USE OF IGS IONOSPHERE PRODUCTS IN TAI

Peter Wolf and Gerard Petit
Bureau International des Poids et Mesures
Pavillion de Breteuil, 92312 Sèvres Cedex, France

Abstract

Several IGS (International GPS Service) analysis centers now provide ionosphere products in the form of global ionosphere maps. Starting in August 1999, the ionosphere products of the IGS CODE (Center for Orbit Determination in Europe) analysis center are used for the ionospheric correction of several long- and medium-distance time links in the TAI network. We show the improvements in stability and accuracy resulting from the use of the IGS products, rather than the standard broadcast Klobuchar model for the ionosphere. When compared to ionospheric corrections from on-site dual-frequency measurements with non-calibrated receivers (the method previously used for two long-distance links), we see roughly equivalent stability, but improved accuracy and reliability, due to the adjustment of satellite and receiver biases in the IGS solution and to the large number of receivers used by the IGS. We expect that in the near future several more time links will be corrected for ionosphere using the IGS products, which should prove advantageous, especially in light of the upcoming strong ionospheric activity due to the solar maximum expected around 2001.

I. INTRODUCTION

When using GPS to compare distant clocks, the ionospheric delays of the received signals can lead to significant errors and, therefore, need to be measured or estimated. This effect becomes even more important during periods of strong solar activity (like during the solar maximum expected around 2001). Up to recently all time links in the TAI network were corrected for the ionospheric delay using either the GPS broadcast Klobuchar [1] model or on-site ionospheric measurements using dual-frequency receivers. The latter was used mainly for the two long-distance links OP(France) – NIST(USA) and OP – CRL(Japan). Starting in September 1998 a new method based on ionospheric maps provided by the CODE (Center for Orbit Determination in Europe) International GPS Service (IGS) analysis center was studied. This study followed the repeated breakdown of dual-frequency receivers used for the two long-distance links and aimed at finding a method that provided improved reliability, whilst not degrading, or even improving, stability and accuracy. By July 1999 the results (see Section III) were found conclusive and the new method was introduced on a routine basis for the two aforementioned long-distance links and three medium-distance links: CRL – AUS(Australia), OP – INPL (Israel), and NIST – USNO (USA). The main criteria for selecting the links are a minimum baseline > 2000 km (for short baselines the improvement with respect to the broadcast model is not significant; see section III), data in the standard GGTTS [2] format (for practical implementation), and relatively small measurement noise (so the improvement would be visible).

The CODE ionosphere maps are available via anonymous ftp to any interested user free of charge. For more detail see, for example, the CODE ionosphere homepage at http://www.cx.unibe.ch/aiub/ionosphere.html. For a detailed description of the CODE solutions see [3],where these are also compared to those provided by other IGS analysis centers.

In Section II, we briefly describe the CODE ionosphere maps and the way they are used to correct for the ionospheric delays in GPS observations and GPS common-view time transfer. We present the results of our study in terms of reliability, stability, and accuracy in Section III, with a discussion and conclusion in Sections IV and V.

II. THE IGS IONOSPHERIC PRODUCTS AND THEIR USE IN TAI

The CODE ionospheric products are provided in the form of daily IONEX (IONosphere EXchange format) files, each of which contains 12 global TEC (Total Electron Content) maps, one for each two-hour period of that day. Each TEC map contains zenithal values for the total electron content and its rms in a 2.5° x 5° latitude, longitude grid covering all longitudes and latitudes from +87.5° to −87.5°. Each IONEX file also contains a set of satellite DCBs (Differential Code Biases) which characterize the time interval between the emission of the GPS code on the two carrier frequencies. The TEC maps are obtained from global solutions using code and carrier phase data from 110 to 130 geodetic dual-frequency receivers distributed worldwide. In these solutions satellite and receiver specific biases (DCBs) are adjusted for each satellite and each receiver. In the absence of a receiver with an absolutely calibrated DCB, an arbitrary condition is imposed (all satellite DCBs add to zero), which implies that all adjusted DCBs are offset by a global, unknown constant. Nonetheless, this method ensures a relative calibration of all receiver and satellite DCBs. For real-time applications predicted IONEX files are made available by CODE, with rapid solutions provided after 1 day and final solutions within 6 days.

For any electromagnetic signal the ionospheric group and phase delays are related to the total electron content along the trajectory [5]. This can be determined from the CODE IONEX files by temporal and spatial interpolation of the TEC maps to obtain the zenithal value for the point and time where the signal crosses the nominal mean height of the ionosphere (450 km) and then mapping this value onto the signal trajectory [5]. In the case of common views, the observations on both sides need to be corrected by the thus-obtained group and/or phase delays, but it is not necessary to include satellite DCBs, as these cancel in the common view. When the aim is to compare locally measured ionospheric delays with those obtained from the TEC maps (see section III.3), satellite DCBs need to be taken into account in the latter, as they always affect the measurements.

Note that all data corrected for the ionospheric delay by on-site measurements or the CODE TEC maps were also corrected for satellite ephemerides errors using IGS post-processed precise ephemerides. This was not done when using the broadcast model for the ionospheric delays, as in this case the ionospheric error is largely dominant.

