Status Report of the IVS Pilot Project - Tropospheric Parameters

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Abstract

In April 2002 the IVS set up the Pilot Project - Tropospheric Parameters and the Institute of Geodesy and Geophysics (IGG), Vienna, was asked to coordinate the project. After a call for participation seven IVS Analysis Centers have joined the project and submitted their estimates of tropospheric parameters (wet and total zenith delays, horizontal gradients) for all IVS-R1 and IVS-R4 sessions since January 1st, 2002, on a regular basis. Using a two-step procedure the individual submissions are combined to stable, robust and highly accurate tropospheric parameters with 1 hr resolution. The zenith delays derived by VLBI are compared with those provided by IGS (International GPS Service). At collocated sites (VLBI and GPS antennas at the same station) rather constant biases are found between the GPS and VLBI derived zenith delays, although the signals recorded by both techniques are subject to the same tropospheric delays. Possible reasons for these biases are discussed.

1. Introduction

In recent years the collaboration between geodesy and meteorology/climatology has become more and more intensive. GPS has proven to be of great importance for meteorology and because of the short delay between the GPS observations and the availability of tropospheric results, these can even be used for weather forecasts. Tropospheric parameters determined by VLBI are mainly useful for climatological studies. Since there is a long history of consistent VLBI sessions since 1984, they comprise accurate information about the long-term development of precipitable water above the VLBI sites. Furthermore, due to the high accuracy of the parameters derived by VLBI, these are of interest for the validation and calibration of parameters determined by GPS, WVR (water vapour radiometer) and other techniques.

In VLBI data analysis tropospheric modeling is one of the major error sources. Therefore, a comparison of tropospheric parameters was part of the 2nd IVS Analysis Pilot Project in 2001. Ten time series submitted by nine Analysis Centers (ACs) were compared by the IVS Associate Analysis Center at the Institute of Geodesy and Geophysics (IGG) of the University of Technology, Vienna. The investigations showed that the series submitted by IVS ACs are consistent and of high quality (Boehm et al., 2002 [1]). At the 7th IVS Directing Board meeting in Tsukuba (Feb. 2002) it was decided to set up an IVS Pilot Project on Tropospheric Parameters coordinated by IGG. This Pilot Project (PP) is a research and study project with a structure similar to the IVS Working Groups. After the call for participation by the IVS Analysis Coordinator in May 2002, six IVS ACs agreed to take part in the PP. In January 2003, the IVS AC at Onsala Space Observatory, Sweden, joined the project as the seventh AC.

A Pilot Project Group (PPG) has been set up to coordinate all activities within the PP and to discuss all steps that should finally lead to operational products. One person per AC that is submitting tropospheric parameters is part of the PPG. The Director of the IVS Coordinating Center and the IVS Analysis Coordinator are ex-officio members of the PPG. Other colleagues experienced in tropospheric research or combination of geodetic time series also joined the group but the number of members is limited to twelve. Harald Schuh, head of the IGG, is chair of the PPG. He is supported by Johannes Boehm as executive secretary of the PP.

Table 1. **IVS ACs taking part in the PP - Tropospheric Parameters.** Onsala Space Observatory joined the PP in January 2003. The contact persons are members of the PPG.

	AC	contact
BKG	Federal Agency for Cartography and Geodesy	Gerald Engelhardt
CGS	Centro di Geodesia Spaziale	Roberto Lanotte
CNR	Istituto di Radioastronomia	Paolo Tomasi
GSF	NASA Goddard Space Flight Center	Dan MacMillan
IAA	Institute of Applied Astronomy	Iraida Vereshchagina
IGG	Institute of Geodesy and Geophysics	Johannes Boehm
OSO	Onsala Space Observatory	Ruediger Haas

Table 2. **Members of the PPG who are not representatives of the ACs that are submitting tropospheric estimates.**

member	affiliation
Arthur Niell	MIT Haystack Observatory
Axel Nothnagel	GIUB Bonn
Harald Schuh	Institute of Geodesy and Geophysics
Nancy Vandenberg	NASA Goddard Space Flight Center

