7 TH EUROPEAN FREQUENCY AND TIME FORUM NEUCHÂTEL - 16 - 17 - 18 MARCH 1993

P. 417 - 421

PRECISE GPS EPHEMERIDES FOR TIME TRANSFER

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ABSTRACT/RESUME

The quality of GPS ephemerides is a key factor in the GPS time transfer technique. In the common-view method, the error can reach 10-20 ns for a single measurement, when using broadcast ephemerides, and several times these values with the full implementation of Selective Availability. The measurements can be corrected in post-processing if precise ephemerides are made available to the user. Recently, international GPS tracking networks have been set up for civilian geodetic purposes. They provide post-processed ephemerides which are estimated to be accurate at the metre level, and the corresponding effect on GPS time transfer should, on average, be down to 1 ns. The accuracy of GPS ephemerides provided by numerous agencies is tested by verifying the closure condition on the sum of three time links around the world. It is found that the precision of GPS time transfer, when corrected using such ephemerides and measured ionospheric delays, reaches 3-4 ns. Uncertainties of several nanoseconds remain in this test of the accuracy of time transfer.

Keywords: GPS time transfer, ephemerides, reference frames.

1. INTRODUCTION

The excellence of worldwide time unification depends on the quality of the clocks kept by the national timing centres and on the means of time comparison. With the Global Positioning System, time comparisons can easily be performed with an accuracy of 10 to 20 nanoseconds over intercontinental distances (Ref. 1). It is possible to improve this performance to 4 to 5 nanoseconds when using measured ionospheric delays and post-processed precise sphemerides (Ref. 2). Until recently, such ephemerides have been available on a regular basis only from the US Defense Mapping Agency and from the US National Geodetic Survey, with a delay of about 6 weeks.

by June 1992, the International Association of Geodesy has up the International GPS Geodynamics Service (IGS) to apport geodetic and geophysical research activities (Ref. 3). Through a number of observatories equipped with GPS applying the collected data, and subject the collected data, and subject centres, it makes its data and products available to make its data

The purpose of this paper is to study the accuracy and precision of GPS time transfer, when using measured ionospheric delays and precise ephemerides provided by several agencies. The test of accuracy is the closure condition provided by the sum of three independent links around the world (Ref. 4). Section 2 presents the ephemerides used in the tests. Section 3 describes the closure experiment and the possible interpretations of a misclosure. Section 4 reviews the results obtained on several closure experiments conducted over the last three years.

2. GPS EPHEMERIDES

2.1 DMA ephemerides

The US Defense Mapping Agency produces precise ephemerides from its own 10-station network. They have been provided to the BIPM on a regular basis since 1990. The description of the computation process can be found in (Ref. 5). The ephemerides represent an Earth-centered Earth-fixed trajectory, referenced to the satellite centre of mass, expressed in the WGS84 reference frame, the time scale being GPS time.

2.2 NGS ephemerides

The US National Geodetic Survey produces precise ephemerides using data from the Cooperative International GPS Network (CIGNET). Since 1991, these have been made available on a free-access computer. The procedure of orbit determination is described in (Ref. 6). The ephemerides represent an Earth-centered Earth-fixed trajectory, expressed in the International Earth Rotation Service (IERS) Terrestrial Reference Frame (ITRF), the time scale being GPS time.

2.3 IGS ephemerides

Seven IGS analysis centres have produced precise ephemerides from the data of the IGS network since June 1992. They are the Center for Orbit Determination in Europe, University of Bern (CODE), the Geodetic Survey of Canada, Ottawa (EMR), the European Space Agency, Darmstadt (ESA), the GeoForschungsZentrum, Potsdam (GFZ), the Jet Propulsion Laboratory, Pasadena, California (JPL), the Scripps Institution of Oceanography, La Jolla, California (SiO), the University of Texas, Austin (UTX). The ephemerides are made available on free-access computers at the IGS data centres. The procedures of orbit determination are described in messages available on the IGS computers (Ref. 7). The ephemerides represent an Earth-centered Earth-fixed trajectory, expressed in the ITRF reference frame, the time scale being GPS time.

3. TEST OF ACCURACY

3.1 Description of the test

All closure experiments reported in this paper use the three links between the Paris Observatory (OP), the National Institute of Standards and Technology in Boulder, Colorado (NIST), and the Communications Research Laboratory in Tokyo (CRL). The GPS data taken at the three sites correspond to the international schedule issued by the Bureau International des Poids et Mesures sor the establishment of TAI. Each link is computed independently using the common-view method, the results being passed through a low-pass filter with a cut-off period of about three days. The scatter of the unfiltered data points relative to the filtered ones provides an estimation of the short term measurement noise. The filtered data are then interpolated to one point per day, and these daily values for the three links are summed to provide one estimation of the closure per each day.

At each site ionospheric delay measurements are performed by dedicated dual-frequency codeless GPS receivers. These measurements are used to compute the ionospheric correction to the raw time-transfer data. A correction for precise ephemerides is also computed for all the data points. In the following, "raw data" means common-view data without corrections (other than those transmitted by the satellites), while "corrected data" refers to data to which have been applied the corrections for ionospheric measurements and precise ephemerides.

In the ideal case, where there is no measurement noise and no systematic error of any kind, the sum of the three time links, although they are completely independent from one another, must be zero. In the real world there is measurement noise, in the time measurements themselves, and in the ionospheric delay measurements. In addition systematic errors are probably present in the ionospheric measurements. Errors in the relative positions of stations and satellites will also cause systematic effects. In the next sections, we consider this particular point in more detail. Finally, although the closure procedure provides a cancellation of calibration errors, it is still possible that short term variations of the calibrations cause systematic effects due to the regularity of the observing schedule over durations of months.

3.2 Realization of terrestrial reservance frames

The station coordinates on the one hand, and the satellite coordinates on the other, are two realizations of a terrestrial reference frame, which can be totally independent. In a first approach, one can state that a realization by a set of station coordinates is a geometric one, while a realization by the ephemerides of satellites is a dynamic one. In general, apart from local effects, the differences between two realizations of a terrestrial reference frame can be represented by a 7-parameter transformation which includes a translation of the origin (3 parameters), a scale factor (1 parameter), and a global rotation of the axes (3 parameters).