III. RESULTS

III.1. RELIABILITY

When using the on-site measurements at OP, NIST, and CRL to correct the two long-distance links, one relies on three dual-frequency receivers located at the laboratories. A failure of either of these receivers renders the use of on-site measurements impossible, with a resulting degradation of the stability and accuracy of the link. This was the case for both links (failure of the receiver at the BIPM used for OP) in March, April, and October 1998 and for the OP-CRL link (failure of the CRL receiver) in September 1998.

The CODE ionospheric maps are based on data from 110 to 140 receivers and are, therefore, much more robust and less sensitive to the failure of any particular receiver, especially when the laboratory is situated in a region with a high density of IGS stations (e.g. Europe or North America).

Consequently, using ionosphere maps presents a vast improvement in reliability with respect to on-site measurements.

III.2. STABILITY

Over short baselines (< 1000 km) the stabilities of the common views using the three available methods for ionospheric corrections (broadcast model, on-site measurements, or TEC maps) are equivalent except for integration times of ~ ½ day where the broadcast model shows a daily periodic effect that is not present for the other two methods. This is shown for the OP-SP(Sweden) link in Figure 1. For TAI, GPS common views are smoothed over five-day periods, for which the stabilities of the three methods are indistinguishable (see Fig. 1).

Figures 2 and 3 show the stabilities of the common views using the broadcast model or the TEC maps for NIST-USNO and CRL-AUS for the May 1999 data. A significant improvement in stability when using TEC maps can be seen for all integration times. In particular, an improvement for $\tau = 5$ days, significant for TAI, is evident.

Figures 4 to 6 show stabilities of long-distance links for all three methods when looking at monthly data sets. We have looked at all such plots for September and October 1998 and February to June 1999. The "typical," i.e. most frequently observed, result is that of Fig. 4 : roughly equivalent stability when using on-site measurements or TEC maps (with, in general, a very minor advantage for on-site measurements) and significant improvement of both with respect to the broadcast model. This is also confirmed when looking at the whole block of five-month data for 1999 (Fig. 7 and 8). However, for some monthly sets, on-site measurements seem to be more stable than TEC maps (Fig. 5) and for others the opposite may be the case (Fig. 6).

Note that for all stability plots data were treated as equally spaced which of course was not the case. In particular, the data from on-site measurements showed gaps of up to one day, with one isolated case of a two-day gap.

III.3. ACCURACY

Table 1 shows the difference in the ionospheric delays obtained from on-site measurements and TEC maps (using the satellite DCBs) averaged over monthly data sets for OP, NIST, and CRL. Only the ionospheric delays calculated for the thirteen-minute tracks of the local NBS-type (single-channel) receivers were used, even in the case where more ionospheric data were available (NIST uses a NIMS-type dual-frequency receiver which provides "all-in-view" ionospheric data). The quoted sigmas are the standard deviations of the data sets.

The observed mean values need not be zero even if the receivers used for the on-site measurements were absolutely calibrated (determination and correction of the receiver DCBs), as the delays from the TEC maps are affected by a global offset in the satellite DCBs (see Section II). However, the values should be equal for the three laboratories if the receivers were absolutely or differentially (which is sufficient for common views) calibrated. This is clearly not the case, which, most likely, is due to the lack of differential calibrations of the receivers, as no calibration campaigns have taken place (at least not recently). Furthermore, CODE determines a set of satellite and receiver DCBs with each solution (up to an arbitrary constant), which is equivalent to repeated differential calibrations of the participating receivers, so a bias in the results from the TEC maps is likely to be significantly smaller than the one resulting from the non-calibrated receivers used for the on-site measurements. Note, also, that the differences vary in time for each laboratory (variations of up to 2 ns). This could be due either to a variation of the global offset in the satellite DCBs determined by CODE or to a variation in the receiver DCBs at the laboratories (due, e.g., to local environmental effects). In the former case the difference between the laboratories should stay constant (they are all affected by the same global offset), which is clearly not the case; indeed the differences between two labs vary as much as the values for individual labs (up to 2 ns). For these reasons the TEC map derived ionospheric corrections are likely to be considerably more accurate (up to a global offset, which cancels in common views) than the presently available corrections from non-calibrated on-site measurements.

IV. DISCUSSION

One would expect that common views corrected by on-site measurements on one hand and TEC maps on the other should differ by the difference of the means shown in Table 1. For example, NIST-OP common views for February 1999 should differ by an average 7.6 ns. However, when looking at the actual common views they differ instead by an average 9.4 ns, and a similar discrepancy can be observed for all other months. This is due to the fact, that in the latter case only a subset of the observations used in Table 1 participate, namely those that look out over the Atlantic. Figure 9 shows the differences between on-site measurement and TEC-map-derived ionospheric delays at NIST for the month of May 1999 as a function of azimuth. The mean value for the observations participating in the common views with OP (azimuth smaller than 100°) is 1.7 ns smaller than the average of the whole data set (given in Table 1). This pattern is observed systematically for all months of observation for NIST, which is not the case for the OP or CRL data. In fact, Weiss et al. [6] have carried out a detailed study of the ionospheric measurement system at NIST and have observed directional biases due to the front-end antenna system that can reach several nanoseconds and would, therefore, explain the discrepancy mentioned above.

