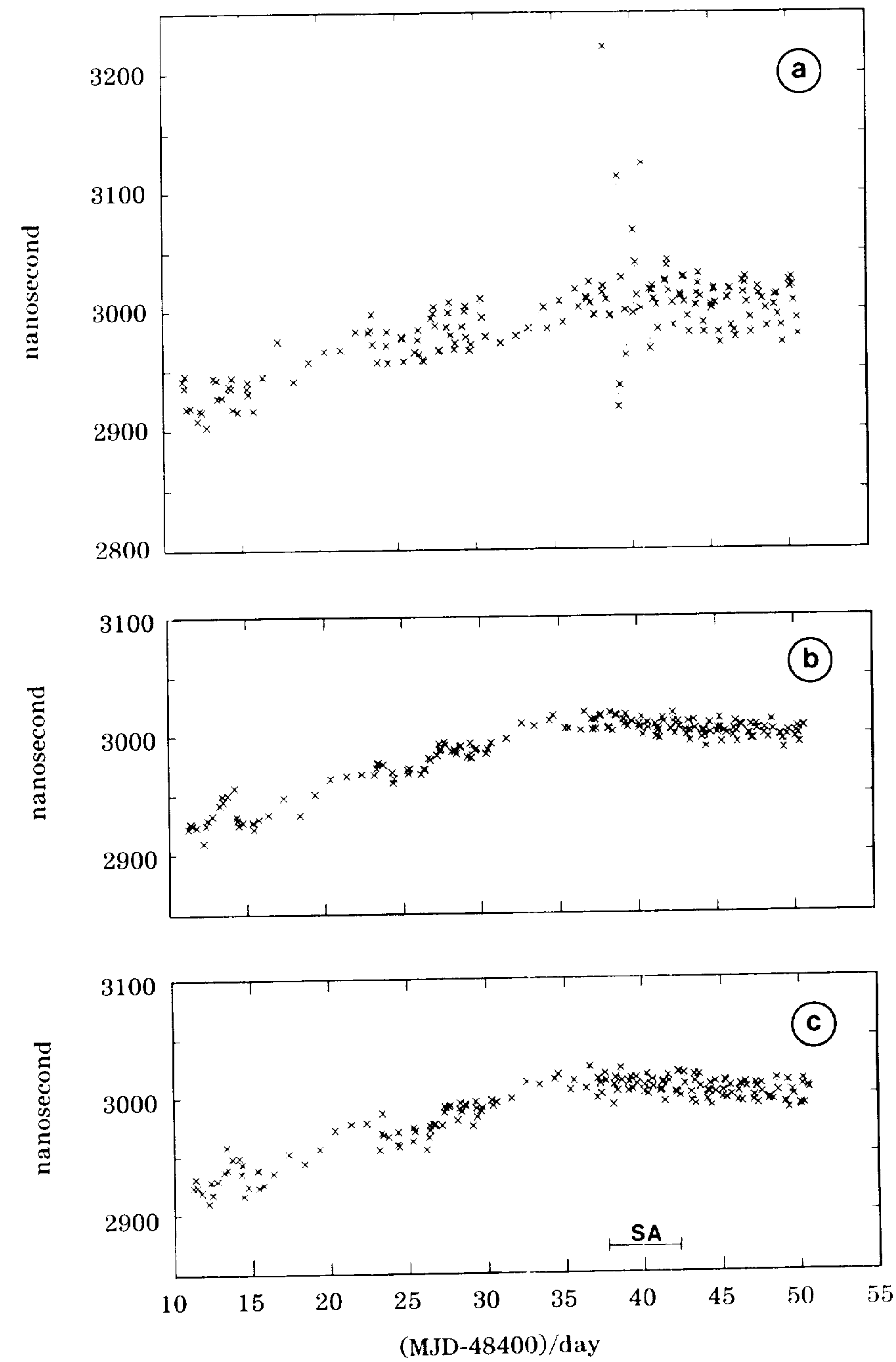

FIGURE 2. *GPS time link UTC(OP)-UTC(CRL) obtained with:*
2-a. non-corrected data,
2-b. data corrected for DMA ephemerides and measured ionospheric delays,
2-c. data corrected for NGS ephemerides and measured ionospheric delays.