When choosing a set of station coordinates and a set of satellite ephemerides to compute the common-view time transfer data, one implicitly assumes that the two realizations of the terrestrial reference frames by the station coordinates and by the ephemerides are the same. If this assumption is not justified, errors will be caused in the time links, which will return a non-zero value when computing the sum of the three links (deviation from closure). However, due to the use of the common-view method and to the long distance of the links, the overall geometry of our network is quite particular, with stations at about the same latitude, regularly spaced in longitude, and with each station observing towards the east for one link,

and towards the west for the other. This geometry has the important consequence that the closure is, to first order, relatively insensitive to a global transformation between the frame of the station coordinates and that of the ephemerides, with one exception: a global rotation about the Z axis (the axis of the poles) fully affects the closure. This can be seen in figure 1, which represents the effect of such a rotation on one link. In this case, the link computed as H(A)-H(B) has a higher numerical value for the geometry A'B' than for the geometry AB. As the geometry of all three links is equivalent regarding a rotation about the Z axis, the effect of such a rotation on the closure is three times its effect on one link. The deviation from closure is estimated to be about 1 ns per 0.004° of rotation about the Z axis (Such a rotation represents about 40 cm at satellite level).

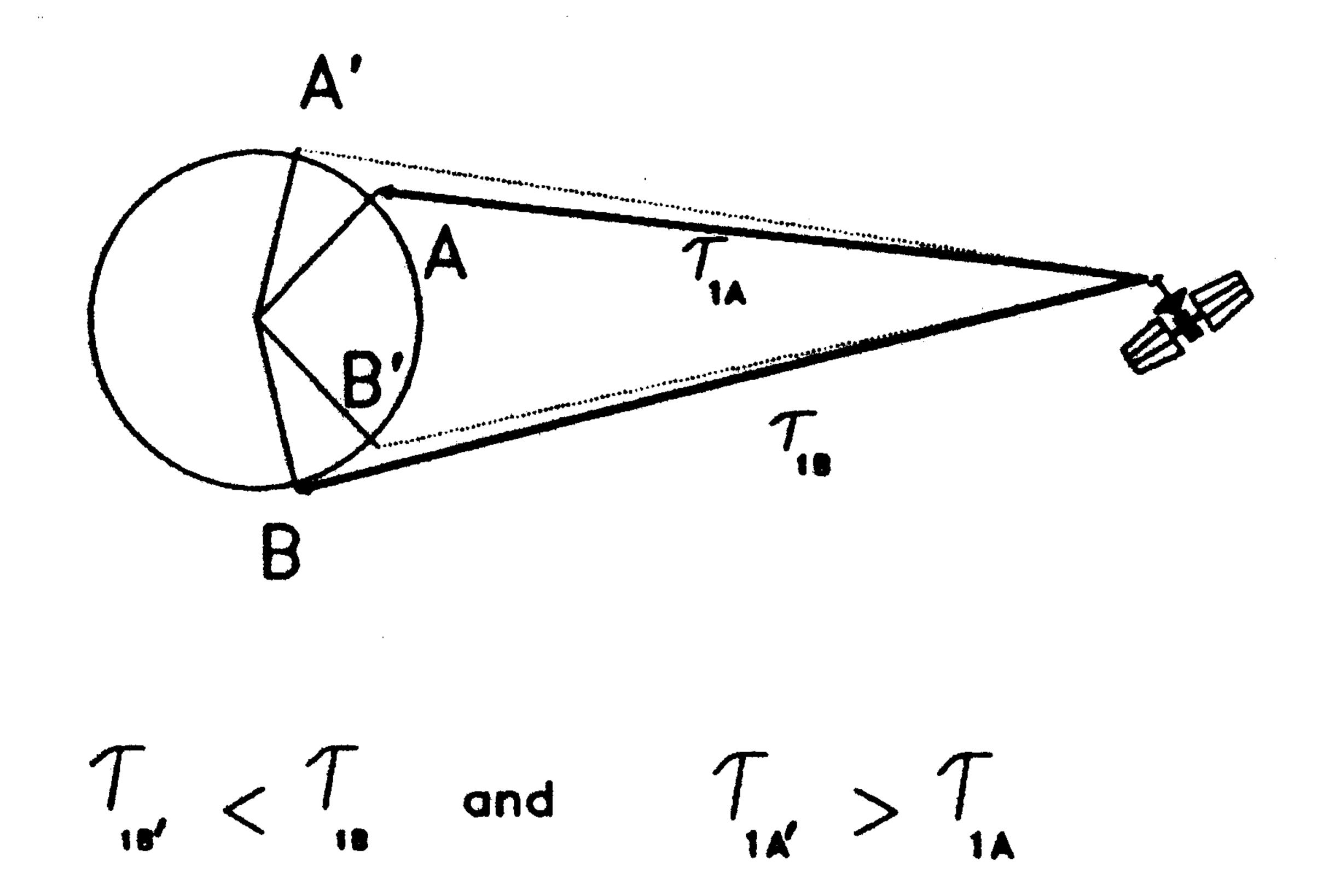


FIGURE 1: Effect of a rotation of the station frame relative to the satellite frame on the GPS time transfer.

3.3 Effect of an error in station coordinates

In addition to a global difference decribed in the previous section, an error in the coordinates of one station can be viewed as a local difference that affects the time links in which this station participates. However, due to the more or less constant geometry of the observations (due east for one link, due west for the other), the effect of an error in the coordinates of one station is a constant misclosure. Based on the geometry of the network, table 1 lists the average effect of errors in station coordinates on the closure. Incidentally one can verify (by summing the values in each column of table 1) that the effect of a global translation, is an error of the same value in a coordinate for all stations, is about zero.

TABLE 1: Misclosure/ns caused by 1 metre of error for each station coordinate

	X	Y	Z
OP	+2	-4	0
NIST	-4	+1	0.5
CRL	+2	+3	0

4. RESULTS

4.1 Closure experiments

The closure has been computed for three periods of the between mid-1990 and end-1992. To account for ephemerides available at different times, the results presented in four groups.

The first represents an extensive study that has conducted over the 393 days from 1990 June 16 (MJD office to 1991 July 13 (MJD 48450). The results have presented in (Refs. 2,4). This test only uses ephemerides and checks the long term consistency of the long term consistency

The second is included in the first, but consists in a 3-week period early in 1991 where a global geodetic experiment named GIG'91 (Ref. 8) was conducted. This ran from 1991 January 22 (MJD 48278) to February 13 (MJD 48300). Available ephemerides for this period were of DMA origin, together with a set produced by the JPL from the GIG'91 data.