Based on the results shown in Section III the BIPM, in agreement with the CCTF working group on TAI, decided to use TEC maps for the two long-distance links (NIST-OP and CRL-OP) and three medium-distance links (OP-INPL, USNO-NIST, and AUS-CRL) from August 1999 onward. Consequently timing laboratories are faced with a decision concerning local ionospheric measurements in the future. Are the investments and efforts spent on obtaining those measurements still justified? What would be the best strategies for the future? It seems to us that the most advantageous strategy for the timing community would be the combination of on-site measurements and global TEC maps, taking advantage of the slightly better stability of the local measurements and the accuracy and reliability of global solutions. The operationally easiest way of achieving this is to buy geodetic (or geodetic-type) dual-frequency, multi-channel receivers at the timing labs and participate in the IGS as regular IGS stations using the data of these receivers. In that case the TEC maps would be determined using also the data from the on-site measurements (the local geodetic receivers), providing improved stability for common views from those locations, whilst still ensuring reliability and accuracy (adjustment of the local DCBs) due to the global solution. In fact, such developments are already on the way for many timing labs for a number of other applications (carrier-phase frequency/time transfer, determination of precise station coordinates, tropospheric corrections, etc.) and, when operational will, therefore, also serve for improved ionospheric corrections without any additional effort by the labs.

V. CONCLUSION

We have described a new method of correcting medium- and long-distance GPS common-view time links in the TAI network for the effect of ionosphere, based on global TEC maps provided by the CODE analysis center of the IGS. This method has been used routinely in TAI production since July 1999. We have shown that it provides similar stability as the best previously used method (on-site dual-frequency measurements), whilst vastly improving reliability and accuracy. For the future we suggest that timing labs become regular IGS stations where possible, which would likely improve the IGS global TEC maps for the location of the lab and, therefore, the stability of the TEC-map-corrected common views, whilst guaranteeing improved reliability and accuracy. Additionally, participating in the IGS can provide other advantages for timing labs, like precise station coordinates, tropospheric corrections, carrier-phase frequency/time transfer, etc.

ACKNOWLEDGMENTS

We thank the CODE analysis center for making its products freely available and, in particular, Stefan Schaer for fruitful exchanges concerning the ionosphere data. Thanks are also due to Marc A. Weiss for pointing out reference [6] and Philippe Moussay for help with hard and software.

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TABLES

$MSIO_{measure} - MSIO_{IGS}$ /ns						
Period	OP		NIST		CRL	
	mean	σ	mean	σ	mean	σ
09 1998	8.1	2.1	1.2	2.7		
10 1998			1.1	3.0	3.1	5.1
02 1999	9,1	2.5	1.5	2.7	4.2	5.5
03 1999	7,8	2.3	2.0	3.5	4.4	5.9
04 1999	7.5	1.9	-0.2	2.3	5.1	3.9
05 1999	7.1	1.8	-0.2	2.4	3.2	3.7
06 1999	7.7	1.9	0.3	2.6	2.8	4.6

Table 1: Monthly averages of the differences in ionospheric delay determined using on site measurements (measure) or TEC maps (IGS). The σ are the standard deviations of the monthly data sets.

