STUDY OF TROPOSPHERIC CORRECTION FOR INTERCONTINENTAL GPS COMMON–VIEW TIME TRANSFER

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Abstract

Current practice is to incorporate general empirical models of the troposphere, which depend only on the station height and the elevation of the satellite, in GPS time receivers used for common–view time transfer. Comparisons of these models with a semi–empirical model based on weather measurements show differences of several nanoseconds. This paper reports on a study of tropospheric correction during GPS common–view time transfer over a short baseline of about 700 km, and three long baselines of 6400 km, 9000 km and 9600 km. It is shown that the use of a general empirical model of the troposphere within a region where the climate is similar does not affect time transfer by more than a few hundreds of picoseconds. For the long distance links, differences between the use of general empirical model and the use of a semi–empirical model reach several nanoseconds.

INTRODUCTION

Among the improvements open to GPS common–view time transfer is increased accuracy in the estimation of the tropospheric delay. It has been assumed until recently that, for satellite elevations above 30°, a general empirical model, depending only on the station height and satellite elevation, is sufficient. However, when carrying out common–view time transfer over long distances (9000 km), elevations as low as 20 are unavoidable. Also, different types of receivers use different tropospheric models which can differ by a few nanoseconds for angles of low elevation[1, 2]. Progress can be made by implementing recently established standards for receiver software which include a common model for estimating signal delays arising from tropospheric refraction[3].

Recent comparisons of the models currently used by GPS time receivers with a semi–empirical model based on weather measurements show differences of several nanoseconds[4, 5, 6]. This discrepancy increases for observations performed in hot and humid regions of the world.

This paper reports on comparisons of GPS common–view time transfers performed using the tropospheric models incorporated in the receivers with transfers performed using a semi–empirical model. These comparisons have been carried out for one short baseline of about 700 km, and three long baselines of about 6400 km, 9000 km and 9600 km. It is shown that the use of the general empirical model of the troposphere within a region of similar climate does not affect time transfer by more than a few hundreds of picoseconds, while for the intercontinental GPS time links, differences between the general empirical model and a semi–empirical model reach several nanoseconds.

TROPOSPHERIC DELAY AND ITS MODELS

The troposphere is the lower layer of the atmosphere extending from ground level to the base of the ionosphere. For radio frequencies, delay due to the troposphere ranges typically from about 10 ns for the zenith to about 100 ns for an elevation of 5° : it depends on the thickness of the troposphere and the content of water vapour along the line of sight. Tropospheric delay is commonly expressed as the sum of two components 'dry' and 'wet'. The 'wet' component is due to water vapour and can reach 15 % of the total correction.

At radio frequencies, unlike optical frequencies, the troposphere is a non–dispersive medium. Thus, the tropospheric delay cannot be estimated from two–frequency measurements as can the ionospheric delay. Instead, estimation of the delay relies on the use of one of a number of models[7]. The 'dry' component can be accurately estimated from models based on surface measurements of atmospheric pressure alone. The 'wet' component is more difficult to model, since measurements of meteorological conditions at the antenna site are generally not representative of conditions along the line of sight.

That several tropospheric models have been developed is mainly because of this difficulty in modelling the 'wet' component. Usually the delays are evaluated in the zenith direction. The zenith corrections are then 'mapped' down to lower angles of elevation using mapping functions. Models are either semi–empirical, based on surface measurements of the local temperature, atmospheric pressure and relative humidity, or empirical, based on a general reference atmosphere requiring only the station height and the angle of elevation to the satellite.

Of the semi–empirical models, some of the best known have been developed by Hopfield and Saastamoinen, and are widely used within the geodetic community. In this paper we use as reference a model developed by the Jet Propulsion Laboratory (JPL) for its deep space missions[8, 9]. Evaluated against balloon measurements, it was found that this model is able to predict the zenith tropospheric delays with an accuracy at the subnanosecond level.

The tropospheric corrections currently used by the timing community are computed according to general empirical models which neglect the contribution due to the 'wet' component. Consequently, the errors resulting from these simple models may exceed 3 ns in a one–way range delay at 20° angle of elevation. The three models usually implemented are NBS[10], STI[11] and STANAG[12]. The STANAG model is recommended in recently established standards for GPS time receiver software. In previous papers these models have been compared with one another and with semi–empirical models. Differences can reach several nanoseconds for low elevation angles.