The third group covers a 2-week period at the beginning of the operation of the IGS network in the summer of 1992. It starts on July 5 (MJD 48808) and ends on July 17 (MJD 48820). Available ephemerides were the ones from the DMA and the NGS, with others from the IGS centres CODE, ESA, JPL and SIO (others were available from IGS, but have not been considered in this analysis).

The fourth group covers a 4-week period of operation of the IGS network in the autumn of 1992. It runs from October 13 (MJD 48908) to November 7 (MJD 48933). Ephemerides from DMA and CODE were used in this analysis.

In each case the same processing scheme was applied, following the description in section 3.1. Figures 2 to 11 present the daily values of the deviation from closure obtained. The results from raw data are shown in figures 2, 4, 6 and 10 for groups 1 to 4, respectively. The results for corrected data are given in figures 3 and 5 for groups 1 and 2, figures 7 to 9 for group 3, and figure 11 for group 4.

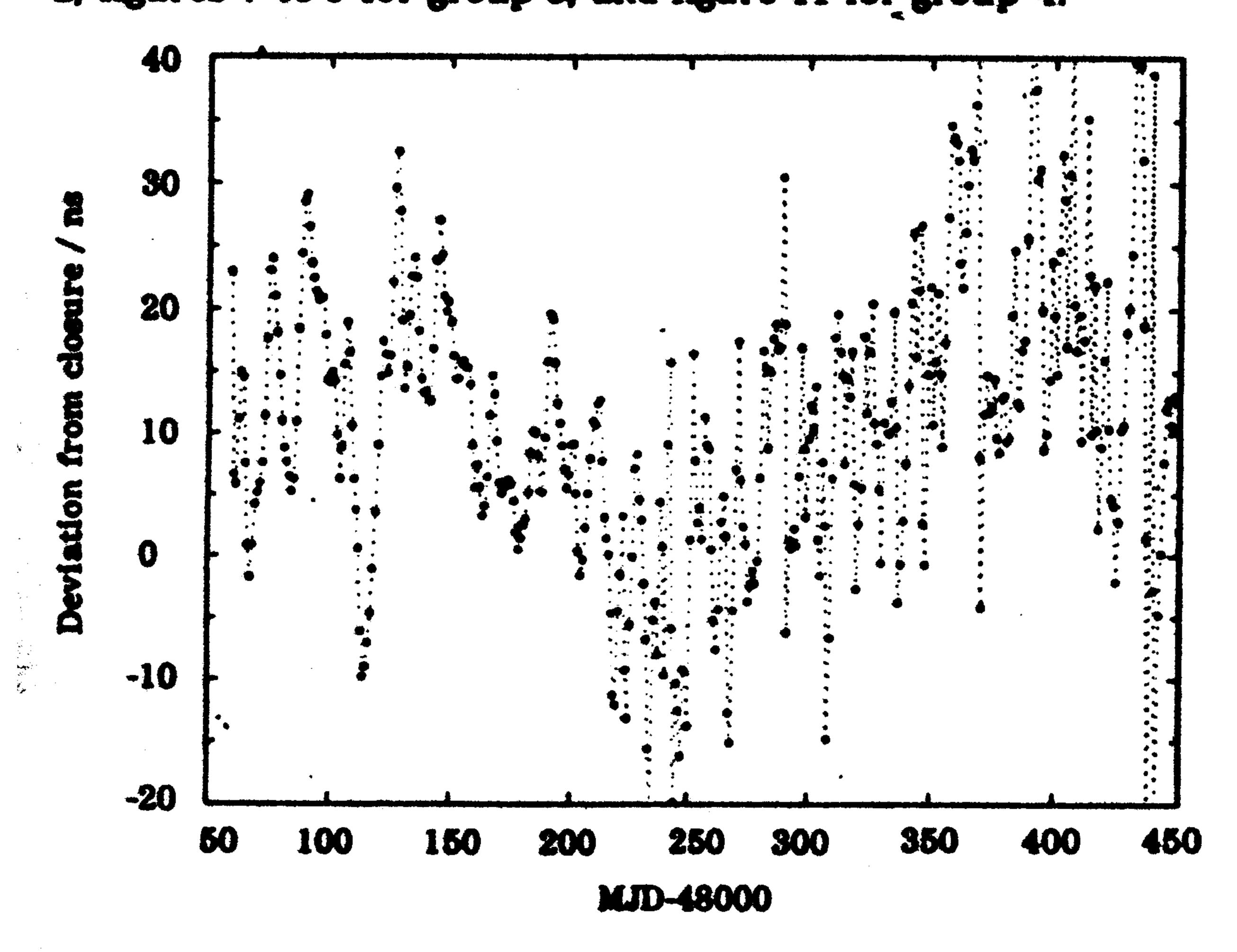
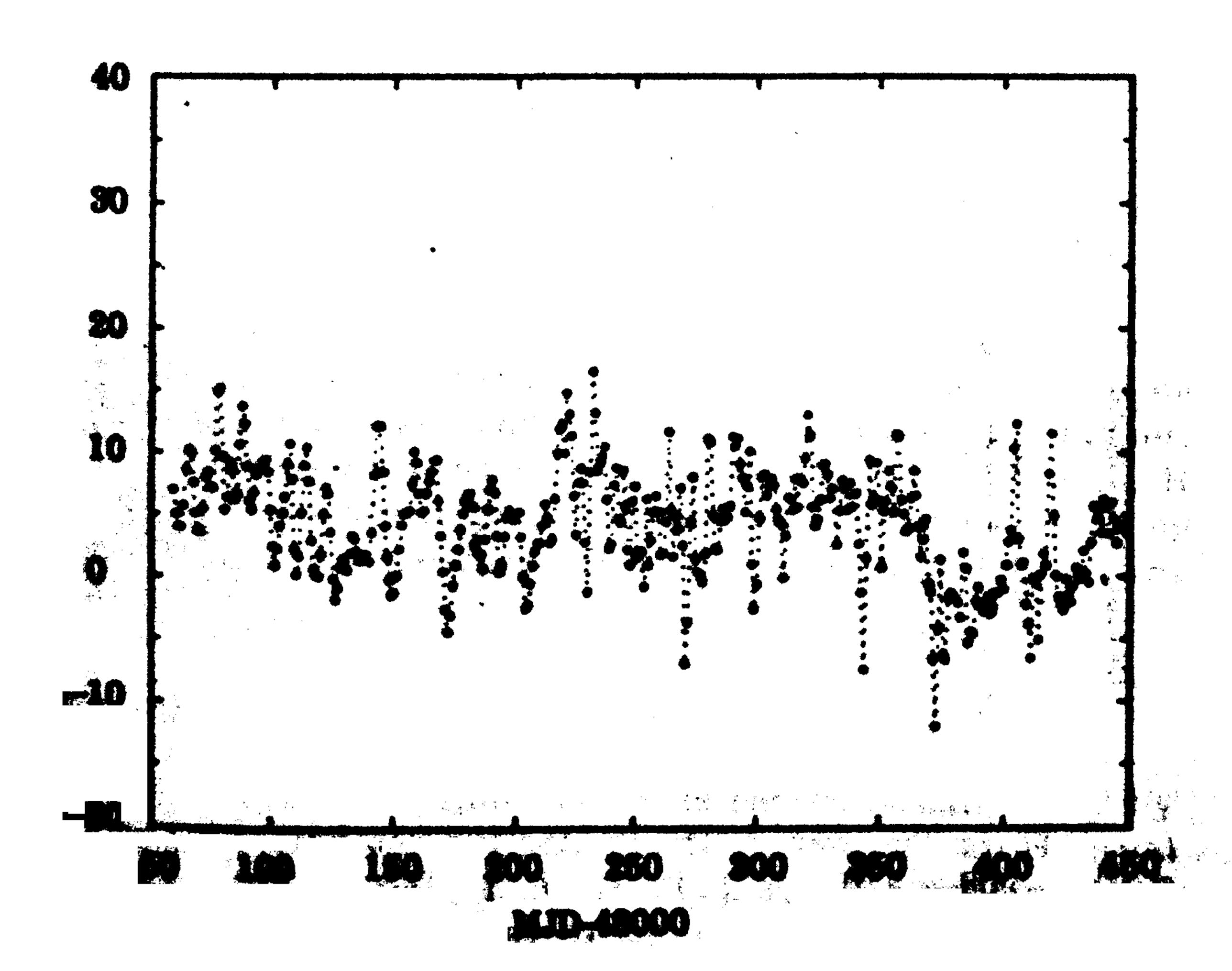