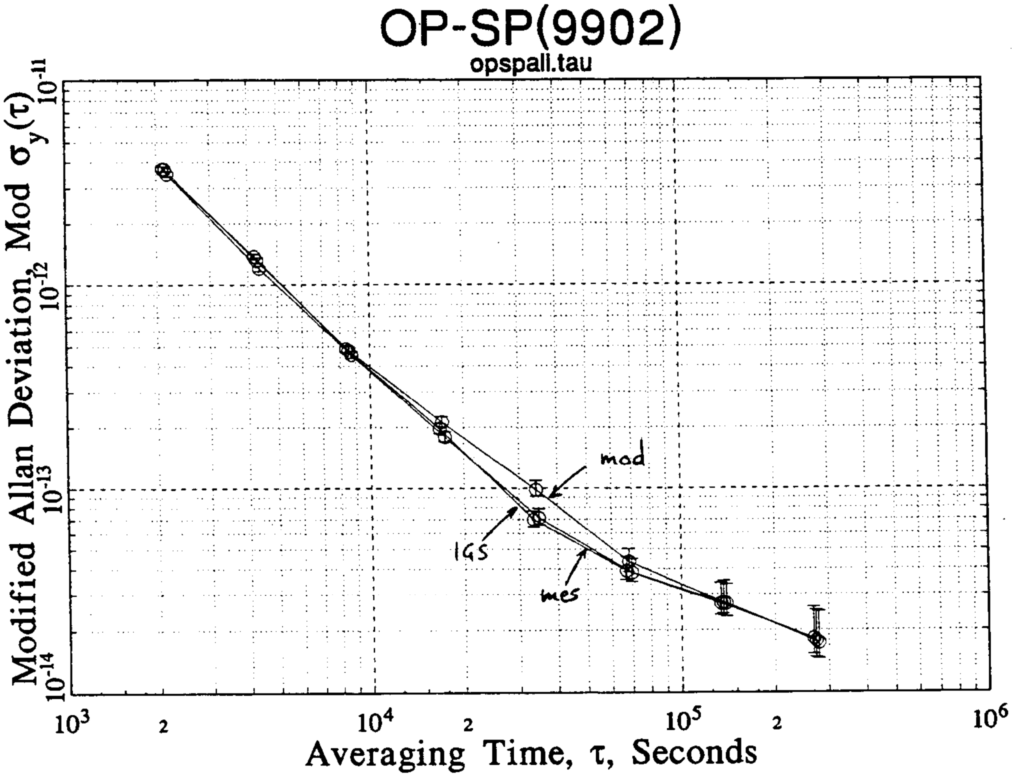
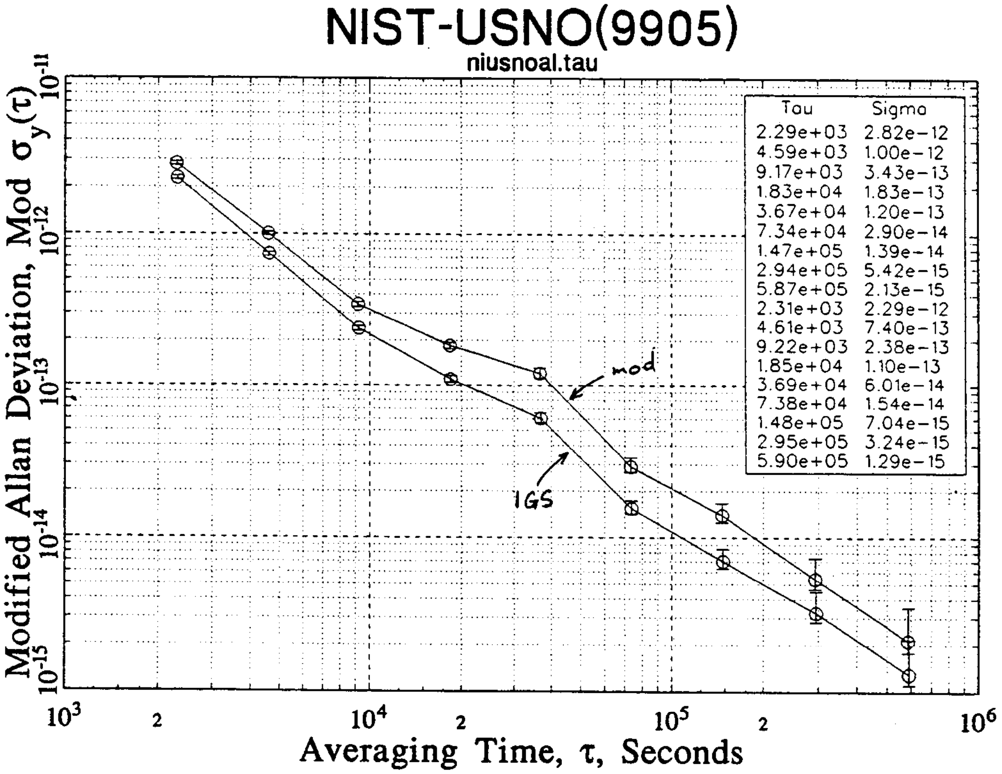


Figure 1: Stabilities of short-distance common views between SP (Sweden) and OP (France) for February 1999 data using three different methods for ionospheric corrections: standard Klobuchar model (mod), on-site measurements (mes), and CODE Tec maps (IGS).



Tau	Sigma
2.29e+03	2.82e−12
4.59e+03	1.00e−12
9.17e+03	3.43e−13
1.83e+04	1.83e−13
3.67e+04	1.20e−13
7.34e+04	2.90e−14
1.47e+05	1.39e−14
2.94e+05	5.42e−15
5.87e+05	2.13e−15
2.31e+03	2.29e−12
4.61e+03	7.40e−13
9.22e+03	2.38e−13
1.85e+04	1.10e−13
3.69e+04	6.01e−14
7.38e+04	1.54e−14
1.48e+05	7.04e−15
2.95e+05	3.24e−15
5.90e+05	1.29e−15

Figure 2: Stabilities of NIST (USA) – USNO (USA) common views for May 1999 (labels as in Fig. 1).