2. Submissions by the ACs

The Pilot Project requests the regular submission of tropospheric estimates of all IVS-R1 and IVS-R4 24 hr VLBI sessions starting with IVS-R1026 and IVS-R4027, i.e. in the second half of 2002. The tropospheric parameters are due 14 days after the database is available on the IVS Data Centers. Most of the ACs have been providing the tropospheric parameters since the beginning of 2002, which allows the generation of a combined series since the start of the R1 and R4 sessions. The total and wet zenith delays are submitted by all ACs. Additionally, all ACs are providing estimates of the horizontal gradients, GSF and IGG are even applying a priori gradients calculated from numerical weather models. Most of the ACs use the CALC/SOLVE software package, only IAA and IGG are applying the QUASAR and OCCAM software, respectively. About half of the ACs fix the ITRF2000, and all ACs use cutoff elevation angles at or below five degrees. The Niell mapping functions (Niell, 1996 [2]) are used throughout – only IGG applies the isobaric mapping function of the hydrostatic part (Niell, 2001 [3]). Meteorological parameters do not have to be submitted because they can be extracted from the databases.

The tropospheric parameters should be provided at every full hour, i.e. in equidistant time intervals of 60 minutes, starting at the first integer hour of the session. For example, if a session starts at 17:30 UTC the first epoch will be 18:00 UTC. These parameters can be determined by interpolating the values estimated at arbitrary epochs to the integer hours. Shorter time intervals, which are integer parts of 60 minutes, are also possible. If other time intervals are used for the

Table 3. **Features of the submissions.** Two ACs use a priori gradients; four ACs are fixing ITRF2000.

AC	a priori gradients	ITRF2000 fixed	software
BKG	no	yes	CALC/SOLVE
CGS	no	no	CALC/SOLVE
CNR	no	no	CALC/SOLVE
GSF	yes	no	CALC/SOLVE
IAA	no	yes	QUASAR
IGG	yes	yes	OCCAM
OSO	no	yes	CALC/SOLVE

computation (e.g., longer time intervals for the gradients) all parameters have to be referred to the same hourly time epochs.

3. Combination Strategy for the Total and Wet Zenith Delays

Each AC that is taking part in the IVS Pilot Project - Tropospheric Parameters submits two files per week, i.e. one for the IVS-R1 and one for the IVS-R4 session. These two are combined to weekly files to be comparable with results provided by the IGS (International GPS Service), although at most VLBI sites there is only one 24 hr session per week.

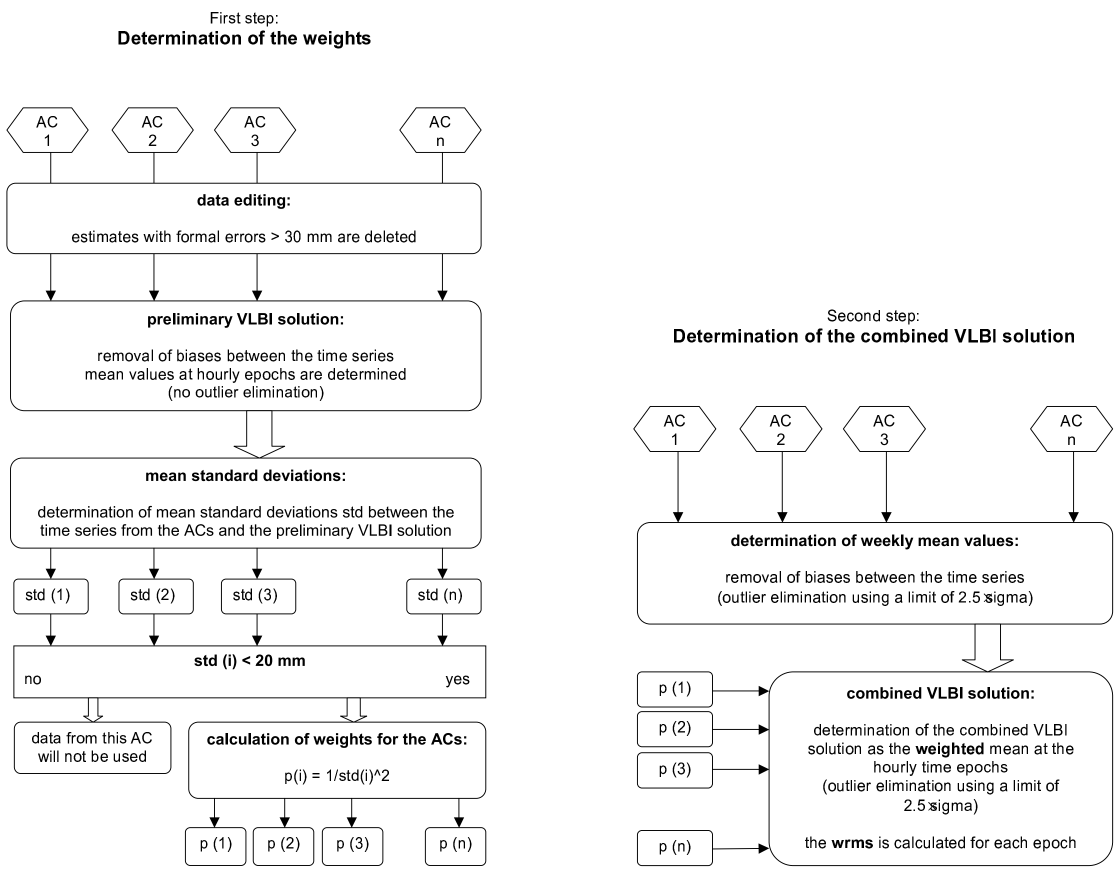
Table 4. **The IVS-R1 and IVS-R4 sessions are combined to weekly files.**