FIGURE 2: Deviation from closure around the world via OP, NIST and CRL with non-corrected data.



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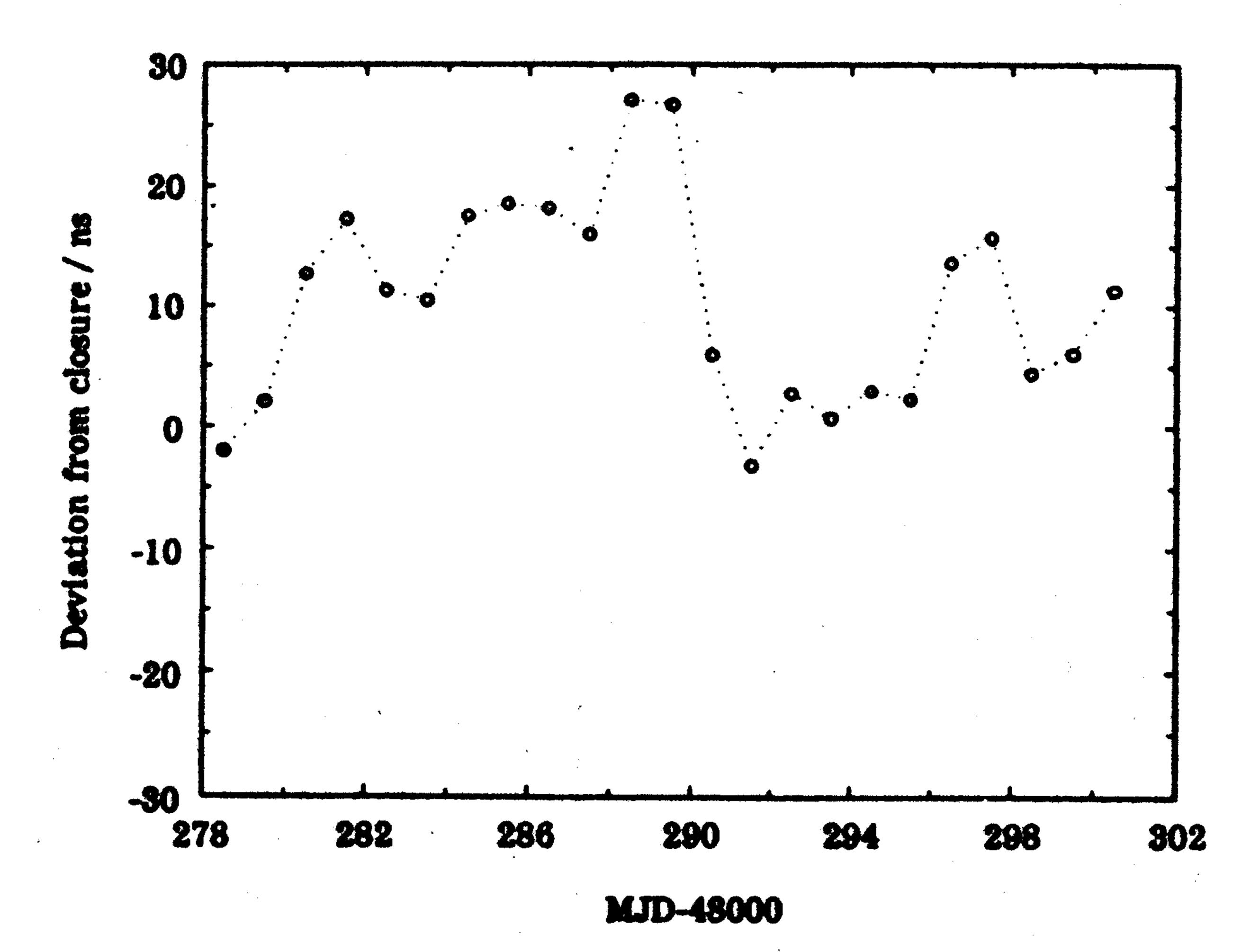


FIGURE 4: Deviation from closure around the world via OP, NIST and CRL with non-corrected data.