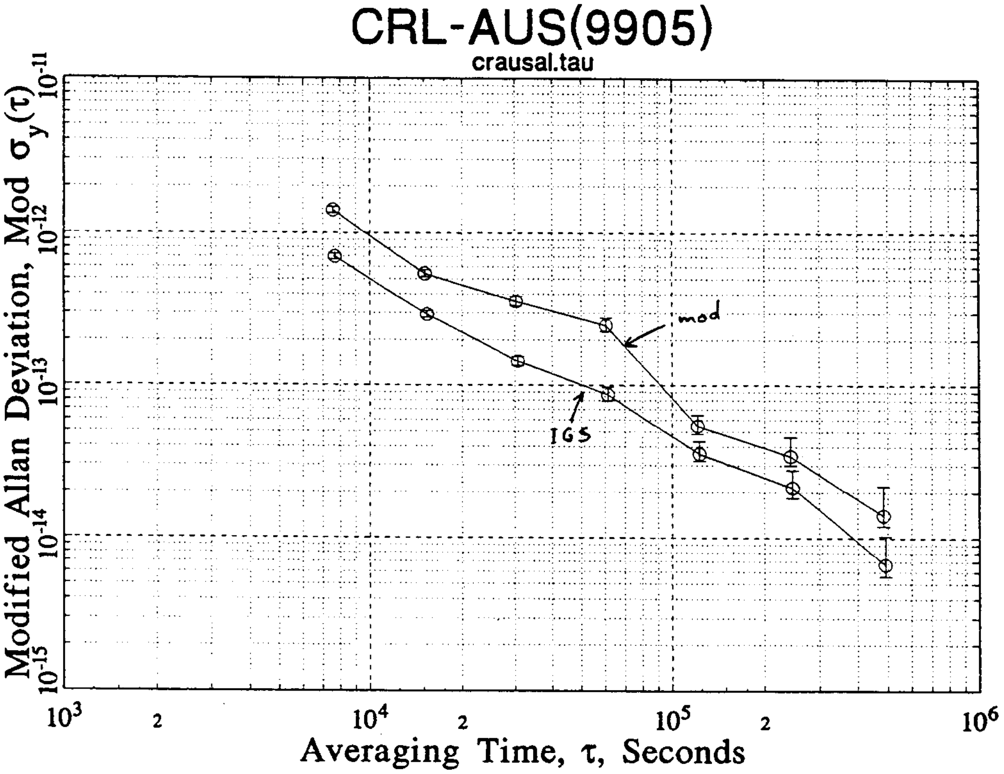


Figure 3: Stabilities of CRL (Japan) – AUS (Australia) common views for May 1999 (labels as in Fig. 1).

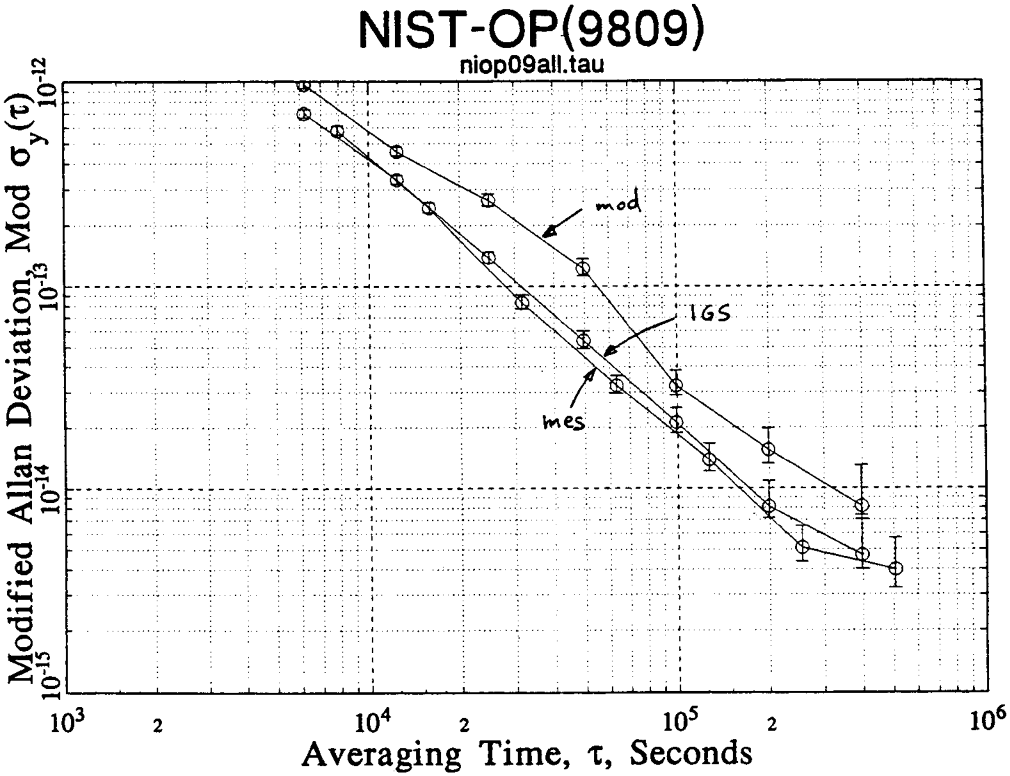


Figure 4: Stabilities of NIST (USA) – OP (France) common views for September 1998 (labels as in Fig. 1).