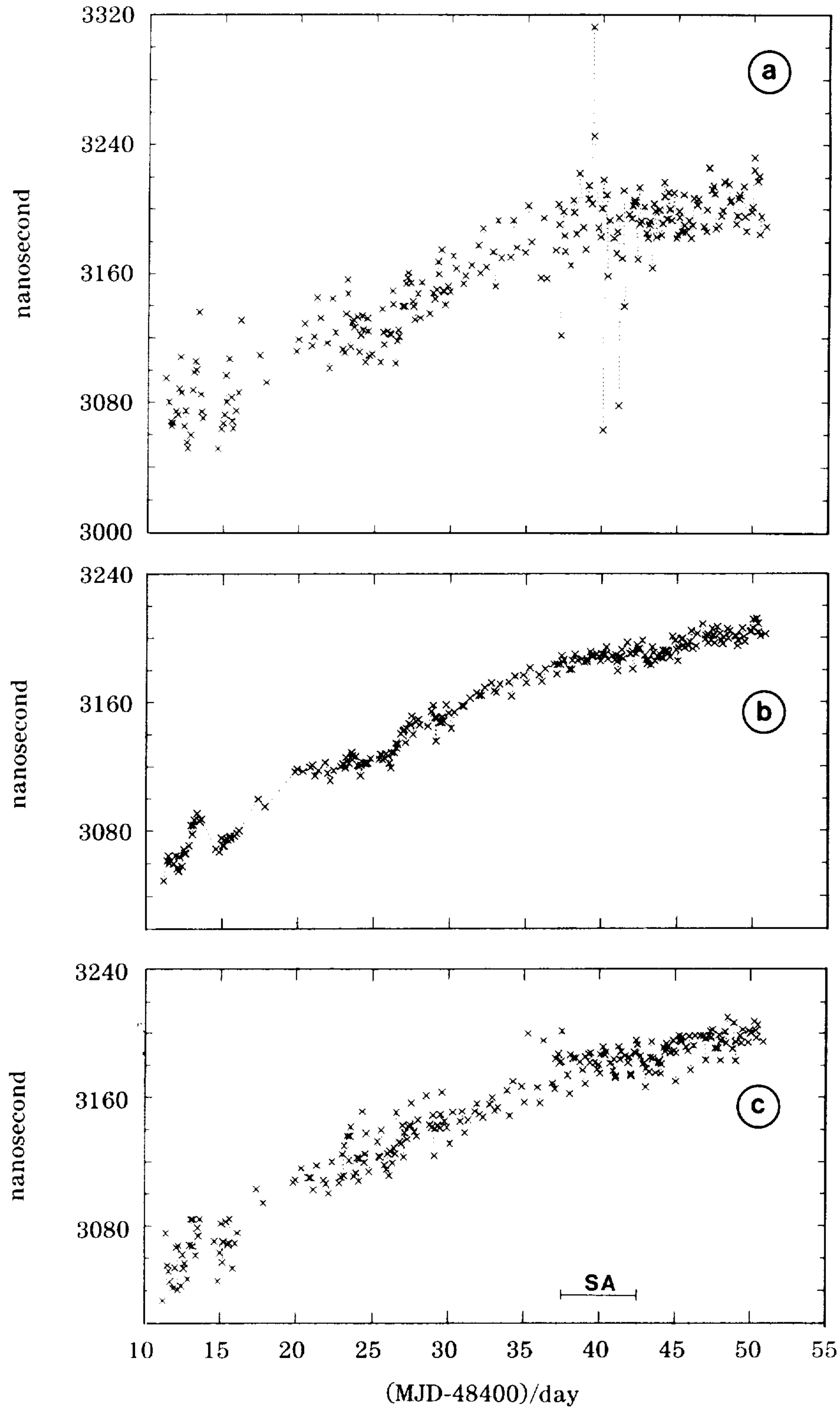

FIGURE 3. *GPS time link UTC(NIST)-UTC(CRL) obtained with:*
3-a. non-corrected data,
3-b. data corrected for DMA ephemerides and measured ionospheric delays,
3-c. data corrected for NGS ephemerides and measured ionospheric delays.

