IVS Pilot Project – Tropospheric Parameters

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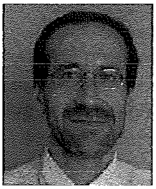 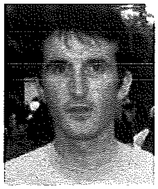

Abstract

In April 2002 the IVS (International VLBI Service for Geodesy and Astrometry) set up the Pilot Project – Tropospheric Parameters, and the Institute of Geodesy and Geophysics (IGG), Vienna, was asked to coordinate the project. Seven IVS Analysis Centers have joined the project until now 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. The individual submissions are combined by a two-step procedure to stable, robust and highly accurate tropospheric parameters with 1 h resolution. The zenith delays derived by VLBI (Very Long Baseline Interferometry) are compared with those provided by the International GPS Service (IGS). At collocated sites (VLBI and GPS antennas at the same station), almost constant biases are found between the GPS (Global Positioning System) 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.

Kurzfassung

Ganz ähnlich wie das GPS-Verfahren ist auch die Radiointerferometrie auf langen Basislinien (Very Long Baseline Interferometry, VLBI) in der Lage, troposphärische Laufzeitverzögerungen in Zenitrichtung sehr genau zu bestimmen. Diese beinhalten unter anderem Informationen über den Feuchtegehalt der Troposphäre an den beteiligten VLBI-Stationen. Die Ergebnisse können nicht nur für meteorologische Zwecke verwendet werden, sondern spielen auch in der Klimaforschung eine Rolle. Wieder einmal zeigt sich, dass sozusagen ein Nebenprodukt geodätischer Messungen von großem Interesse für Nachbardisziplinen der Geodäsie sein kann. Zwar ist die globale Verteilung von VLBI-Stationen nicht so hoch wie bei GPS und eine Auswertung in Echtzeit ist noch nicht möglich, aber dennoch sind die troposphärischen Laufzeitverzögerungen der VLBI auf Grund ihrer hohen Genauigkeit von großer Bedeutung für Vergleiche mit Ergebnissen von GPS oder anderen Techniken, wie z. B. Wasserdampfradiometern. Außerdem können für einige VLBI-Stationen konsistente Zeitserien der troposphärischen Parameter von beinahe 20 Jahren ermittelt werden, die für klimatologische Studien herangezogen werden können. Aus diesen Gründen wurde im April 2002 durch den IVS (International VLBI Service for Geodesy and Astrometry) das 'Pilot Project – Tropospheric Parameters' eingerichtet, und das Institut für Geodäsie und Geophysik (IGG) der TU Wien wurde mit der Koordination des Pilotprojekts betraut. Mittlerweile nehmen sieben VLBI-Analysezentren teil und reichen regelmäßig ihre Schätzungen der troposphärischen Parameter (totale und feuchte Laufzeitverzögerung in Zenitrichtung, horizontale Gradienten) der IVS-R1 und IVS-R4 Experimente seit 1. Jänner 2002 ein. Die einzelnen Abgaben werden am IGG in einem zweistufigen Verfahren zu genauen und stabilen troposphärischen Parametern mit stündlicher Auflösung kombiniert. Diese Laufzeitverzögerungen in Zenitrichtung wurden mit den vom IGS (International GPS Service) ermittelten Werten verglichen. An Stationen mit VLBI- und GPS-Antennen treten konstante Differenzen zwischen den Laufzeitverzögerungen auf, obwohl beide Verfahren den gleichen troposphärischen Einflüssen unterliegen. Mögliche Gründe dafür werden diskutiert.

1. Introduction

In the last few years, the collaboration between geodesy and meteorology/climatology has become more and more intensive. GPS (Global Positioning System) has proved to be very important 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 (Very Long Baseline Interferometry) 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 their high accuracy, the parameters derived by VLBI 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 (International VLBI Service for Geodesy and Astrometry) 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., 2002b, [2]). 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.

	IVS Analysis Center
BKG	Federal Agency for Cartography and Geodesy, Germany
CGS	Centro di Geodesia Spaziale, Italy
CNR	Istituto di Radioastronomia, Italy
GSF	NASA Goddard Space Flight Center, U.S.A.
IAA	Institute of Applied Astronomy, Russia
IGG	Institute of Geodesy and Geophysics, Austria
OSO	Onsala Space Observatory, Sweden

Table 1: IVS ACs taking part in the PP – Tropospheric Parameters. Onsala Space Observatory joined the PP in January 2003.