GPS week	IVS-R1 session	IVS-R4 session
1147	—	IVS-R4 001
1148	IVS-R1 001	IVS-R4 002
1149	IVS-R1 002	IVS-R4 003
1150	IVS-R1 003	IVS-R4 004
...	...	...

Before the combination, the data submitted by the ACs are edited using a limit of 30 mm for the formal errors. Estimates with larger formal errors are discarded. No interpolation has to be carried out to get the tropospheric parameters at the same time epochs because the ACs were asked to provide their estimates at integer hours (see section 2). The combination itself is a two-step procedure which is carried out site by site, week by week and parameter by parameter (see Figure 1).

In the first step preliminary VLBI time series of the total and wet zenith delays are produced. This combination comprises the removal of biases and the calculation of the mean values at each epoch without any outlier elimination. Then the mean standard deviations between the preliminary VLBI time series and the time series of the ACs (shifted to the common mean) are computed for each week and each station. If a standard deviation is larger than 20 mm at a certain station, data from this AC will not contribute to the second step of the combination. Furthermore, a mean value of the standard deviations for all VLBI sites is determined for each AC. These mean standard deviations are used for assigning weights to the individual AC solutions in the final (second) combination.

In the second step the biases between the weekly time series are removed at each station using a (2.5 x sigma)-outlier elimination. Then the VLBI values of the tropospheric parameters at each epoch are calculated as weighted means. Again, outliers are removed using a limit of (2.5 x sigma).



a. First step of the combination procedure. Weights for the individual ACs are determined and 'bad observations' are discarded.

b. Second step of the combination procedure. The combined VLBI solution is determined using outlier elimination.

Figure 1. **Two step procedure to determine a combined VLBI solution for the total and wet zenith delays.** This procedure is very similar to that developed by the IGS.

With the approach described above, one VLBI time series is determined for the total and one for the wet zenith delays. Two examples with the wet zenith delays as submitted by the ACs and the combined solution can be seen in Figure 2 and Figure 3. While Figure 2 (Wettzell) shows a rather good agreement between the ACs (2.1 mm), the mean of the standard deviations of the combined hourly results in Figure 3 (Kokee) is about twice as large (4.4 mm). In some sessions there were gaps in the observations at certain stations that have not been recognized by the ACs.

