TROPOSPHERIC CORRECTIONS TO GPS MEASUREMENTS USING LOCALLY MEASURED METEOROLOGICAL PARAMETERS COMPARED WITH GENERAL TROPOSPHERIC CORRECTIONS

D. Kirchner and C. Lentz
Technical University Graz, Austria

H. Ressler
Space Research Institute, Graz, Austria

Abstract

At the Technical University Graz (TUG), Austria, the Global Positioning System (GPS) has been used for time transfer purposes since the early 80's and from that time on local meteorological parameters are recorded together with each measurement (satellite track). The paper compares the tropospheric corrections (delays) obtained from models usually employed in GPS receivers and those using locally measured meteorological parameters.

INTRODUCTION

In order to calculate the path delay of the signals received from GPS satellites — as with any one-way system — one has to know the satellite and user positions with high accuracy and furthermore has to apply corrections for the propagation delays in the ionosphere and troposphere[1]. In the case of time laboratories the GPS antenna coordinates are usually known with high accuracy in a common reference frame and post-processed ephemerides are accessible within a few weeks from different agencies and the ionospheric delay can be measured using dual-frequency receivers[2,3]. The tropospheric delay is — for the frequencies used here — frequency-independent and can therefore not readily be established. Different models are employed in GPS timing receivers using general empirical atmospheric models which only take into account the station height and the elevation of the satellite. For increased accuracy models based on actually measured local surface temperature, atmospheric pressure and relative humidity may be used. At the Technical University Graz (TUG), Austria, the Global Positioning System (GPS) has been used for time transfer purposes since the early 80's and from that time on together with each measurement (satellite track) local meteorological parameters are

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recorded. The paper compares the tropospheric delays obtained from models usually employed in GPS receivers and those using locally measured meteorological parameters. Results are given for measurements done according to the GPS common–view tracking schedules issued by the Bureau International des Poids et Mesures (BIPM) during the years 1991 and 1992.

TROPOSPHERIC DELAY AND USED MODELS

The tropospheric excess delay D_T is given by

$$D_T = \frac{10^{-6}}{c} \int N(s)ds \tag{1}$$

where N is the refractivity given by $(n-1)10^6$ with n the index of refraction of air and c is the velocity of light in vacuo and the integral is evaluated along the signal path[4]. For frequencies below 30 GHz N is given by

$$N = 77.6(\frac{p}{T} + 4810\frac{e}{T^2}) \tag{2}$$

where T is the absolute temperature in Kelvin, p is the total atmospheric pressure and e is the partial pressure of water vapour both in millibars[4,5]. This form is widely used and accurate within 0.5% for the range of atmospheric parameters normally encountered[4]. The first term in Equation 2 is called the dry component N_d and the second term the wet component N_w and thus with

$$N = N_d + N_w \tag{3}$$

the tropospheric delay according to Equation 1 is composed of a dry component and a wet component due to dry air and water vapour effects, respectively, and can be written in the following form

$$D_T = D_{Td} + D_{Tw} = \frac{10^{-6}}{c} \int N_d(s)ds + \frac{10^{-6}}{c} \int N_w(s)ds \tag{4}$$

The main part of the total delay results from the dry component but the remaining part resulting from the wet component is highly variable due to the high variability both temporally and spatially of the water vapour concentration. Usually the integrals are evaluated in zenith direction and from the obtained zenith delay D_T^z the delay D_T for arbitrary elevation angles is computed by means of mapping functions $\mathbf{MF}$[6,7]. Thus the tropospheric delay D_T is given by

$$D_T = D_{Td}^z \times \mathbf{MF}_d + D_{Tw}^z \times \mathbf{MF}_w \tag{5}$$

The accuracy of the calculated tropospheric delay depends upon the degree to which the atmospheric model used to determine the refractivity profile $N(s)$ reflects local atmospheric

conditions[7]. Models are employed which either use a general empirical reference atmosphere only requiring the station height and the respective elevation angle to the satellite to calculate the tropospheric delay or which are based on surface measurements of the refractive index thus requiring the measurement of the local meteorological parameters i.e. temperature, atmospheric pressure and relative humidity. Models of the first type are usually implemented in GPS receivers. The model used in receivers of NBS type (NBS model)[3], the model used in STI TTS–502 receivers (STI model)[3] and the model recommended in the STANAG Doc. 4294 (STANAG model)[8] will be compared with models of the second type namely the ones by Hopfield[9], Saastamoinen[9] and Chao[10,11]. Of the latter models the first two are widely used within the geodetic community[12] and the last one was developed by the Jet Propulsion Laboratory (JPL) and is employed in the original Master Control Stations (MCS)[1]. In the following the Hopfield model will be used as reference. Apart from the tropospheric models investigated in this paper there exist many other models. The main reason for that is the difficulty in the modelling of the water vapour content[9].