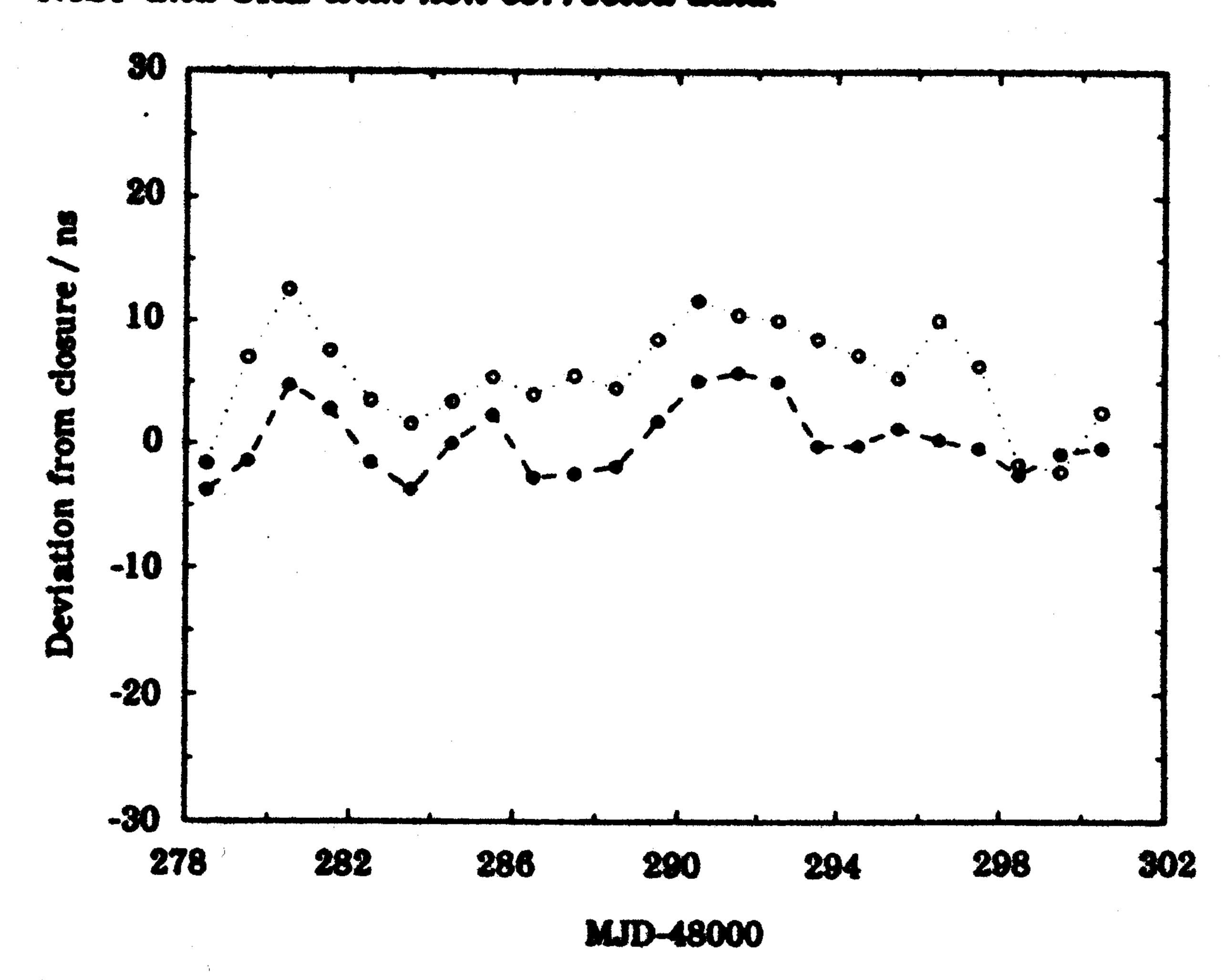


FIGURE 5: Deviation from closure around the world via OP, NIST and CRL with data corrected for measured ionospheric delay and precise ephemerides from DMA (open circles) or JPL (filled circles).

4.2 Discussion of the results

4.2.1 Precision of the time transfer

The precision of the time transfer, and thus the effect of ephemerides on it, can be estimated from the scatter of the difference between unfiltered and filtered data, as stated in section 3.1. This procedure yields values that range from 3 ns to 6 ns, depending on the length of the link and on the ephemerides used. The best result (2.4 ns) is for the OP-NIST link (the shortest one) using the JPL ephemerides of the GIG'91 campaign. Such values are estimates of the precision of one single 13 min measurement. Given that there is measurement noise on the time measurements and on the ionspheric delays, at the level of a few nanoseconds, this implies that the contribution of the ephemerides is generally down to 1 ns, or even less, when using any of the precise ephemerides. This, in turn, implies that the precision of the ephemerides is at the level of one metre.

42.2 Difference france france

From the figures presenting corrected data, it can be seen that the bits of the three links is generally not zero, and the decidation beautiful boundance can peach 15 mg. As noted in decidon 2, this can have a member of causes and it is not appropriate how to seepant her the absolute value of the deviation from closure. But it all cases, the differences between the possible using different sphemerides can easily be interpreted.

It is evident from the figures that, in general, results using different ephemerides follow the same pattern with a more or less constant offset of a few nanoseconds (The sole exception to this is the result with NGS ephemerides obtained in the first few days of the series shown in figure 7). This behavior can be related directly to a global rotation between the frames of the ephemerides, as explained in section 3.2. To check this, we have determined the best-fitting 7-parameter transformation between several of our satellite ephemerides.

From this, for example, it is found that the transformation from CODE to DMA, computed for 7 days during the July 92 period and 7 days during the November 92 period, consists mainly of a scale factor of 5×10^{-8} , which has almost no effect on the closure, and of a rotation of -0.015" about the Z axis, which exactly accounts for the offset of 4 ns between the results with CODE and DMA ephemerides (figures 7-8 and 11). Incidentally, the scale factor is certainly due to CODE and DMA using different values for the gravitational constant GM of the Earth. In a similar analysis, it is found that the transformation from the GIG'91 JPL ephemerides to the DMA ones consists also in the same scale factor, and a rotation about the Z axis of -0.013". This accounts for the offset clearly present between the two results of figure 5.