THE EXPERIMENT

To illustrate the possible impact on GPS common–view time transfer of the approximate models of tropospheric delay used in GPS time receivers, four time laboratories, listed below, were chosen. Several criteria contributed to this choice. The basic criterion was the availability of meteorological data recorded at the site. Next, two time laboratories had to be located in the same climatic zone (BIPM and OCA) and the other laboratories had to be situated as far away as possible and in climatic zones as different as possible. This last criterion was the most difficult to fulfil as can be seen from the table below, which lists the geographical latitudes of the sites.

Participating time laboratories in this experiment were:

BIPM, Bureau International des Poids et Mesures, Sévres, France, Lat. = 49 N, H = 127 m,

OCA, Observatoire de la Côte d'Azur, Grasse, France, Lat. = 43 N, H = 1322 m,

USNO, United States Naval Observatory, Washington D.C., U.S.A., Lat. = 39 N, H = 51 m,

CRL, Communications Research Laboratory, Tokyo, Japan, Lat. = 36 N, H = 130 m.

The GPS time receivers operating at the BIPM, the OCA and the CRL used the NBS type tropospheric model, and the receiver used at the USNO used the STI type tropospheric model.

Four GPS common–view time links , listed below, were considered. The short baseline link, BIPM–OCA, was analysed to see if there is any impact of approximated tropospheric delay on GPS common–view time transfer in the same climatic zone. The three long baseline links were considered for their climatic differences and low angles tracks.

BIPM - OCA,	of 700 km, with 32 daily CV possible, according to Inter. GPS CV Sched. No 20,
OCA - USNO,	of 6400 km, with 18 daily CV possible, according to Inter. GPS CV Sched. No 20,
OCA - CRL,	of 9000 km, with 14 daily CV possible, according to Inter. GPS CV Sched. No 21,
USNO - CRL,	of 9600 km, with 8 daily CV possible, according to Inter. GPS CV Sched. No 21.

The BIPM–OCA link was analysed in terms of the available meteorological data for 22 and 23 April 1993, and three other links were analysed for 26 August 1993.

Elevation angles by track and location are given in Figures 1, 5, 9, and 13. For each link, the track was computed at both sites using both the simple empirical model in the receiver and the JPL semi–empirical model based on surface weather measurements. The results are given in Figures 2, 3, 6, 7, 10, 11, 14, and 15. Differences between the two models ranging from 0.4 ns to 1.1 ns for the short baseline link, and from 1 ns to 6 ns for long baseline links, can be observed. Next, the common views between the two sites were computed using the receiver and JPL models. The peak to peak differences between the two computations for individual common views do not exceed a few hundreds of picoseconds for the short baseline link (Figure 4) and reach 5 ns for the long distance links (Figures 8, 12, and 16). For two longest long links, OCA–CRL and OCA–USNO, a clear bias of a few nanoseconds may be observed. This is so because low elevation angles and limited number of common views were available. For the shortest of the long distance links, OCA–USNO, large discrepancies in the results may be seen (Figure 8). This is due to the large differences in the elevation angles at both sites (Figure 5).

CONCLUSIONS

1. The use of a standardized tropospheric model in GPS time receivers is essential for accurate time comparisons.
2. For GPS time links within a region of similar climate, the use of a simplified standard tropospheric model is sufficient for 1 nanosecond accuracy.
3. For intercontinental GPS time links: common views should be performed at the same elevations at each side, the use of a more sophisticated model based on surface measurements should be considered and studied more closely.

Acknowledgements

The experimental part of this work was done at the BIPM thanks to the loan of a commercial cæsium clock from the USNO (Washington, DC, USA). The staff of the Time Section of the BIPM is grateful to the USNO for its generosity.

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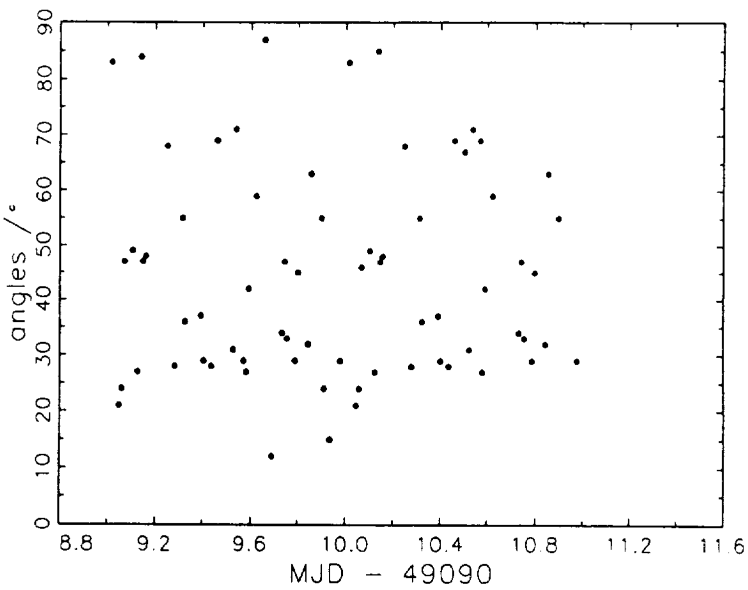

FIGURE 1. Elevation angles of each track on 22-23 April 1993 at the BIPM and OCA. They are the same within 1°.