2. Submissions by the ACs

Most of the ACs have provided their tropospheric parameters beginning with January 2002. That allows the generation of a combined series since the start of the IVS-R1 and IVS-R4 sessions. Total and wet zenith delays as well as gradients are submitted by all ACs. GSF and IGG even apply a priori gradients calculated from numerical weather models. Most of the ACs use the CALC/SOLVE software package, only IAA and IGG apply the QUASAR and OCCAM software, respectively. About half of the ACs fix the ITRF2000, and all ACs use cutoff elevation angles at or below 5°. The Niell mapping functions (Niell, 1996, [5]) are used throughout – only IGG applies the isobaric mapping function of the hydrostatic part (Niell, 2001, [6]). Meteorological parameters can be extracted from the databases.

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

Table 2: Features of the submissions. Two ACs use a priori gradients; four ACs fix ITRF2000.

The tropospheric parameters should be provided for every full hour, i.e. in equidistant time intervals of 60 minutes, starting at the first integer hour of the session. If other time intervals are used for the computation (e.g., longer time intervals for the gradients), all parameters have to be referred to the same hourly instants. More details about the Pilot Project – Tropospheric Parameters, the Pilot Project Group and the submissions of the ACs are described in Schuh et al. (2003, [8]).

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, namely one for the IVS-R1 and one for the IVS-R4 session. They are combined to weekly files in order to be comparable with results provided by the IGS, although most VLBI sites take part in one 24 h session per week only.

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
...	...	...

Table 3: The IVS-R1 and IVS-R4 sessions are combined to weekly files.

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 instants 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).

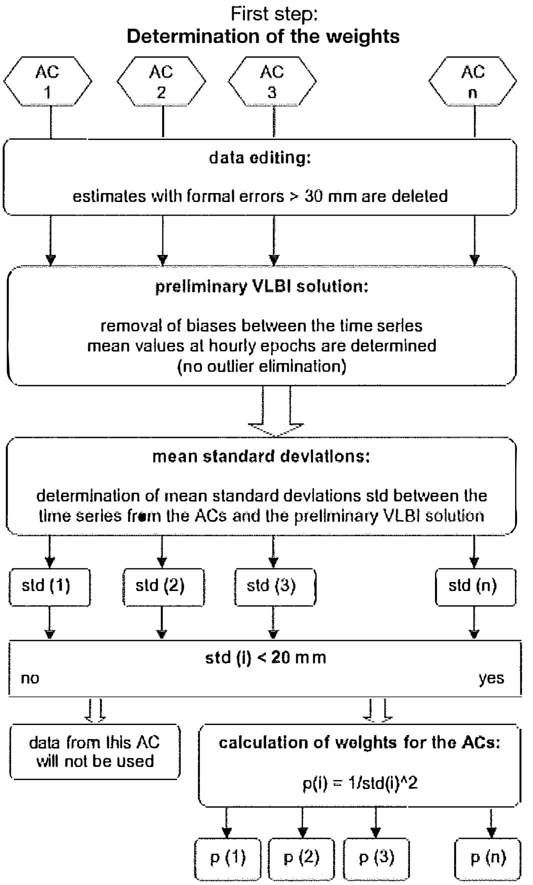

Figure 1a.: First step of the combination procedure. Weights for the individual ACs are determined and 'bad observations' are discarded.

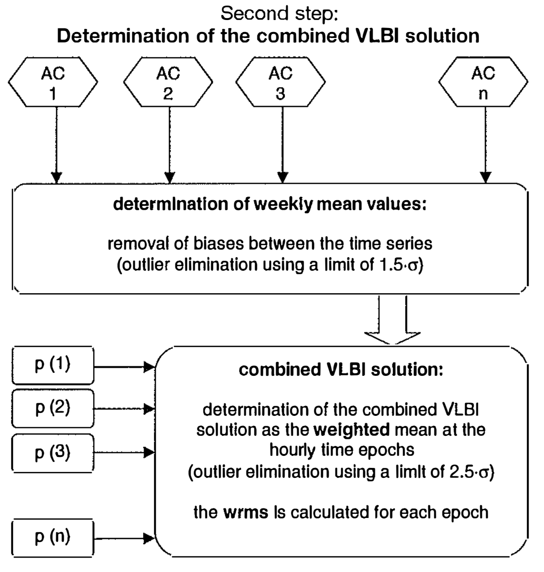

Figure 1b: Second step of the combination procedure. The combined VLBI solution is determined using outlier elimination.