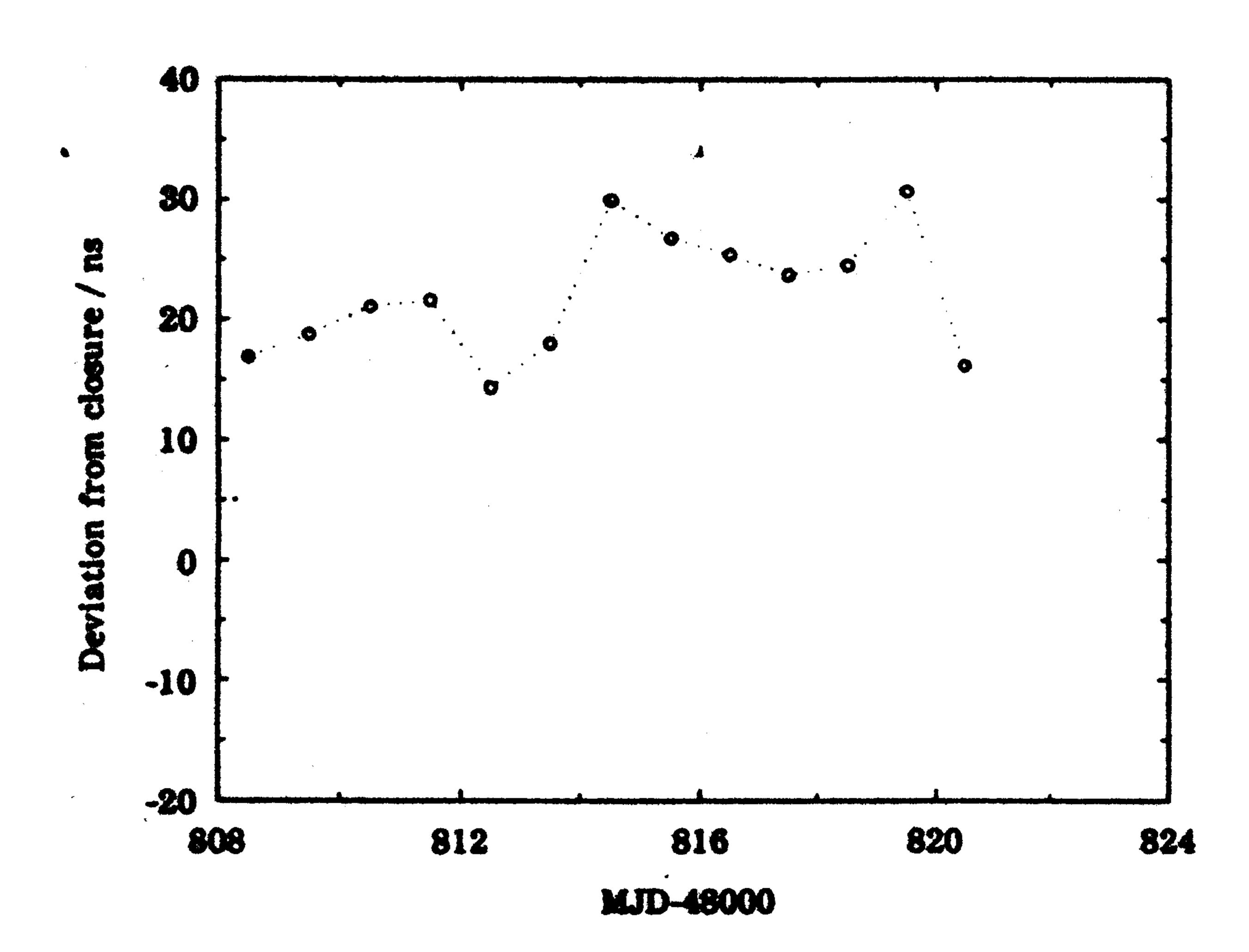
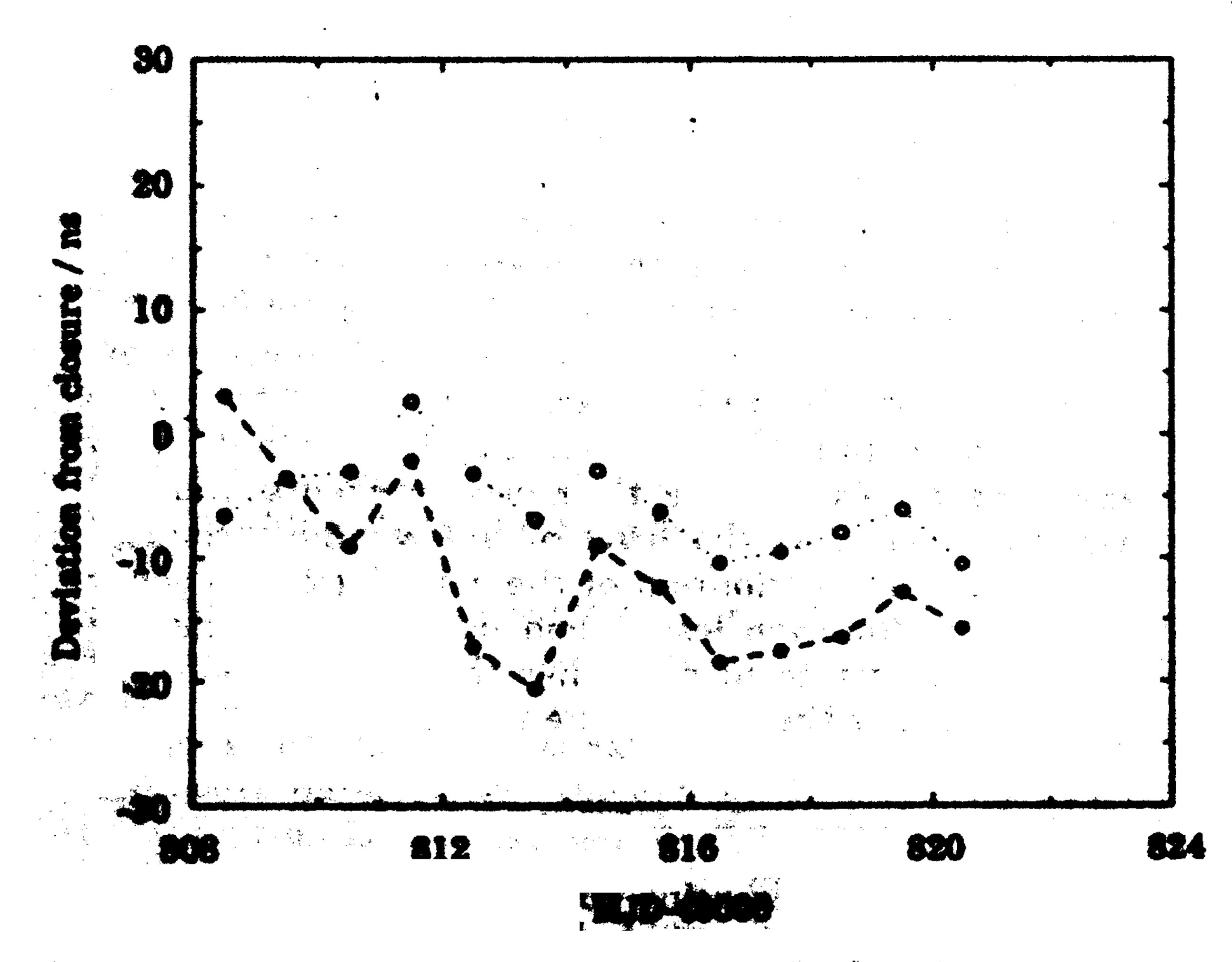


FIGURE 6: Deviation from closure around the world via OP, NIST and CRL with non-corrected data.