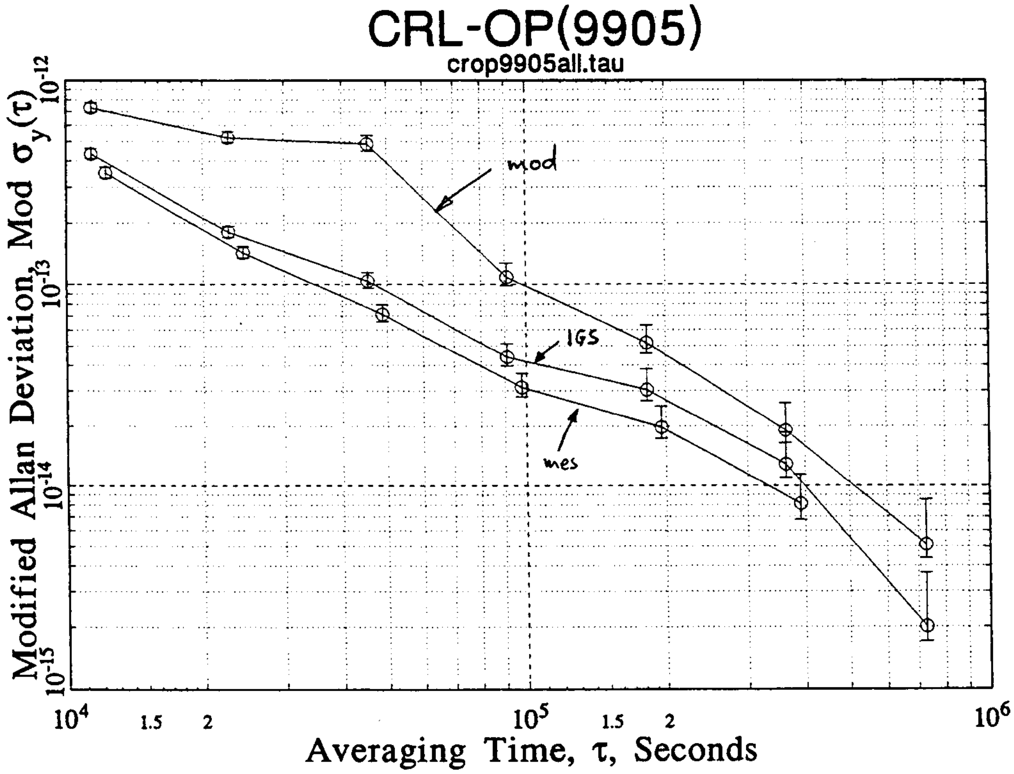


Figure 5: Stabilities of CRL (Japan) – OP (France) common views for May 1999 (labels as in Fig. 1).

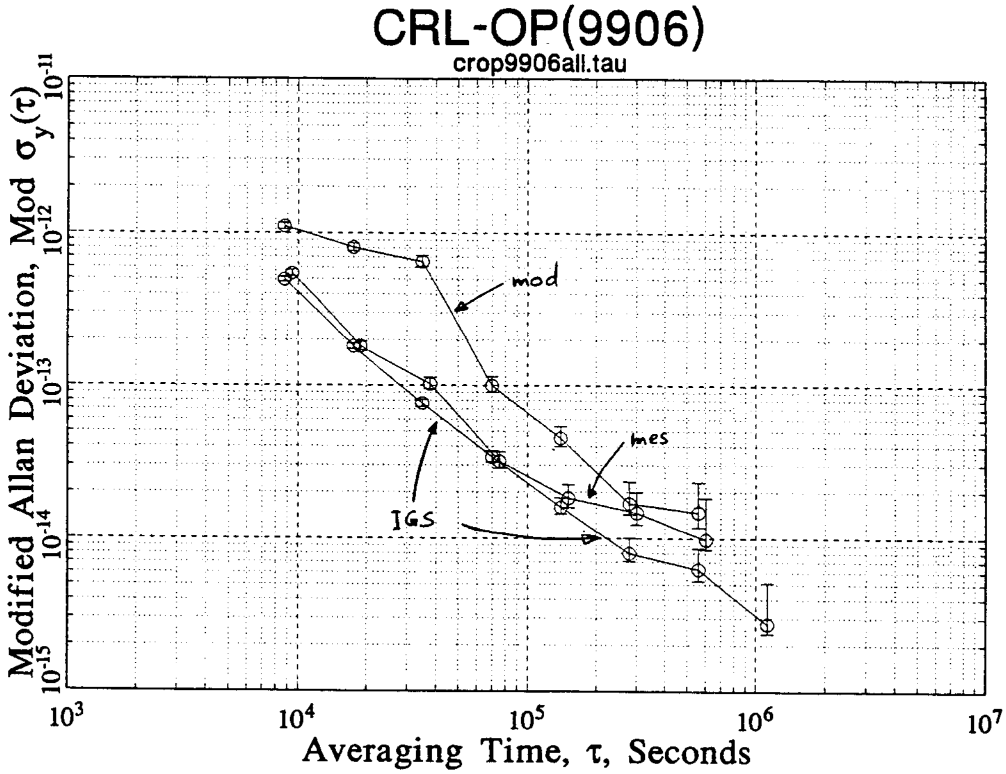


Figure 6: Stabilities of CRL (Japan) – OP (France) common views for June 1999 (labels as in Fig. 1).