DATA AND RESULTS

Table 1 gives the tropospheric delays in zenith direction for the above mentioned models at Graz (h = 540 m) whereby for the Hopfield, Saastamoinen and Chao models average meteorological conditions (T=11°C, p = 955 mbar, RH = 70%) computed from the data of 1991 and 1992 (see Figs. 5 → 10) are used.

Table 1 Tropospheric delays in zenith direction for average meteorological conditions (T=°C, p = 955 mbar, RH = 70%) at Graz (h = 540 m)			
Tropospheric Delay in ns			
Model	Dry Comp.	Wet Comp.	Dry Comp. + Wet Comp.
NBS			6.73
STI			7.33
STANAG			7.66
Hopfield	7.27	0.31	7.58
Saastamoinen			7.56
Chao	7.12	0.36	7.48

The dependence of the dry component on temperature and atmospheric pressure and the dependence of the wet component on temperature and relative humidity of the tropospheric zenith delay computed by means of the Hopfield model are shown in Fig. 1 and Fig. 2, respectively. Indicated are the values for average conditions at Graz. The high variability of the wet component leading to large contributions in hot and wet climates can clearly be seen from Fig. 2. The mapping functions for the dry and wet components for this model are depicted in Fig. 3. The differences between the tropospheric delays given by the Hopfield model and the other models as function of the elevation angle — thus showing the influence of the different mapping functions used by the different models — based on the values given in Table 1 is

plotted in Fig. 4. The large differences for low elevation angles caused by the different mapping functions are usually not relevant for the GPS common–view time transfer because in practice also for common–view time transfers over long distances the elevation angles usually employed are greater than 15 degrees (see Fig. 11). Because an elevation angle of about 15 degrees is the limit for some receivers using a type of choke ring groundplane for the antenna to reduce multipath effects this elevation angle was chosen as limit in the comparisons. The temperature, atmospheric pressure and relative humidity for the GPS measurement times (satellite tracks) according to the BIPM common–view schedules are plotted in Figs. 5 → 10 whereby the single measurements and daily means are given for each meteorological parameter. Fig. 11 shows the elevation angles at which the common–view time transfer measurements according to the different BIPM common–view schedules were performed in 1991 and 1992. The tropospheric delays computed by means of the Hopfield model and NBS model for this period are plotted in Figs. 12 and 13. For low elevation angles a change by 1 degree — this is the resolution of the old format for GPS data exchange which in the new format has been changed to 0.1 degree[14] — already causes large variations in the tropospheric delays. For the same period means over seven days of the differences between the Hopfield model and the other models are shown in Fig. 14 revealing model dependent offsets and seasonal patterns. To explain the differences between 1991 and 1992 one has to look at the meteorological parameters and the elevation angles for this period (see Figs. 6 and 8 and Fig. 11). The differences for 1991 between the Hopfield model and the ones by Saastamoinen, Chao, NBS, STI and STANAG for each satellite track are plotted in Figs. 15 → 19 and daily means of the same differences are shown in Fig. 20 and Fig. 21, respectively.

CONCLUSION

Models simply using the station height and the elevation angles to the satellites observed are easy to implement and therefore widely used. The three models investigated i.e. the NBS model, the STI model and the STANAG model give different tropospheric corrections for the zenith direction and use different mapping functions causing differences of up to several nanoseconds. Therefore employing models of this type the use of the same model in all timing receivers is recommended[14,15]. Tropospheric corrections obtained by these models and models using locally measured meteorological parameters differ by up to several nanoseconds. By averaging — for example the use of daily means — as usually done in GPS time transfer practice these differences are greatly reduced (see Fig. 21). Employing models which use locally measured meteorological data spatial and temporal variations of the refractive index are taken into account, but there are still differences for the single measurements of up to about one nanosecond between the models investigated (see Fig. 16). For daily means these differences are below one nanosecond, but one has to consider that these are still differences between models. A problem with the use of the latter models is that data are needed for the calculation of the tropospheric delay which are not provided by the GPS receivers itself and that the uncertainty of estimating the refractive index from local surface measurements may cause additional measurement noise due to measurement uncertainties and model deficiencies. Delay stabilities of GPS time transfer receivers now in use are in general of the order of some nanoseconds. Assuming the use of receivers of highest delay stability and asking for accuracies

of one nanosecond or even better for GPS time transfers over long distances one has to use models based on actual meteorological parameters. To estimate the accuracy of tropospheric corrections obtained by models using surface measurements these models and those employing more refined techniques such as the use of data provided by water vapour radiometers should be compared.