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 mean values at each time 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

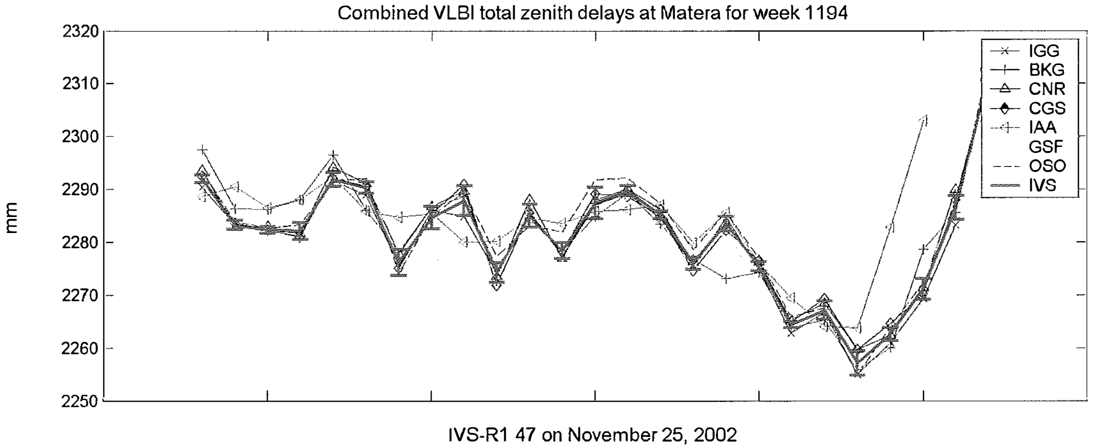

Figure 2: Submissions for the wet zenith delays at Matera by the various Analysis Centers (GPS week number 1194) and the combined VLBI solutions (red bold line with error bars). A rather good agreement between the time series can be seen. The mean of the standard deviations of the combined hourly results is ± 1.5 mm.

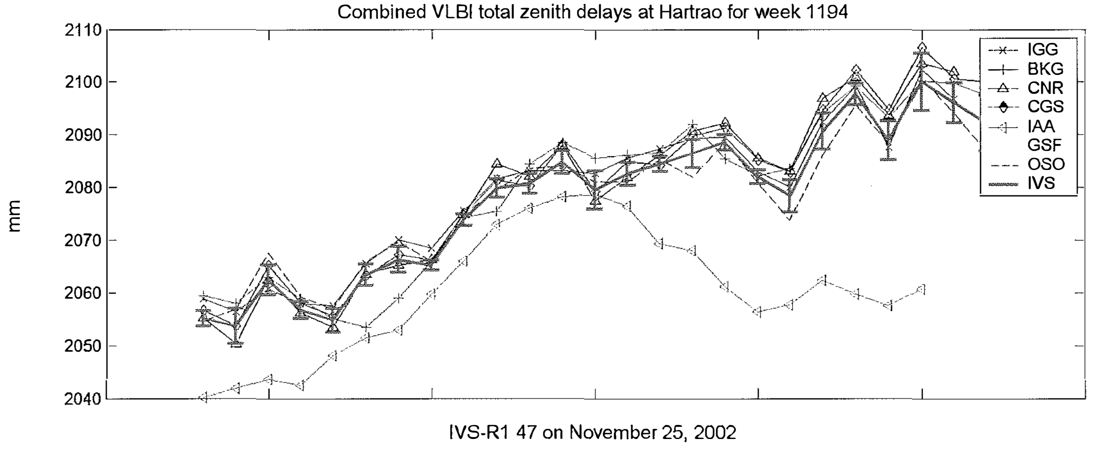

Figure 3: Submissions for the wet zenith delays at Hartrao by the various Analysis Centers (GPS week number 1194) and the combined VLBI solutions (red bold line with error bars). The mean of the standard deviations of the combined hourly results is ± 2.5 mm.