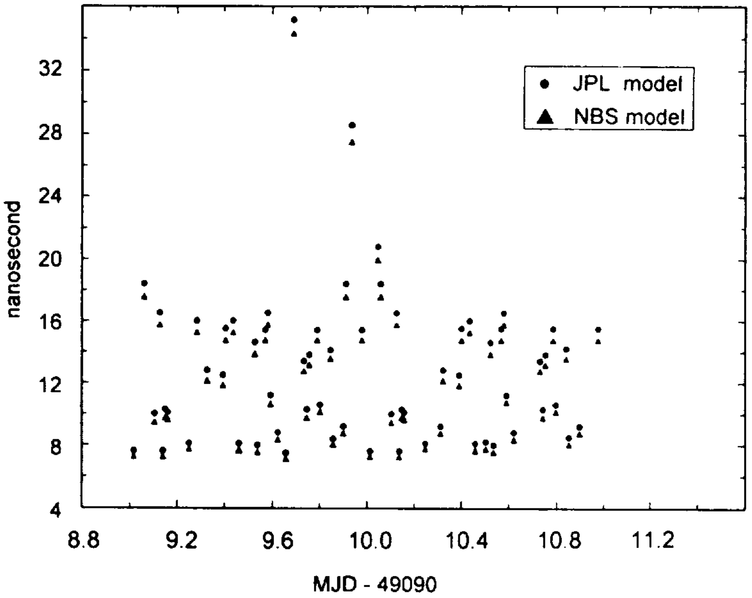

FIGURE 2. Tropospheric delays according to the JPL and the NBS models at the BIPM on 22-23 April 1993 for each track in the direction of the OCA.

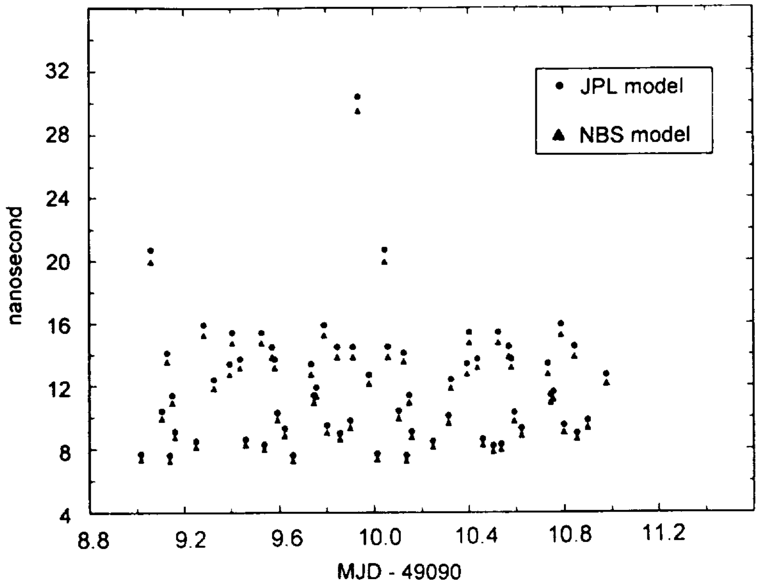

FIGURE 3. Tropospheric delays according to the JPL and the NBS models at the OCA on 22-23 April 1993 for each track in the direction of the BIPM.