ACKNOWLEDGEMENTS

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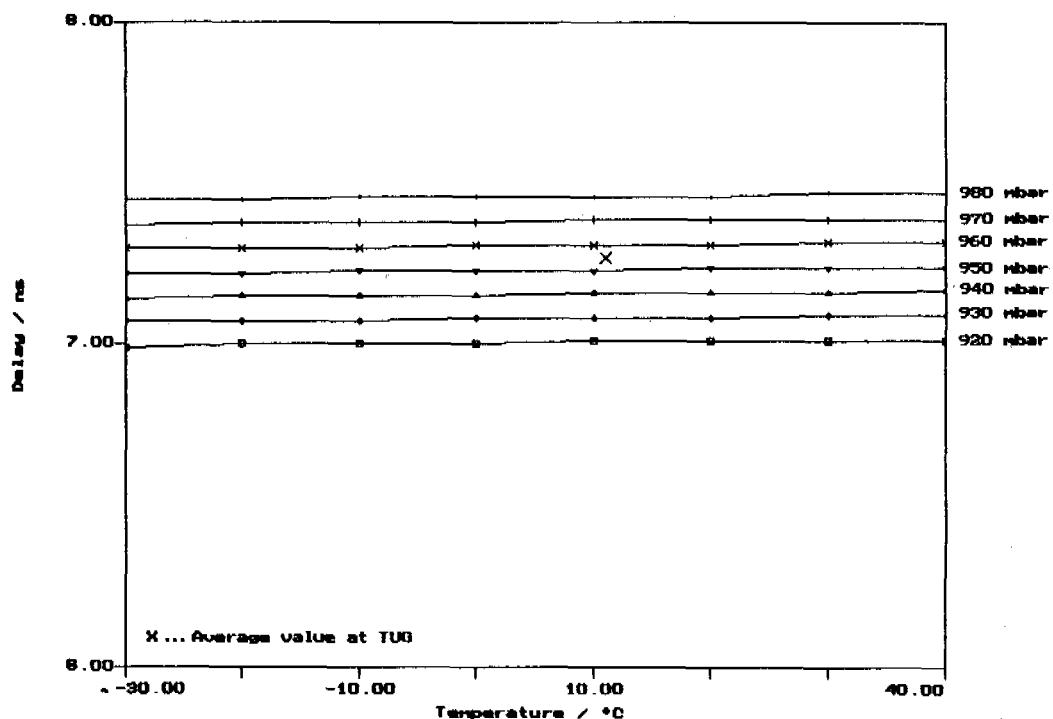
Fig. 1 Hopfield model: tropospheric zenith delay, dry component.
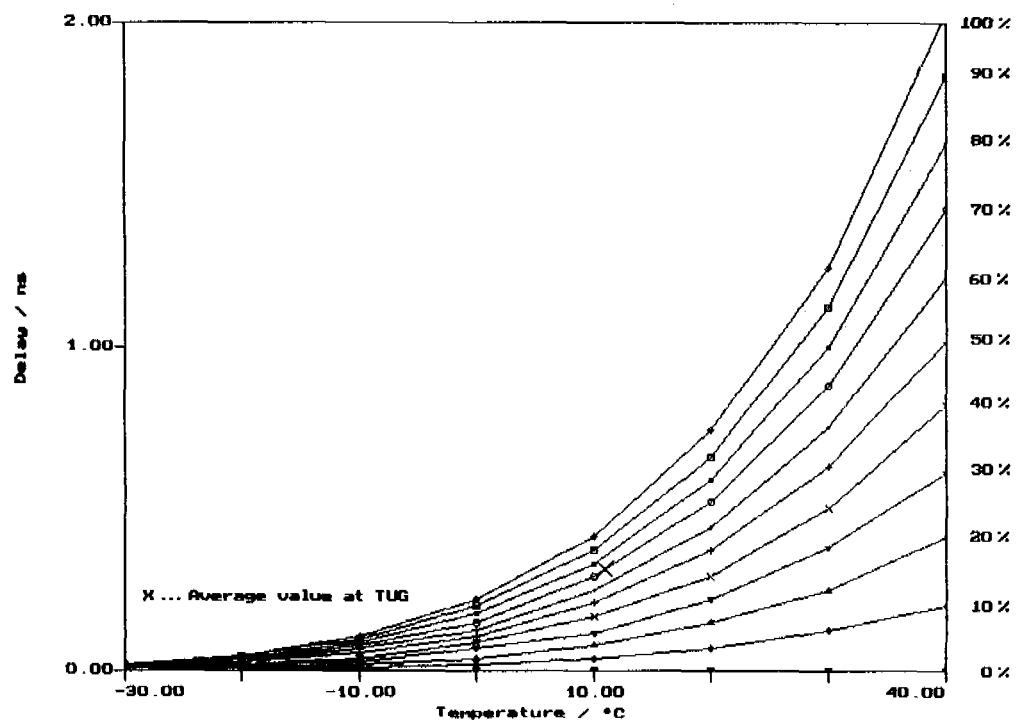