Picker 7: Devices of Front selection because the world old OP, NET and CRE with data corrected for measured temperation like and precise aphenocials from DMA (open circles) or NGS (filled stroke).

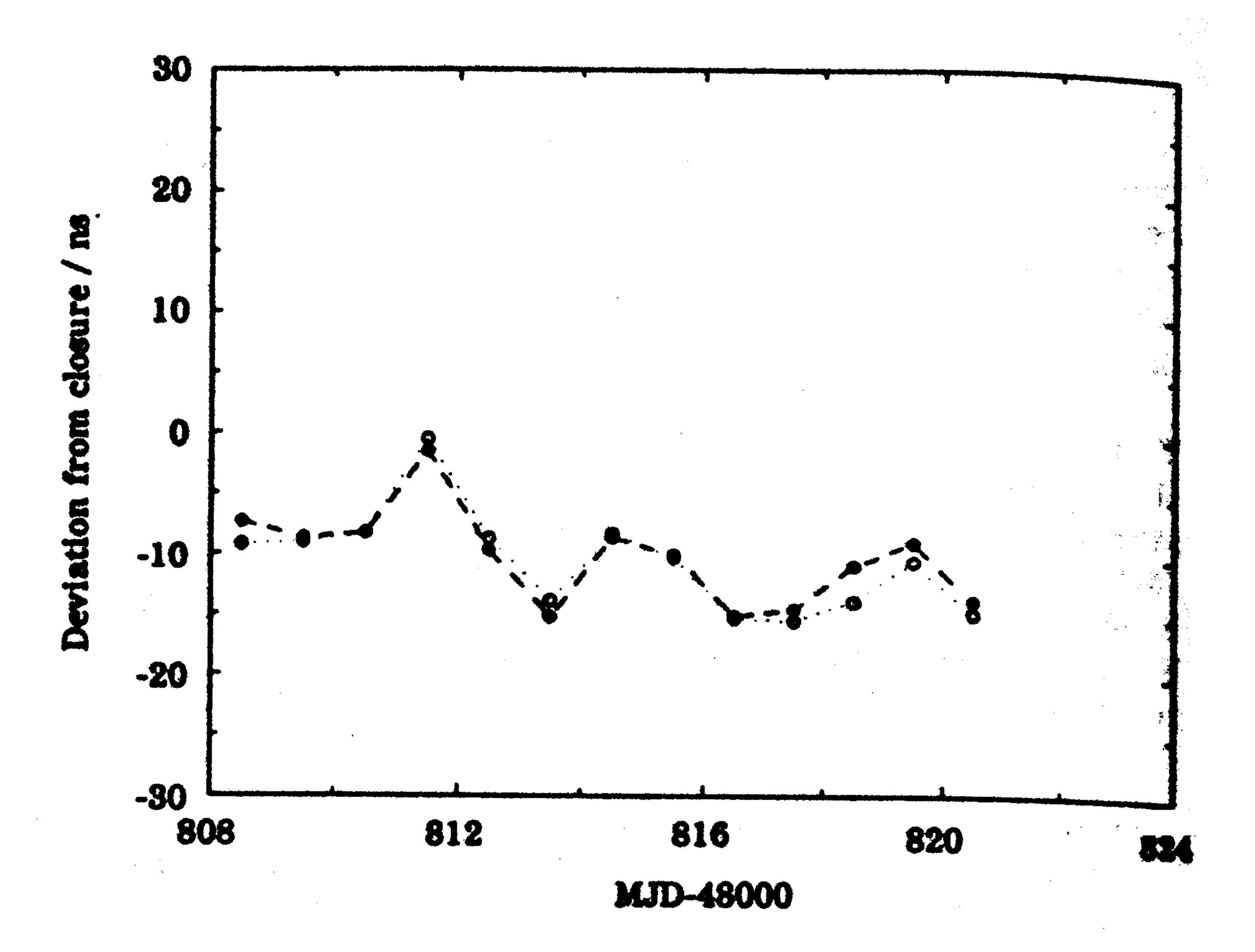


FIGURE 8: Deviation from closure around the world via OP, NIST and CRL with data corrected for measured ionospheric delay and precise ephemerides from CODE (open circles) or ESA (filled circles).