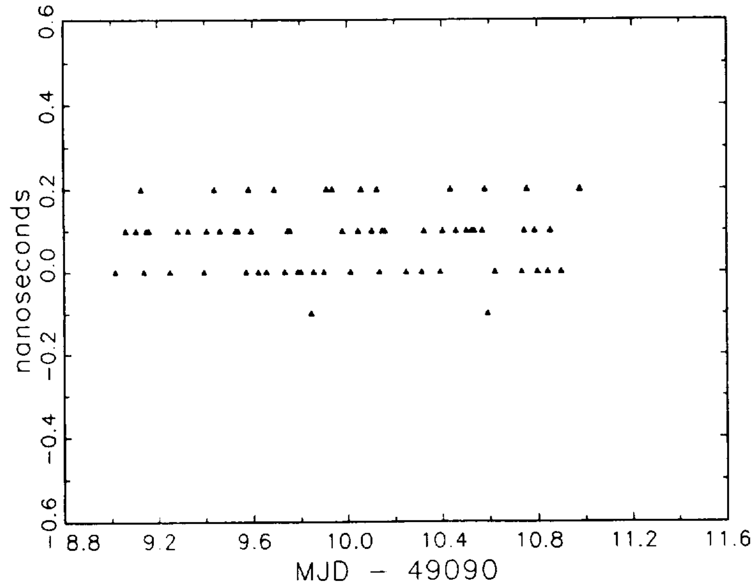

FIGURE 4. [BIPM Cs clock - OCA Cs clock] as obtained by GPS common views with the NBS tropospheric model minus [BIPM Cs clock - OCA Cs clock] as obtained by GPS common views with the JPL tropospheric model for each track on 22-23 April 1993.

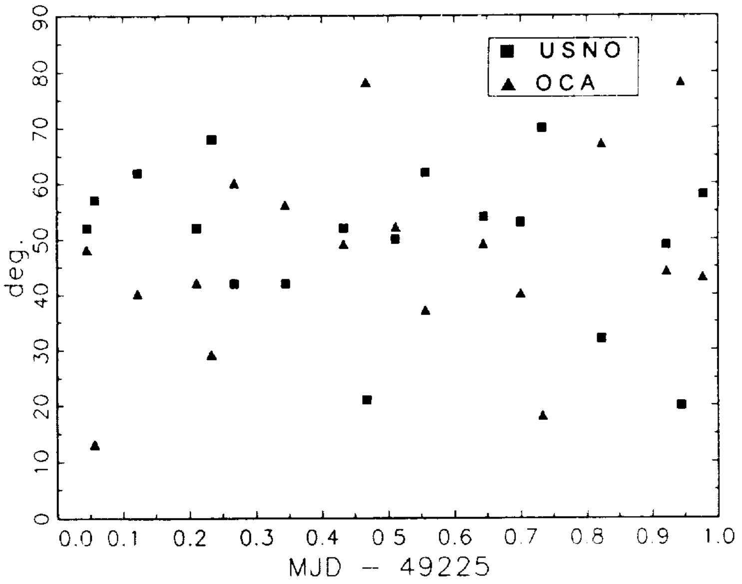

FIGURE 5. Elevation angles of each track on 26 August 1993 at the OCA in the direction of the USNO and at the USNO in the direction of the OCA.

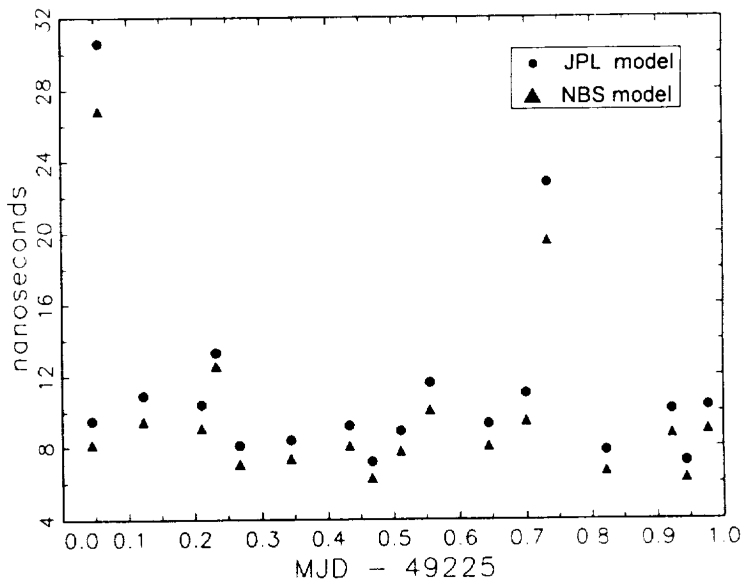

FIGURE 6. Tropospheric delays according to the JPL and the NBS models at the OCA on 26 August 1993 for each track in the direction of the USNO.