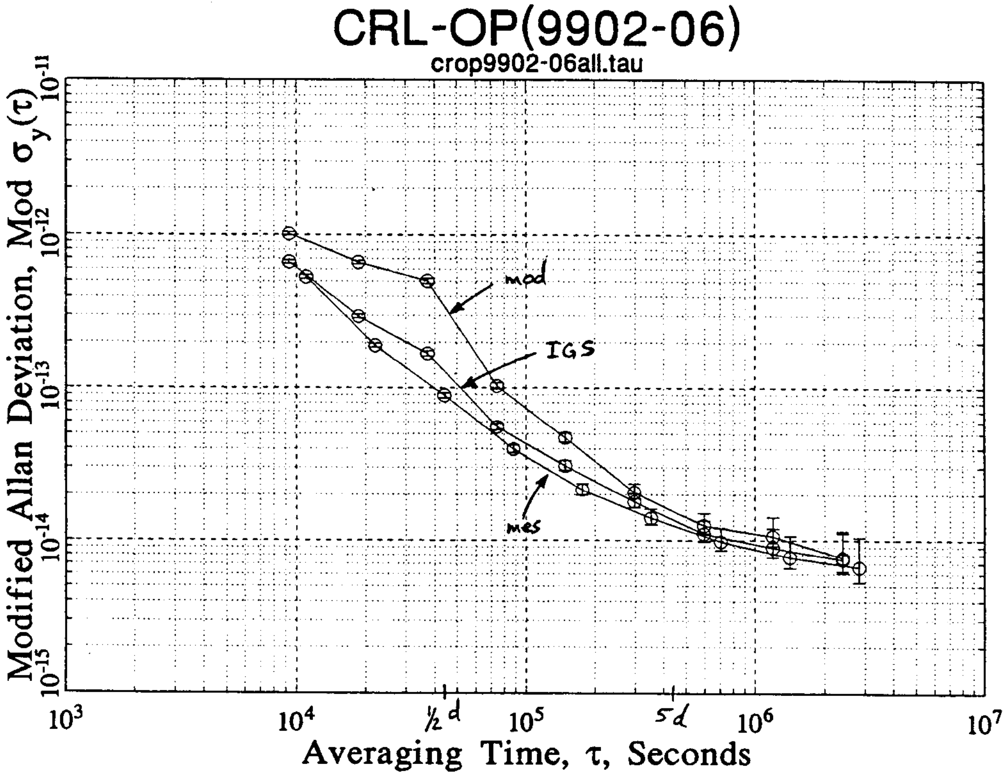


Figure 7: Stabilities of CRL (Japan) – OP (France) common views for February through June 1999 (labels as in Fig. 1).

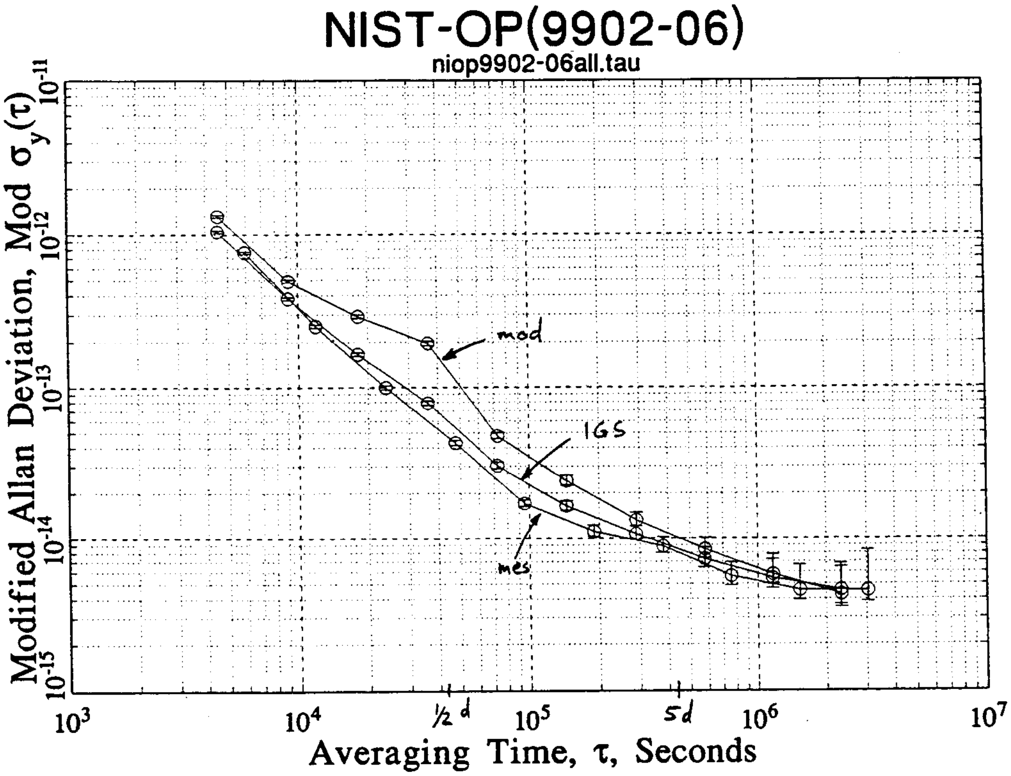


Figure 8: Stabilities of NIST (USA) – OP (France) common views for February through June 1999 (labels as in Fig. 1).