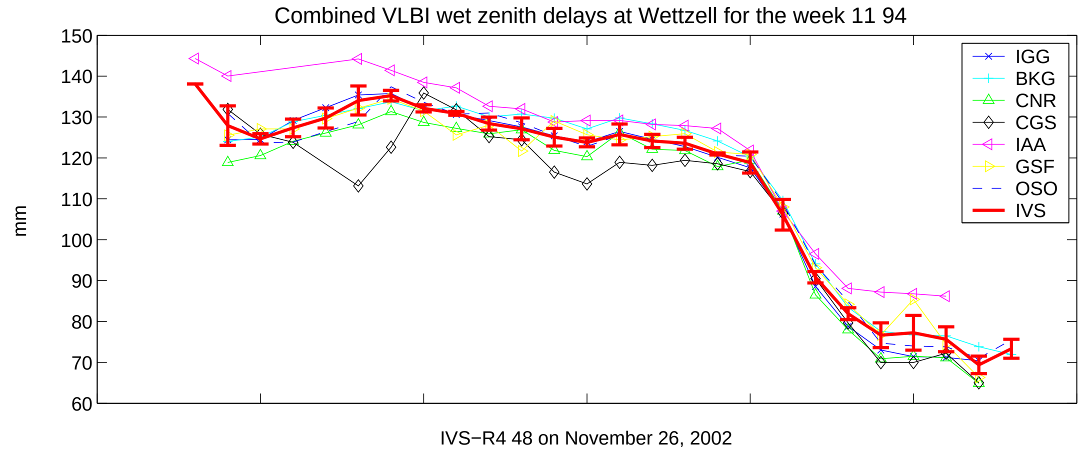


Figure 2. **Submissions for the wet zenith delays at Wettzell** by the various Analysis Centers (GPS week number 1194) and the combined VLBI solutions (red bold line with errorbars). A rather good agreement between the time series can be seen. The mean of the standard deviations of the combined hourly results is 2.1 mm.

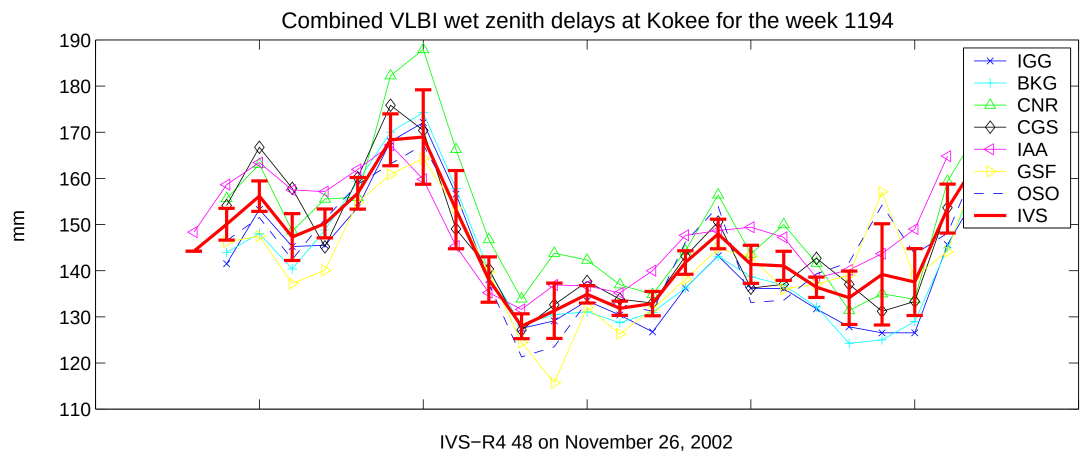


Figure 3. **Submissions for the wet zenith delays at Kokee Park** by the various Analysis Centers (GPS week number 1194) and the combined VLBI solutions (red bold line with error bars). The mean of the standard deviations of the combined hourly results is 4.4 mm, i.e. twice as large as for Wettzell (see Figure 2).

For example, if there were no observations in the middle of a 24 hr session, the ACs might not be aware of this fact because they are using piecewise linear functions with constraints for the rates of the zenith delays. Another critical case occurs when no pressure data is available for a station and the ACs use assumed mean values for the pressure. Then the estimated wet delays are not used for the final product. To avoid these problems, IGG discards all combined estimates if there are no pressure data available in the database within one hour of the combination epoch.

Furthermore, so far a combined solution is only computed if there are data from at least three ACs contributing. Finally for cross checking, meteorological data are taken from the databases to compute the hydrostatic zenith delays at each station using the formula of Saastamoinen (1972 [4]). If the difference between the total and the hydrostatic plus wet delay of the combined solution is larger than three mm, the combined value at this time epoch is discarded.

4. Accuracy of the Combined Zenith Delays

There are two kinds of accuracies that can be investigated. On the one hand, there is the accuracy of the absolute values. Apart from systematic errors that might be inherent in the zenith delays submitted by all ACs the weekly biases between the ACs should be a good criterion to evaluate the (remaining) absolute accuracy. Possible reasons for systematic biases in the VLBI estimates might be:

- errors in the terrestrial reference frame (at least for those solutions where the ITRF2000 is fixed),
- errors in the mapping functions,
- reflector bending, ...