Fig. 2 Hopfield model: tropospheric zenith delay, wet component.
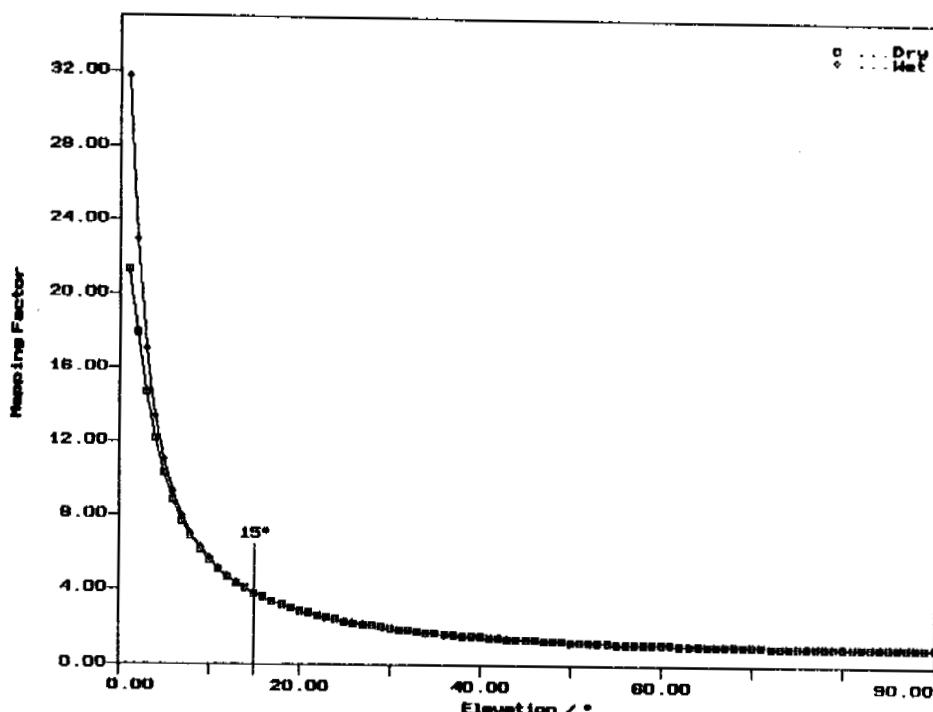
Fig. 3 Hopfield model: mapping functions for dry component and wet component.
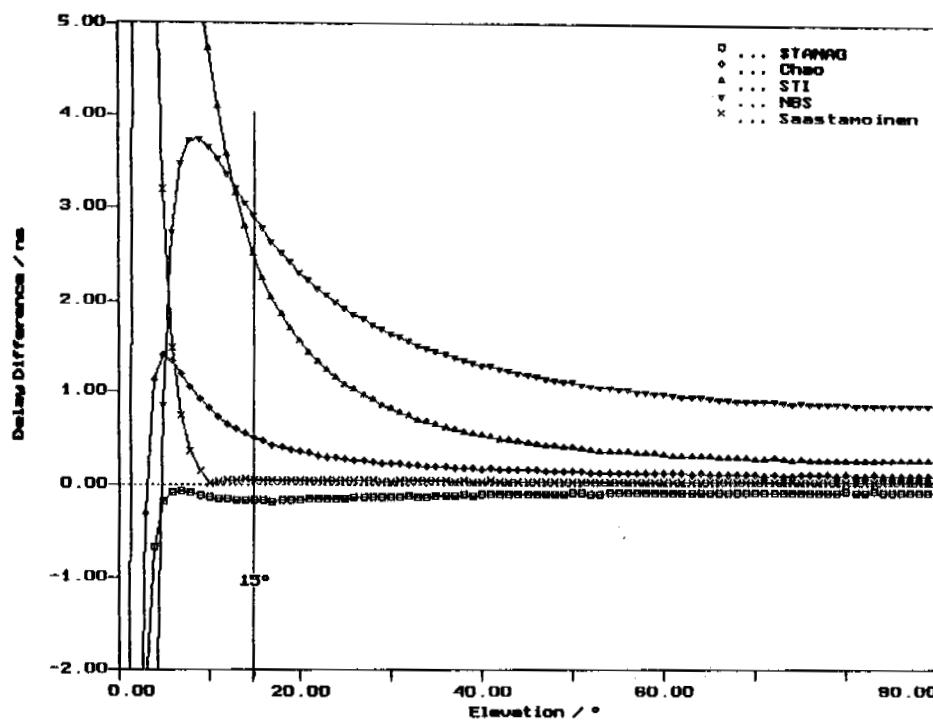