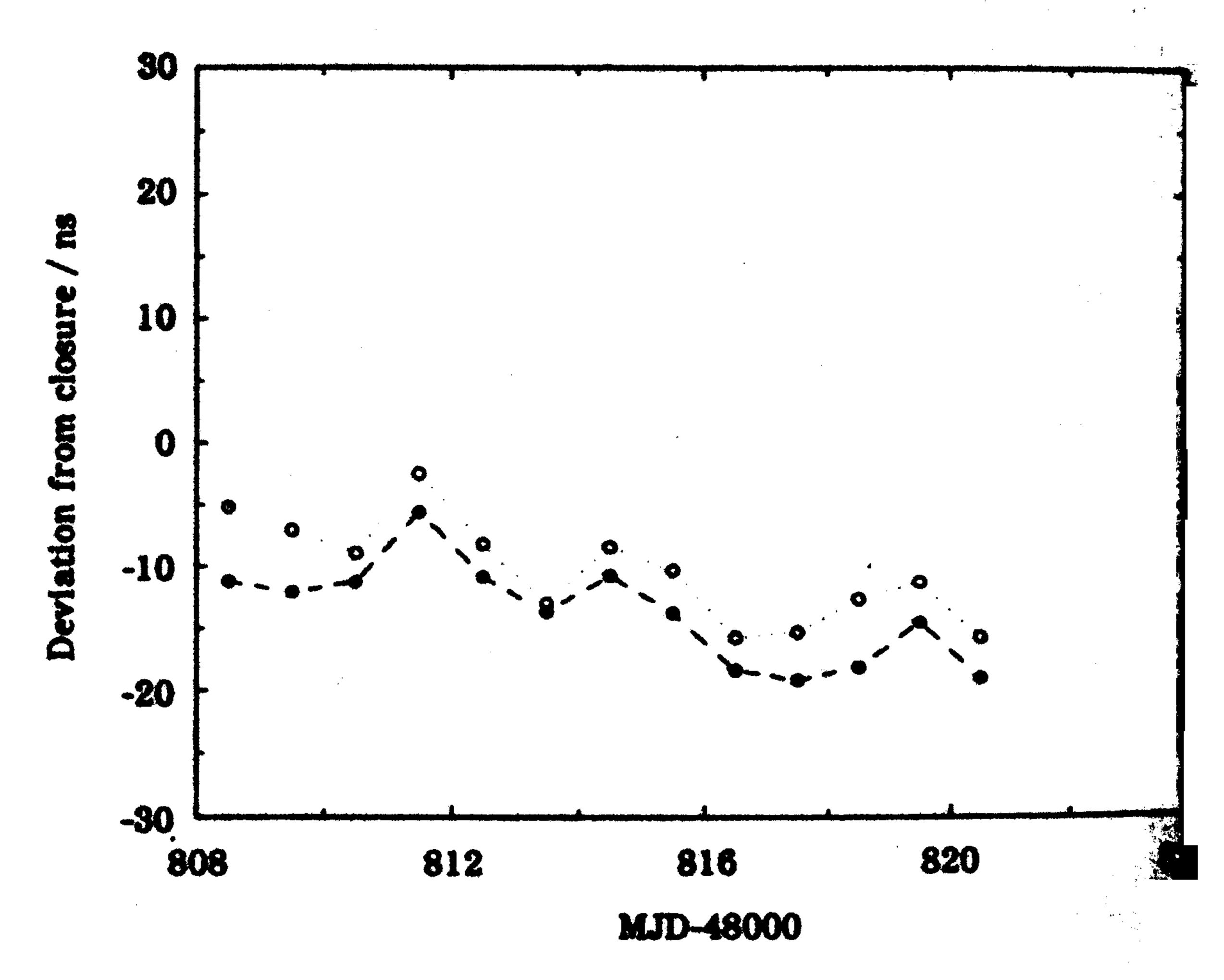
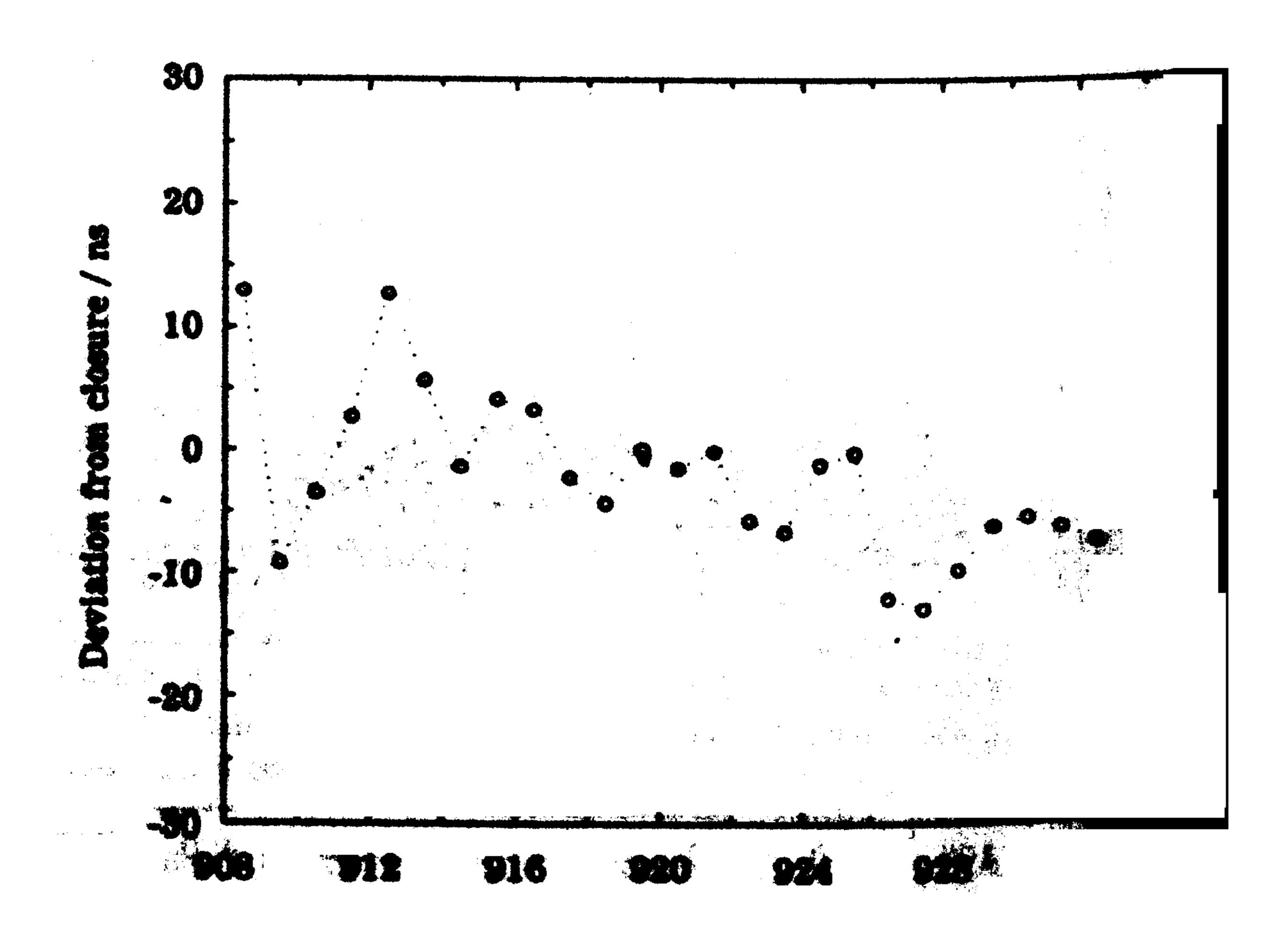


FIGURE 9: Deviation from closure around the world via III NIST and CRL with data corrected for measured ionosphere delay and precise ephemerides from JPL (open circles) SIO (filled circles).



PROPERTY: Development from closure property fills.

NEST and CRL total mon-corrected data.