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 limit of 1.5 σ (σ ... standard deviation). Then the VLBI values of the tropospheric parameters at each time are calculated as weighted means. Again, outliers are removed that exceed a limit of 2.5 σ.

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 Figures 2 and 3. While Figure 2 (Matera) shows a rather good agreement between the ACs ($\pm$1.5 mm), the mean of the standard deviations of the combined hourly results in Figure 3 (Hartrao) is larger (2.5 mm). Anyway, the combined series is usually much smoother and thus probably more stable and robust than the individual submissions of the ACs. On the other side, short period variations of the zenith delays as for instance at Matera (Figure 2) seem to be reproduced by the combined values. In some sessions there were gaps in the observations at certain stations that have not been recognized by the ACs. For instance, if there were no observations in the middle of a 24 h 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 adopted 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 around the combination time.

Furthermore, so far a combined solution is only computed if there are at least data from three ACs contributing. Finally for cross checking, meteorological data are taken from the databases to compute the hydrostatic zenith delays at each station by the formula of Saastamoinen (1973, [7]). If the difference between the total and the hydrostatic plus wet delay of the combined solution is larger than 3 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 due to the VLBI technique 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 of the terrestrial reference frame (at least for those solutions where the ITRF2000 is fixed),
- errors of the mapping functions,
- unmodelled effects (atmospheric loading, antenna deformation, ..)

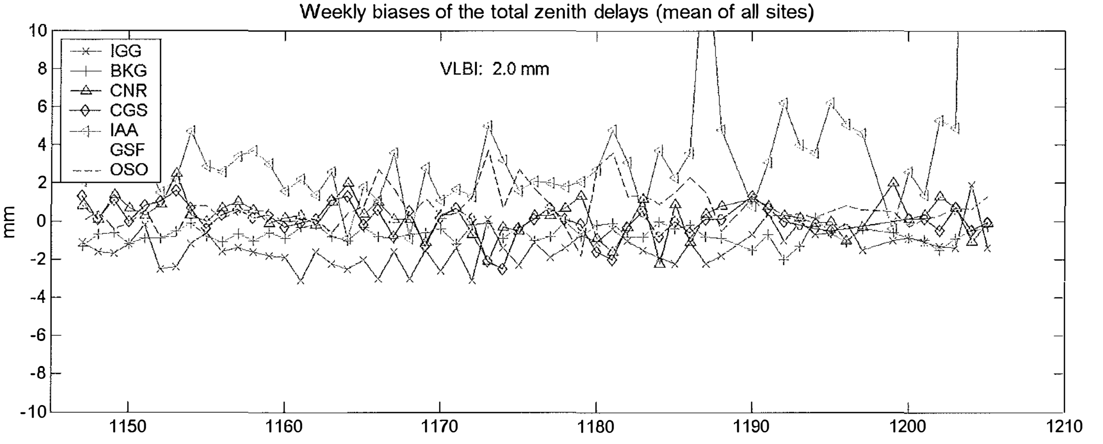

Figure 4: Weekly biases of the total zenith delays in 2002. The biases are within ± 2 mm for most of the ACs.

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 instants 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.

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 ~$\pm$1.8 mm.

5. Comparison with tropospheric parameters determined by IGS

The IGS has produced tropospheric parameters for 150 IGS sites since 1997 (Gendt, 1996, [4]). This allows to compare at collocated sites (stations with VLBI and GPS antennas nearby) the combined total zenith delays derived by VLBI within the IVS-PP with those published by the IGS.