Fig. 4 Differences between the tropospheric delays given by the Hopfield model and the Saastamoinen, Chao, NBS, STI and STANAG models for average meteorological conditions at TUG.
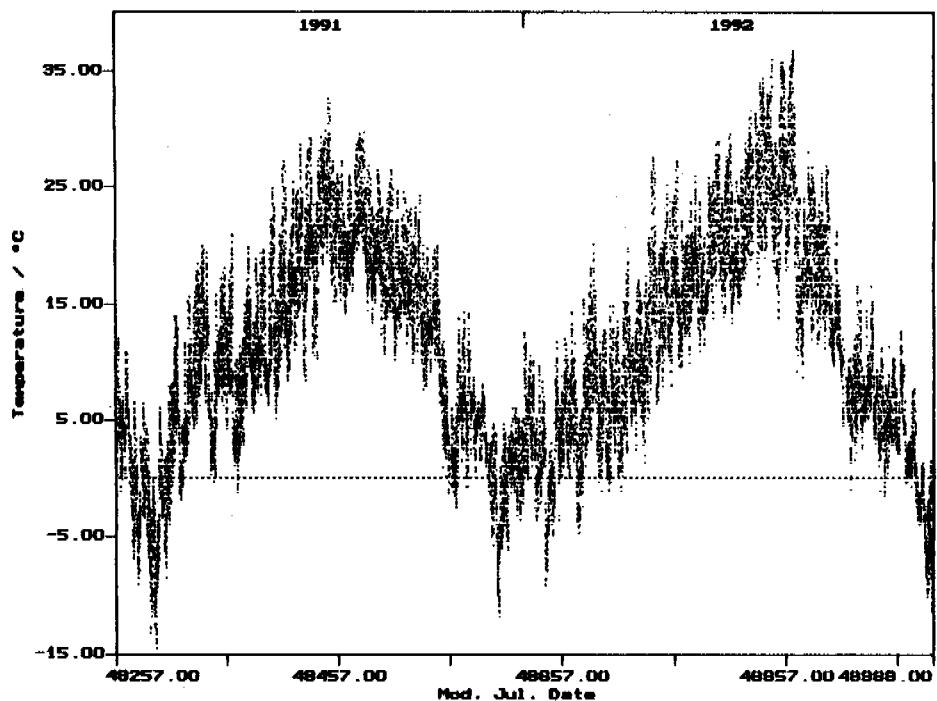
Fig. 5 Temperature at TUG for each satellite track.
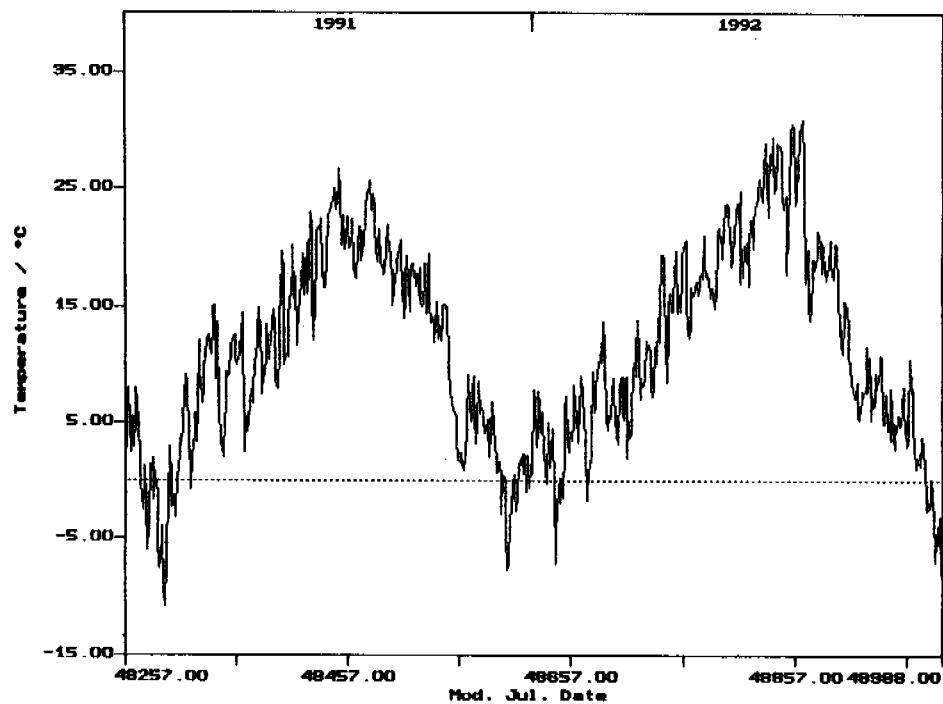
Fig. 6 Temperature at TUG (daily mean).