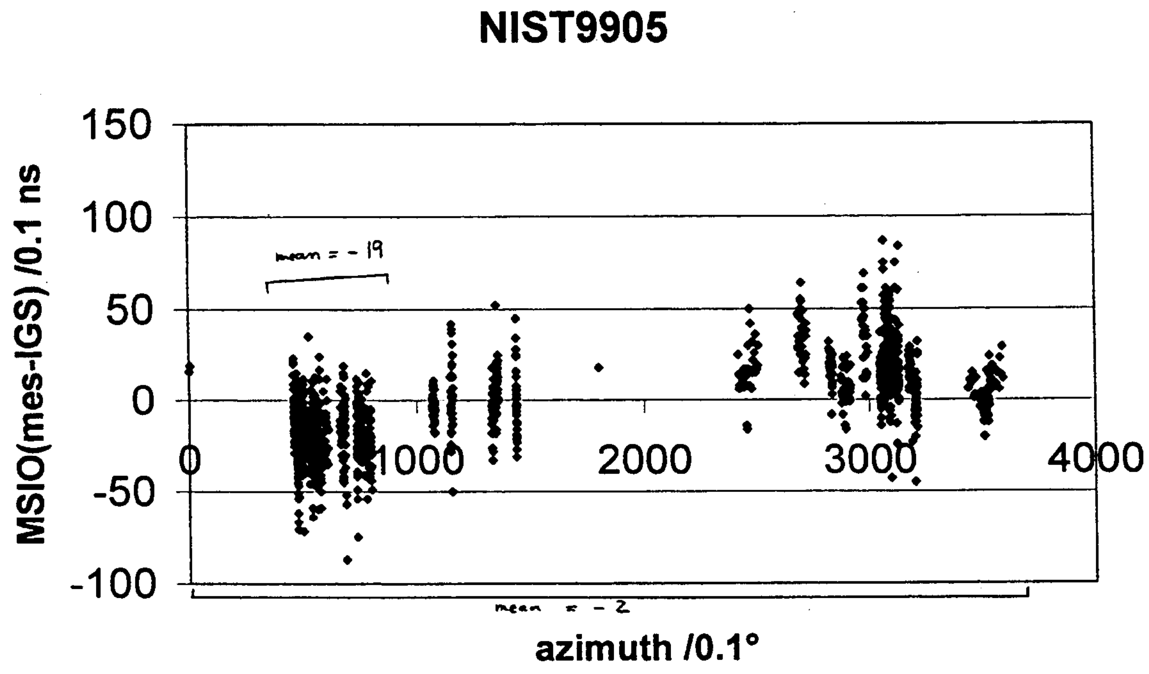


Figure 9: Difference in ionospheric delay determined using on-site measurements (measure) or TEC maps (IGS) as a function of azimuth at NIST for May 1999. Each point corresponds to a 13-minute track of the local NBS-type (single-channel) receiver.

Questions and Answers

DAVID ALLAN (Allan's Time): It seems like, given what Robin Giffard just showed us, that this ought to be a technique that should be studied, since you can use a single frequency to get an absolute value of the TEC.

PETER WOLF (BIPM): What he just said?

ALLAN: Yes.

WOLF: That only works for the receivers where you have phase measurements as well.

ALLAN: Yes.

WOLF: So your standard TTR-6, I'm not sure that you get that out.

ALLAN: You have to have a phase measurement, obviously.

WOLF: Yes.

DEMETRIOS MATSAKIS (USNO): Another possibility would be, every time NIST is looking towards Paris, those maps are picking up a contribution from a receiver in Kansas which is contributing. Have you looked into that possibility?

WOLF: Well, there's not much you can actually look at. I suppose what you're thinking about is that the maps themselves will be biased looking that way or that way, because that way there will be a contribution from a receiver, say, in Kansas which will not exist when looking at the other directions.

What would that contribution be like? If it's the receiver bias of that Kansas receiver, it will be taken out because biases are adjusted for each particular solution. Now, it might be the multi-path of that particular receiver or of a receiver around NIST that contributes to the map and, therefore, corrupts the map in some sense. Now, the only thing I can say about that is that you have several receivers contributing to the map, to some extent the average multi-path of the different receivers. So each geodetic receiver won't typically have the same multi-path effects, because they're locally environment-induced.

It is possible that it could be due to the map, to some extent – the effect we're seeing. That's why I said there's more investigation that should be done. In particular, look at another receiver and see whether that's a similar multi-path effect when compared to the IGS maps. In which case, the case is strong that it would be the receiver. But I've not looked into that in more detail.