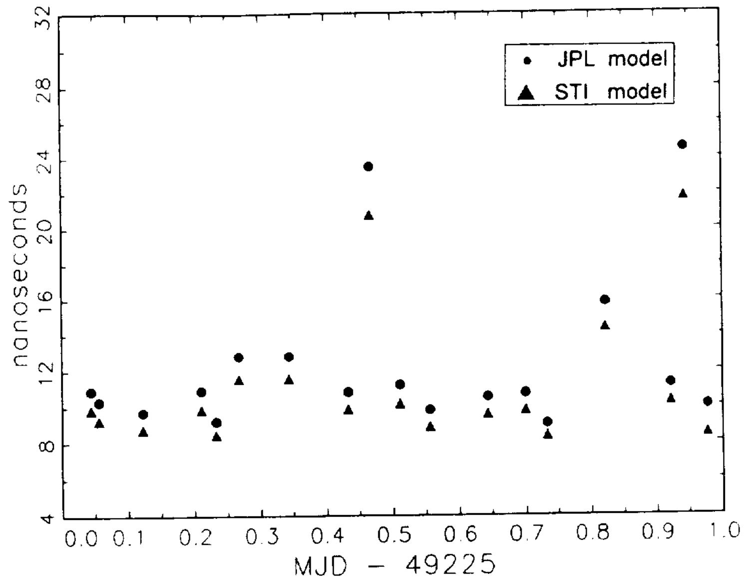

FIGURE 7. Tropospheric delays according to the JPL and the STI models at the USNO on 26 Agust 1993 for each track in the direction of the OCA.

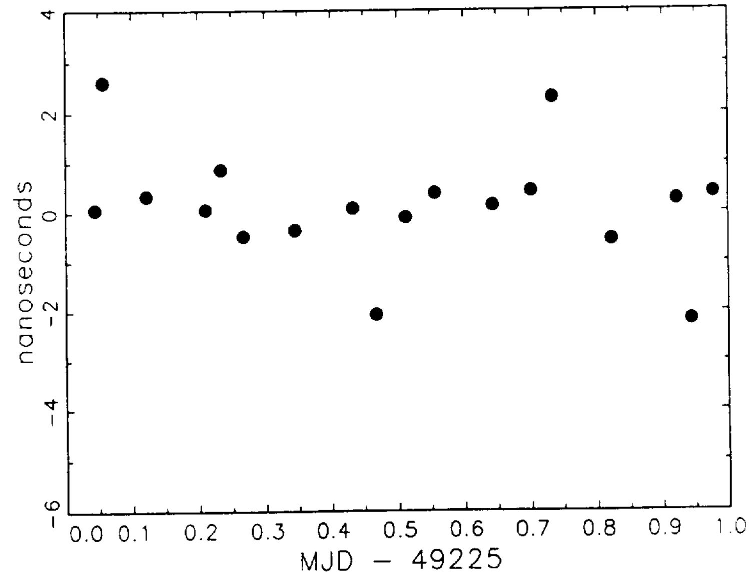

FIGURE 8. [OCA Cs clock - UTC(USNO Master Clock)] as obtained by GPS common views with the NBS and STI tropospheric models minus [OCA Cs clock - UTC(USNO Master Clock] as obtained by GPS common views with the JPL tropospheric model for each track on 26 August 1993.

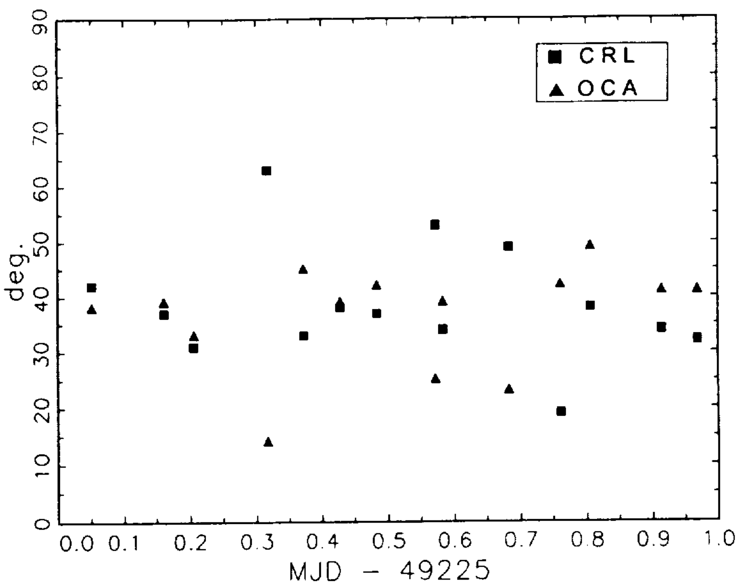

FIGURE 9. Elevation angles of each track on 26 August 1993 at the OCA in the direction of the CRL and at the CRL in the direction of the OCA.