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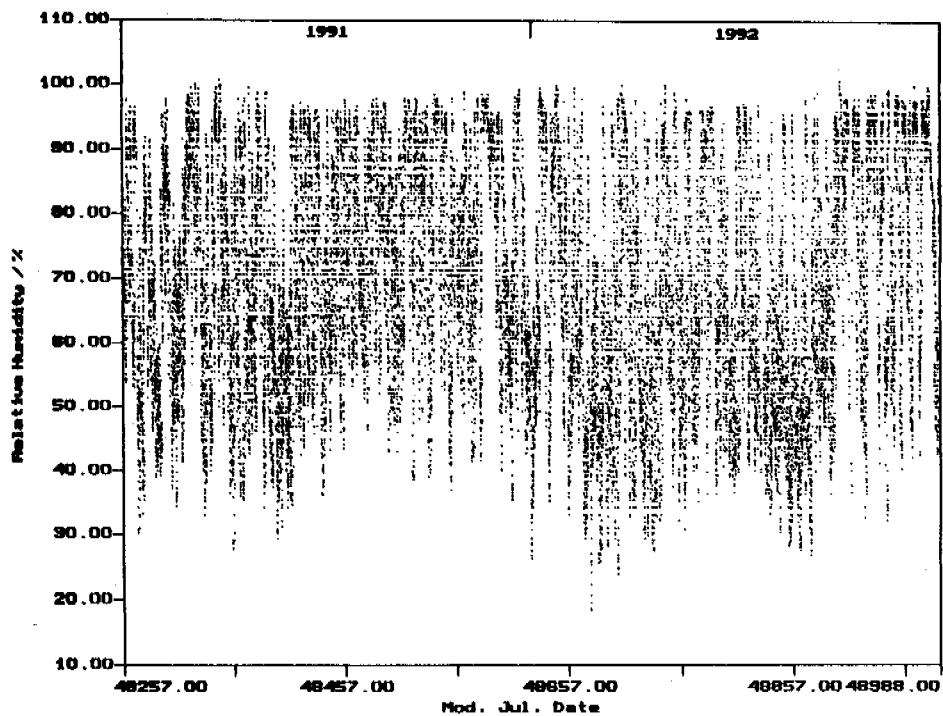
Fig. 7   Relative humidity at TUG for each satellite track.
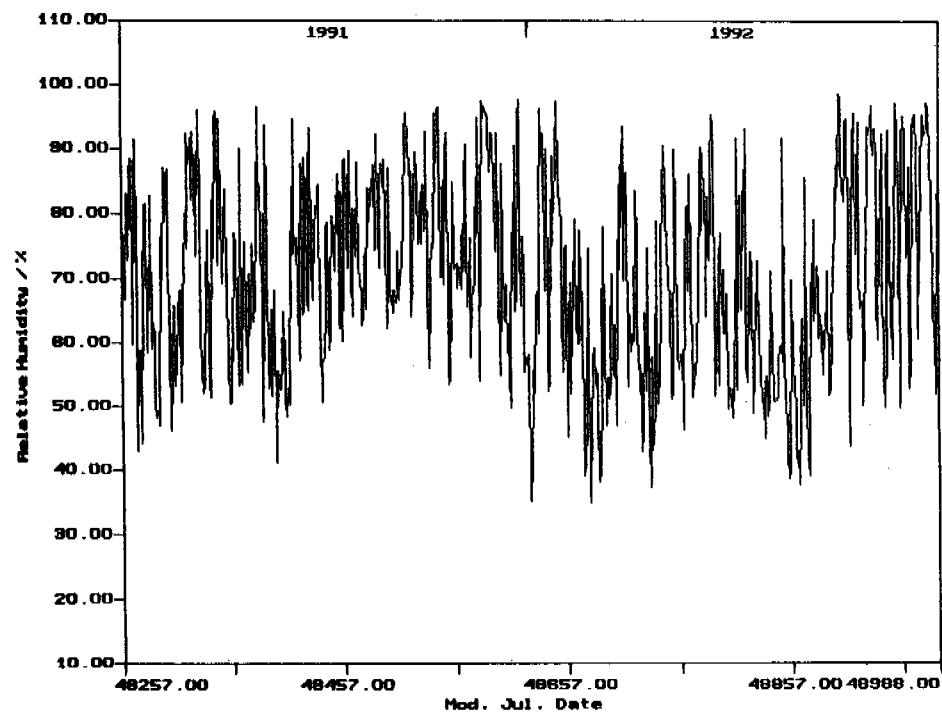