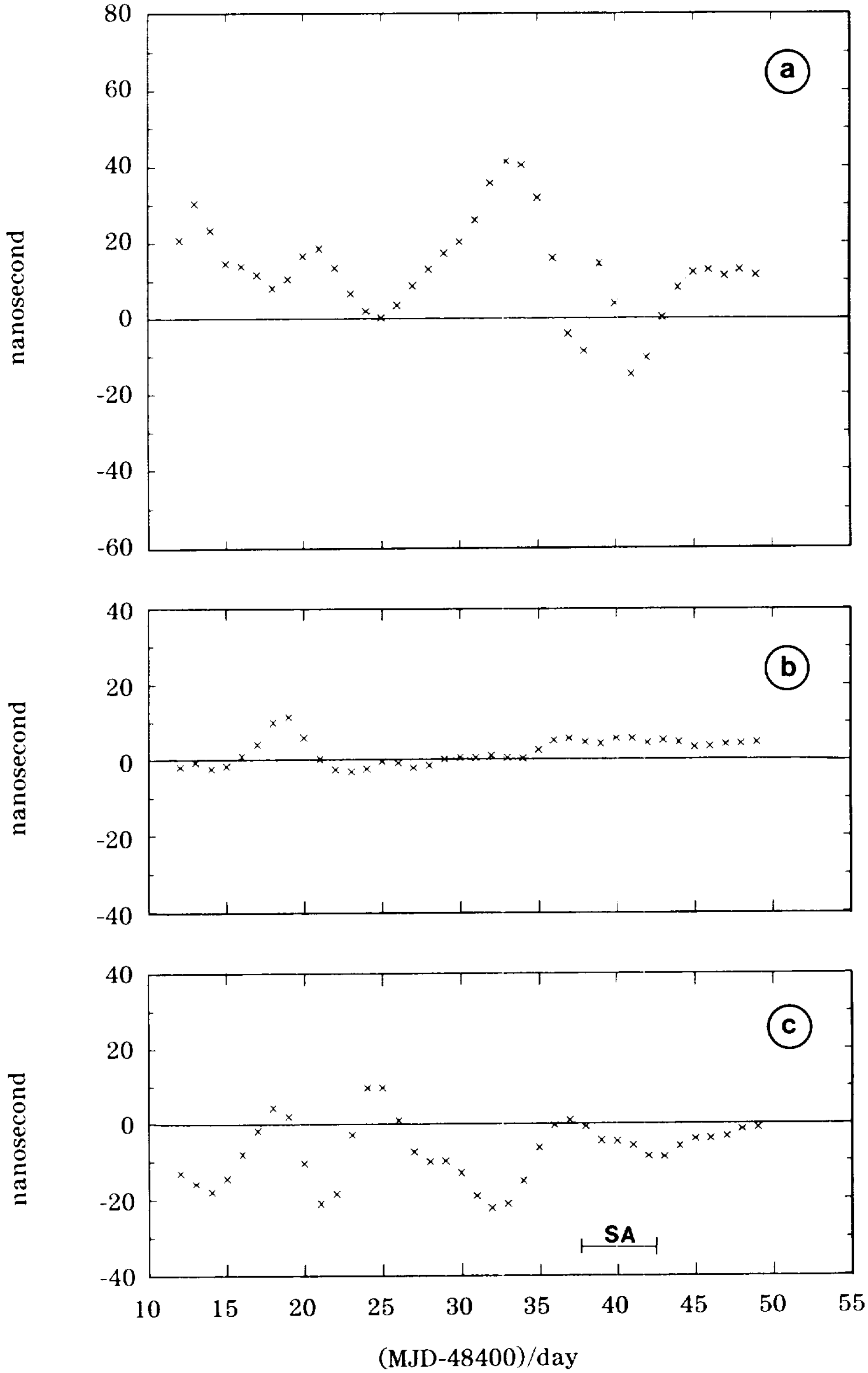

FIGURE 4. *Deviation from closure around the world via OP, NIST and CRL obtained with:*
4-a. non-corrected GPS data,
4-b. data corrected for DMA ephemerides and measured ionospheric delays,
4-c. data corrected for NGS ephemerides and measured ionospheric delays.

QUESTIONS AND ANSWERS

Professor Leschiutta, Politechnico Di Turino: Both DMA and NGS precise ephemeris correct for the ionospheric effects. Can you elaborate concerning a couple of questions? Do they use the same model, the same receiver, the same algorithm in order to correct for the ionospheric effects?

Mr. Lewandowski: I am not sure how they produce the corrections. I can only tell you what we are doing for the ionosphere. We use an ionosphere calibrator which was developed at the BIPM and is used also in Tokyo. NIST has produced another type which is used in Boulder. So, for this work, the same type of calibrators were used for all the data. Each of them should, theoretically, give a one nanosecond accuracy, but it is probably a few nanoseconds.

Samuel Ward, ex-JPL: Does that NGS offset that appears to be a bias occur because of a seasonal effect and the data span is too short?

Mr. Lewandowski: This is a short period so it is difficult to talk about seasonal effects. It is only a 38 day period. It *could* be, why not?