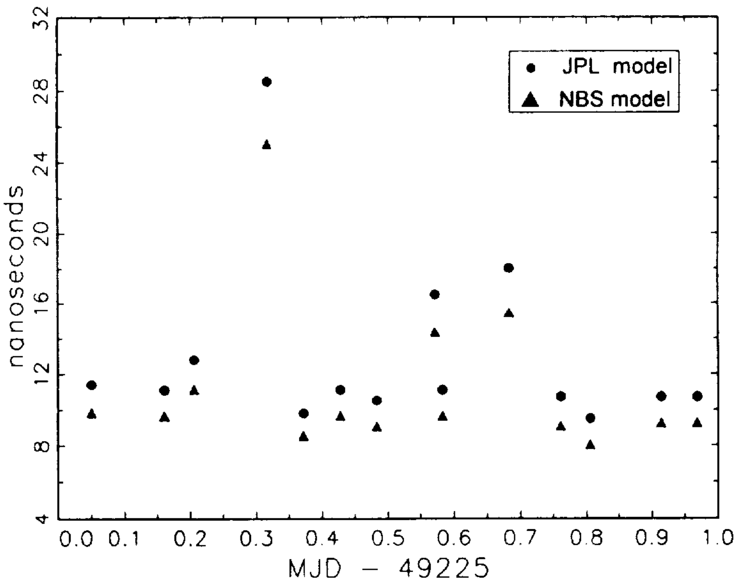

FIGURE 10. Tropospheric delays according to the JPL and the NBS models at the OCA on 26 August 1993 for each track in the direction of the CRL.

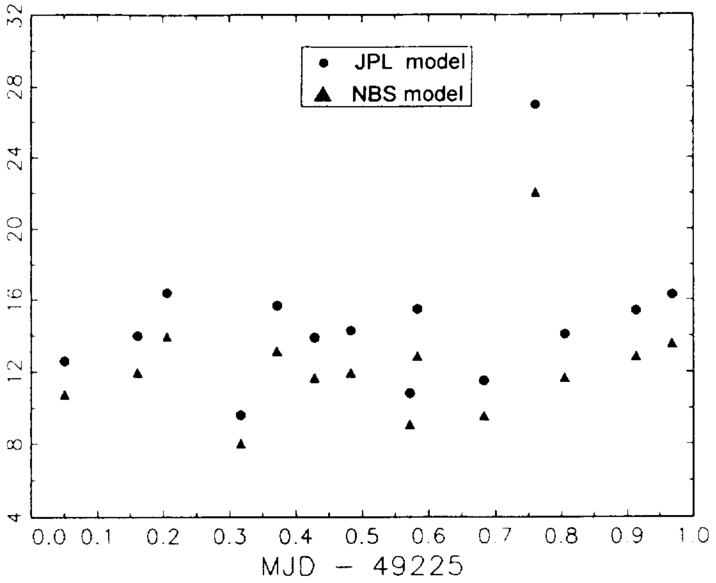

FIGURE 11. Tropospheric delays according to the JPL and the NBS models at the CRL on 26 August 1993 for each track in the direction of the OCA.

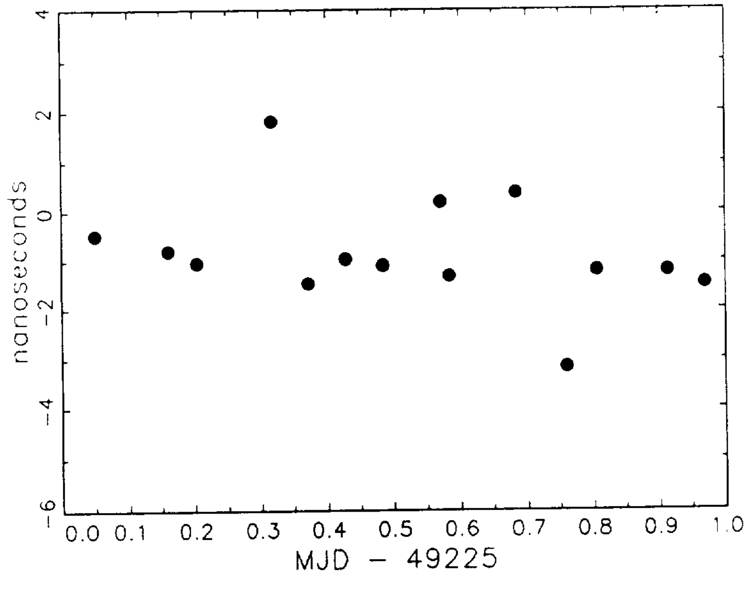

FIGURE 12. [OCA Cs clock - UTC(CRL)] as obtained by GPS common views with the NBS tropospheric model minus [OCA Cs clock - UTC(CRL)] as obtained by GPS common views with the JPL tropospheric model for each track on 26 August 1993.