Fig. 8   Relative humidity at TUG (daily mean)

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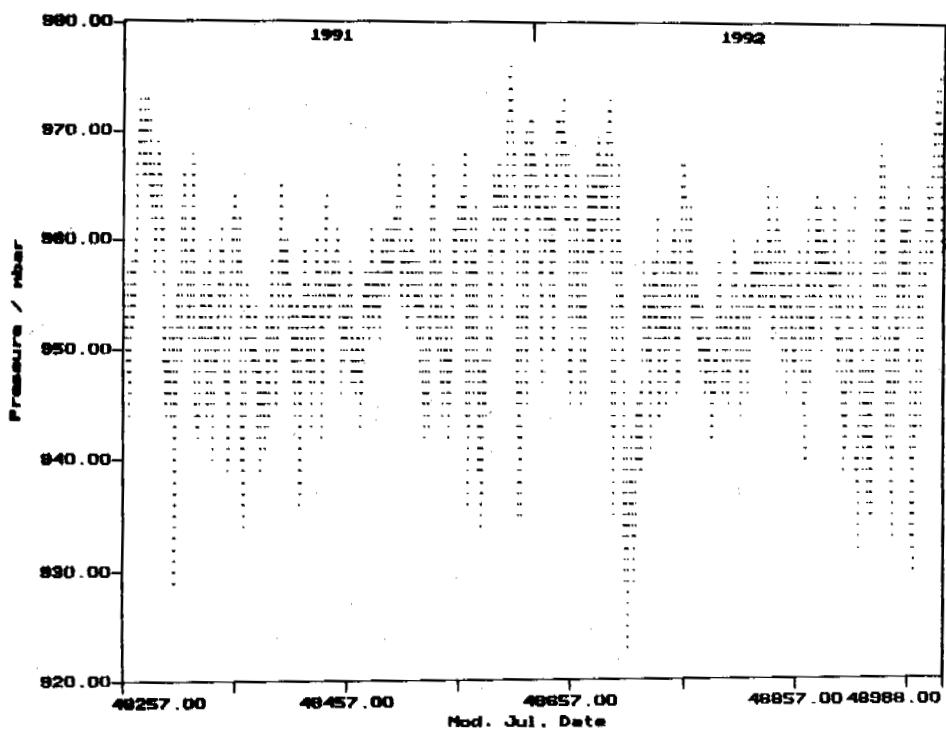
Fig. 9 Atmospheric pressure at TUG for each satellite track.
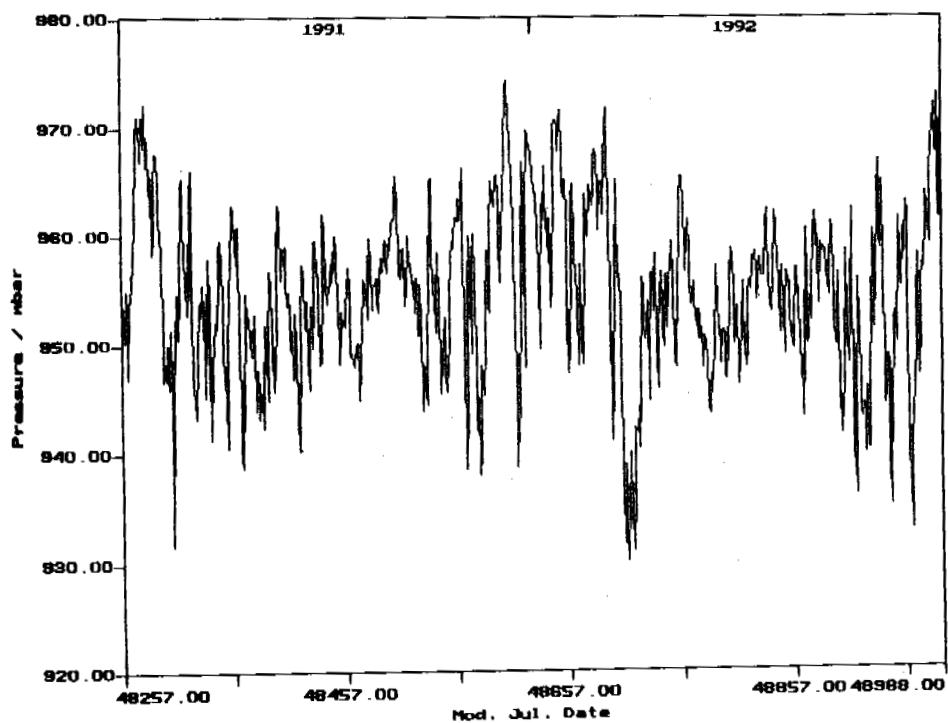
Fig. 10 Atmospheric pressure at TUG (daily mean).

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QUESTIONS AND ANSWERS

Tony Liu, The Aerospace Corporation: I have a question as to whether you have considered using water vapor radiometers in your analysis. If you have, what success or problems have you encountered?

Dieter Kirchner: No, and the reason is very simple. The cost for a water vapor radiometer is several times the cost of a GPS receiver. And this would cause a problem for the general use. Of course for evaluation, it would be of interest. But we only compared models with each other and not models with *in situ* measurements.

Pat Romanowski, Allen Osborne Associates: I just have a question as to the distribution that you showed when you were comparing the different models and the differences. And I notice that they were skewed to one side. And I was wondering if you could comment on that. In most cases; I believe there was only one case that was an exception.

Dieter Kirchner: It is very easy to comment. This is a very general model which makes general assumptions for the refractivity; it uses a reference atmosphere. And the offset here is simply given by the figure with which you start at mean sea level. So it is simply which model do you use for your general model.

Pat Romanowski: Well, the point I want to make was the skewness of the data. For instance, it doesn't seem to be —

Dieter Kirchner: Okay, this is simply a yearly effect. This difference here between our reference model which takes into account the measured values at the surface and this model which takes global average and a time average cannot take into account the unit change of humidity and air pressure; and therefore, you see the different seasons; you see the winter, spring, summer and fall, and winter again.

Pat Romanowski: Are there actually two models represented in the graph?

Dieter Kirchner: In the graph is the difference between the Hopfield(?) Model and the NBS Model.

Pat Romanowski: And my question is why is the difference so terribly one sided?

Dieter Kirchner: Now I understand, I am sorry. You are thinking of this density distribution; and this is because most of the elevation angles are around here; and we have only a few elevations which are low elevations. And the differences are of course larger for the low elevations. And therefore most of the measurements are done here.

Pat Romanowski: The elevation of satellites? Okay, thank you.