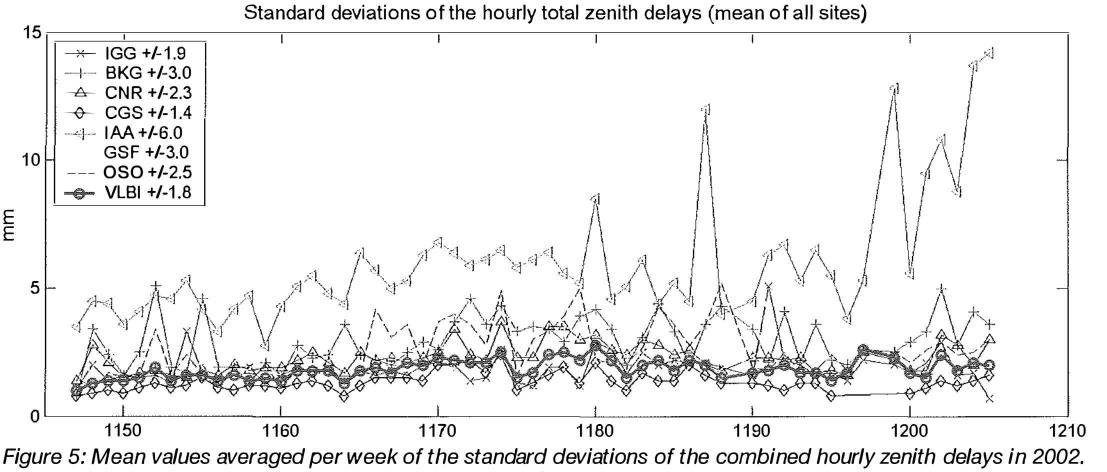

Figure 5: Mean values averaged per week of the standard deviations of the combined hourly zenith delays in 2002. Additionally, the mean values of the standard deviations for all stations are shown that were achieved by the individual ACs.

site	IVS acronym	IGS acronym	height diff. [m]	std. IVS [mm]	std. IGS [mm]
Algopark	ap	algo	23.0	±1.6	±2.2
Fortleza	ft	fort	3.3	±2.6	±4.4
Gilcreek	gc	fair	14.2	±1.5	±2.2
Hartrao	hh	hrao	2.3	±2.4	±3.1
Hobart26	ho	hob2	24.9	±2.4	±2.6
Matera	ma	mate	8.7	±1.8	±3.9
Medicina	mc	medi	18.1	±1.1	±1.3
Nyales20	ny	nyal	6.5	±1.4	±1.6
Seshan25	sh	shao	8.2	±1.8	±4.4
Wettzell	wz	wtzr	4.1	±1.5	±1.8
Onsala60	on	onsa	13.8	±1.0	±1.8

Table 4: Collocated sites with VLBI and GPS antennas. The 2-letter IVS acronyms and the 4-letter IGS acronyms are given as well as the height differences (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.

Because both services, IGS and IVS, use very similar combination strategies, a comparison of the mean values of the hourly standard deviations is possible. Table 4 shows these values for identical times at collocated sites. As mentioned before, the relative accuracy of the VLBI derived total zenith delays is at the ±2 mm level, and for most of the stations treated here 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 means of meteorological data recorded at the VLBI stations for the calculation of the differential hydrostatic and wet delays. Table 5 shows the mean biases between the time series and the standard deviations after removing these biases.

from the systematic effects for VLBI described above, there might be some problems with GPS observations as well:

- higher cutoff elevation angles applied in GPS (larger than 10 degrees),
- multipath effects,
- phase center variations of the antennas,
- errors of satellite ephemerides,
- same mapping function for the hydrostatic and wet delays

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 of the combined hourly VLBI results is at the 2–4 mm level. The first year of

site	bias	std	site	bias	std	site	bias	std
ap	7.1	±4.8	ft	13.5	±9.6	gc	4.2	±3.7
hh	5.2	±8.1	ho	3.2	±7.4	ma	3.9	±6.8
mc	1.4	±4.6	ny	4.1	±3.8	sh	1.5	±6.0
wz	2.4	±4.3	wf	4.8	±4.5			

Table 5: 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.

Although the standard deviations between the IVS and VLBI time series are at the ±5 mm level or even worse, it is noticeable that all mean values of the total zenith delays derived by GPS are larger than those derived by VLBI. The positive biases are between +1.4 mm (Medicina) and +13.5 mm (Fortaleza). This confirms first results reported by Boehm et al. (2002a, [1]). Apart

the Pilot Project clearly showed that comparing and combining the results of several ACs which use different VLBI software or apply different analysis strategies allows

- to give feedback to the individual AC in case of any problems,
- to determine stable, robust and highly accurate final IVS products with standard devia-

tions that are usually significantly smaller than those of the individual submissions.

Zenith delays derived by VLBI can be compared to those derived by GPS and WVR. The always positive and almost constant biases between the GPS and VLBI time series at collocated sites need to be investigated in more detail.

The other field of application for zenith delays derived by VLBI is the contribution to climatological studies, at least when the time series cover a longer time interval. First results are reported by Boehm et al. (2003, this issue, [3]).

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