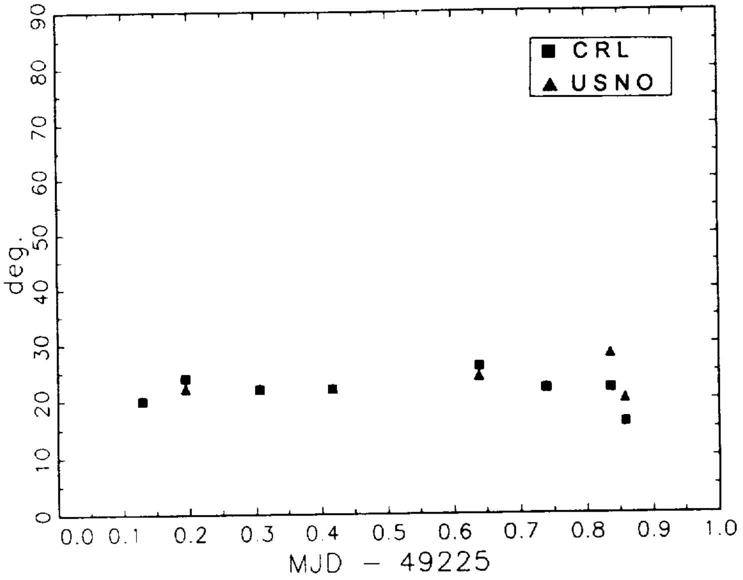

FIGURE 13. Elevation angles of each track on 26 August 1993 at the USNO in the direction of the CRL and at the CRL in the direction of the USNO.

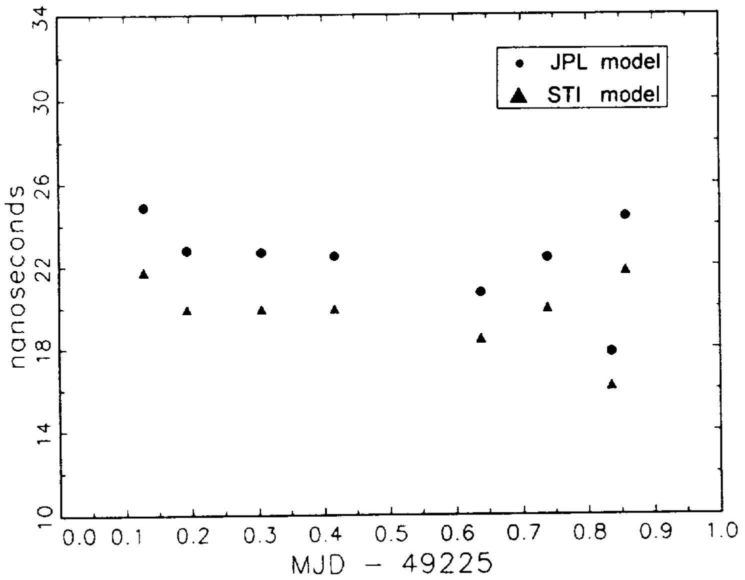

FIGURE 14. Tropospheric delays according to the JPL and the STI models at the USNO on 26 August 1993 for each track in the direction of the OCA.