On the other hand, relative accuracies can be determined after removing the weekly biases between the time series when the standard deviations at the hourly epochs are evaluated.

4.1. Absolute Accuracies

As can be seen in Figure 4, the weekly biases of the total (and wet) zenith delays are within +/- 2 mm for most of the ACs. This indicates that, apart from systematic effects as described above, the accuracy of the absolute values of the zenith delays is at the 2 mm level, which is a mean value for all VLBI sites.

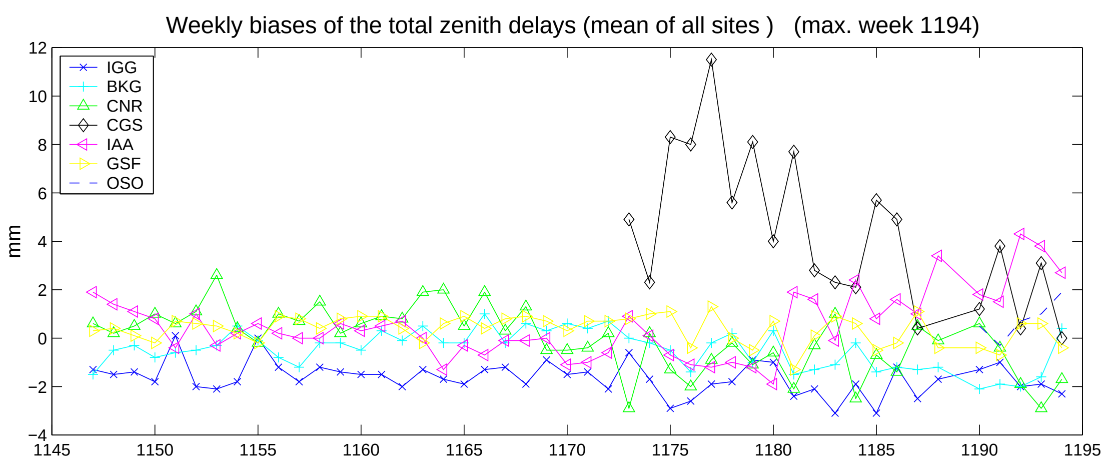


Figure 4. **Weekly biases of the total zenith delays in 2002.** The biases are within +/-2 mm for most of the ACs.

4.2. Relative Accuracies

Relative accuracies can be calculated as the mean standard deviations at the hourly epochs after removing the weekly biases. Figure 5 shows the mean values (averaged per week) of the hourly standard deviations of the combined VLBI solution (red solid line) of the total zenith delays (mean of all sites). Additionally, the mean standard deviations of the hourly estimates of the individual time series against the combined VLBI solution are shown. Thus, the relative accuracy of the combined VLBI zenith delays is at the 2 mm level.

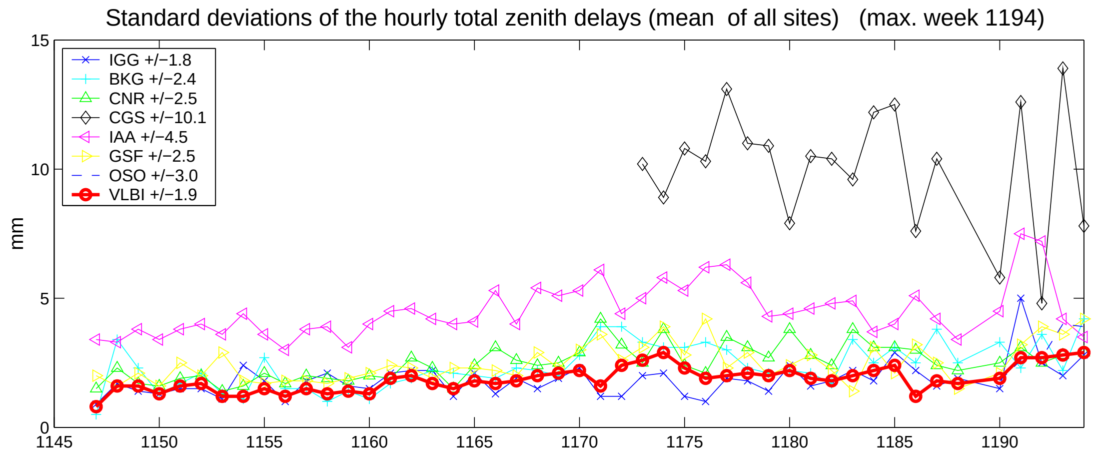


Figure 5. **Mean values of the hourly standard deviations (averaged per week) in 2002.** Additionally, the mean values of the hourly standard deviations for all stations are shown for the ACs.