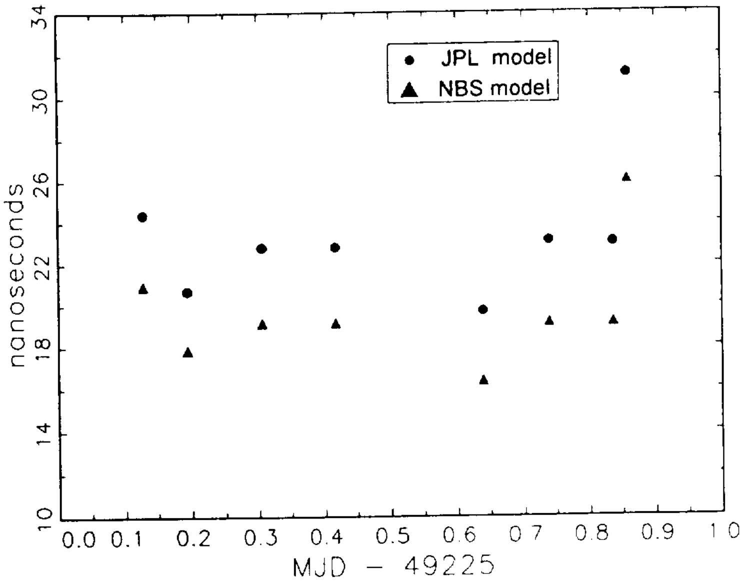

FIGURE 15. Tropospheric delays according to the JPL and the NBS models at the CRL on 26 August 1993 for each track in the direction of the USNO.

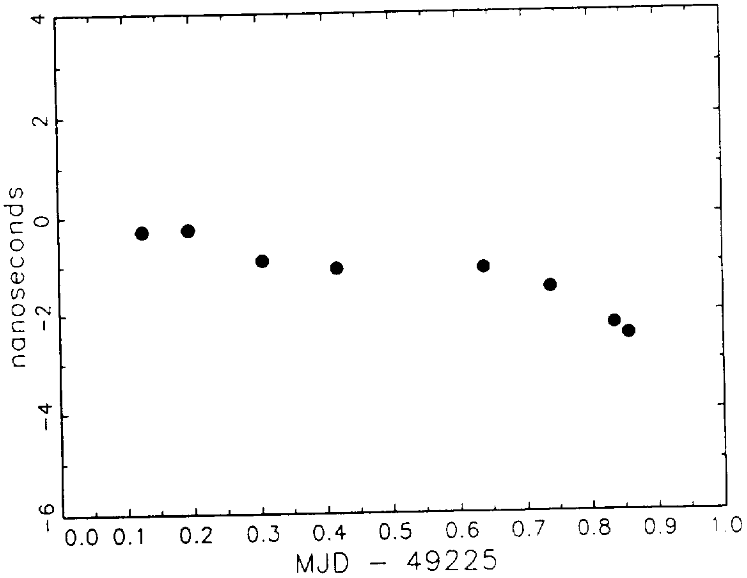

FIGURE 16. [UTC(USNO Master Clock) - UTC(CRL)] as obtained by GPS common views with the STI and NBS tropospheric model minus [UTC(USNO Master Clock - UTC(CRL)] as obtained by GPS common views with the JPL tropospheric model for each track on 26 August 1993.

QUESTIONS AND ANSWERS

MARC WEISS (NIST): I wonder if you did a comparison of the effects of using measurements of humidity versus not using measurements of humidity, say, in the more accurate models, like the CHEL model? I'm asking this because even if we use the CHEL model, it's easy to use it in the receivers; but still, if we have to measure the humidity and have other measurements that go into it, that's a lot harder.

DR. LEWANDOWSKI (BIPM): It was considered to include in the standard format the measurement of humidity temperature. But this point was discussed, and finally the majority of the involved people decided not to do it, because of this external measurements to the receiver.

But there is a possibility to add additional columns with these measurements. But this issue of measuring meteor conditions comes in laboratories which measure international time links. So it's not of concern to many people; it's for those who want to do more accurate studies.

MARC A. WEISS (NIST): So my question is whether you compare using measurements versus not using measurements in the tropospheric model. What differences does that produce?

W. LEWANDOWSKI (BIPM): In measuring and not measuring? It was peak differences up to five ns in the intercontinental time links.

DAVID ALLAN (ALLAN'S TIME): I would like to actually make a comment in regard to the melting pot method which the USNO has introduced or has used, I think, quite effectively. In this case, of course, the satellites are at high elevation angles. And the question is -- and maybe this is really a question of Dr. Winkler -- one would like to do the same thing that has been done with common view, that is, go A to B, B to C, C back to A; and you get closure around the globe so you can test the around-the-world accuracy. And because of the high altitudes that you can achieve in using the melting pot method, it would be interesting to do the same thing, A to B, B to C, and go around the globe and check the closure on that. I don't know whether that's been done or not. Dr. Winkler, do you know?

W. LEWANDOWSKI (BIPM): Of course, using melting pot and high elevations improves the conditions. But again, for very accurate time links, measuring meteor conditions should be considered also, for any observations. If you want to go down under one ns.

At this moment, when we have troubles with receivers, they are noisy at the level of 10 ns, and this issue is not so urgent. But with future receivers, and if we want to go down under one ns, it should be gathered.