5. Comparison with Tropospheric Parameters Determined by IGS

The IGS (International GPS Service) has been producing tropospheric parameters for 150 IGS sites since 1997 (Gendt, 1996 [5]). This allows us to compare at collocated sites (stations with VLBI and GPS antennas nearby) the combined total zenith delays derived by VLBI (IVS) with those derived by GPS (IGS).

Because both services, IGS and IVS, are using a very similar combination strategy, a comparison of the mean values of the hourly standard deviations is possible. Table 5 shows these values for identical epochs at collocated sites. As mentioned before, the relative accuracy of the VLBI derived total zenith delays is at the 2 mm level, and it is slightly better than that from GPS.

In a second step, the biases and standard deviations between the IGS and IVS time series of the total zenith delays are determined. The height differences between the VLBI and GPS stations are accounted for by using the meteorological data from the VLBI databases for the calculation of the differential hydrostatic and wet delays. Table 6 shows the mean biases between the time series and the standard deviations after removing these biases.

Although the standard deviations between the time series are at the 5 mm level or even worse, it is remarkable that all mean values of the total zenith delays derived by GPS are larger than those derived by VLBI. The positive biases are between +1.1 mm (Medicina) and +13.5 mm (Fortaleza). Apart from the systematic effects for VLBI described above there might be some problems with

Table 5. **Collocated sites with VLBI and GPS antennas.** The 2-letter IVS acronym and the 4-letter IGS acronym are given as well as the height difference (VLBI - GPS) between the antennas. The last two columns show mean values of the hourly standard deviations for the combined IVS and IGS time series for identical epochs.

site	**IVS acronym**	**IGS acronym**	**height diff.**	**std. IVS**	**std. IGS**
Algopark	Ap	ALGO	23.0	1.8	2.4
Fortleza	Ft	FORT	3.3	2.7	4.6
Gilcreek	Gc	FAIR	14.2	1.6	2.2
Hartrao	Hh	HRAO	2.3	2.5	3.0
Hobart26	Ho	HOB2	24.9	2.0	2.8
Matera	Ma	MATE	8.7	2.0	4.0
Medicina	Mc	MEDI	18.1	1.3	1.3
Nyales20	Ny	NYAL	6.5	1.5	1.5
Seshan25	Sh	SHAO	8.2	1.9	4.4
Wettzell	Wz	WTZR	4.1	1.6	1.9
Onsala60	On	ONSA	13.8	1.2	1.8

Table 6. **Biases (IGS minus IVS) and mean values of the hourly standard deviations in mm at collocated sites for the combined IVS and IGS time series.** Although the height difference between the antennas is taken into account all biases are positive.

site	**bias**	**std**	**site**	**bias**	**std**	**site**	**bias**	**std**
ap	7.2	+/- 4.9	ft	13.5	+/- 10.0	gc	4.4	+/- 3.7
hh	5.2	+/- 8.0	ho	3.4	+/- 6.0	ma	3.9	+/- 7.2
mc	1.1	+/- 5.3	ny	3.7	+/- 4.0	sh	1.9	+/- 5.6
wz	2.5	+/- 4.5	wf	5.2	+/- 4.3			

GPS observations as well:

- higher cutoff elevation angles (larger than 10 degrees),
- phase center variations,
- errors of satellite ephemerides,
- multipath effects, ...

6. Results and conclusions

VLBI is capable of determining very accurate tropospheric zenith delays. Apart from systematic errors that might be inherent in the VLBI technique the accuracy is at the 2-4 mm level. Therefore, zenith delays derived by VLBI can be compared to those derived by GPS and WVR. The task of comparing the gradients remains to be done.

The other field of application for zenith delays derived by VLBI is the contribution to climatological studies, at least when the time series get longer.

The results of the IVS Pilot Project - Tropospheric Parameters can be found in weekly directories at ftp://cddisa.gsfc.nasa.gov/vlbi/ivs-pilottro . The files are called sswwww.zpd when ss is the 2-letter station acronym and wwww is the GPS week number. ACs that would like to join the PP are very welcome; please contact the authors for details.

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