Combination Studies Using the CONT02 Campaign

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Abstract

This report gives an overview of the combination studies performed by the Forschungseinrichtung Satellitengeodäsie TU München (FESG) and the Deutsches Geodätisches Forschungsinstitut (DGFI) based on the data of the IVS CONT02 campaign. The presented results demonstrate the high potential of a combination of VLBI, GPS and SLR data.

1. Introduction

The 15-days CONT02 campaign of the International VLBI Service for Geodesy and Astrometry (IVS) was used for various comparison and combination studies together with data from other space geodetic techniques. Due to a broad spectrum of common parameters, the studies mainly focussed on the combination of VLBI and GPS. As both techniques make use of microwave signals, identical tropospheric parameters, i.e., zenith delays and horizontal gradients, can be estimated from the VLBI and GPS data for each observing station and can be combined together with the station coordinates and Earth orientation parameters (EOP). In view of a combination with other observing techniques, one big advantage of the CONT02 campaign compared to other VLBI sessions can be seen in the continuous availability of eight observing stations for the whole time span. The participating stations were Algonquin Park, Gilmore Creek, Hartebeesthoek, Kokee Park, Ny-Alesund, Onsala, Westford and Wettzell. All stations are equipped with a permanent GPS antenna and the appropriate local tie information is available (for Ny-Alesund see Steinforth et al. 2003; else, ITRF2000 local ties are available, see Altamimi et al. 2002). The situation is much worse regarding the co-location of VLBI and SLR, because only two of the eight observing VLBI stations can be used, namely Wettzell and Hartebeesthoek. Therefore, a stable combination of these reference frames can only be realized via GPS-SLR co-locations.

2. Data and Processing

In a first step, daily normal equations for each technique were generated for the time span of CONT02, i.e. October 16-30, 2002. The analysis of the VLBI data was done at DGFI using the software OCCAM (Titov et al. 2001), and the GPS analysis was performed at FESG using the Bernese GPS Sofware 5.0 (Hugentobler et al. 2004). It is important to mention that both software packages were prepared in such a way that identical a priori models and identical parameterizations could be used for these special studies. This is crucial for a rigorous combination on the normal equation level and to ensure that the results are identical to those obtained by a combination on the observation level. The SLR solution was also processed with the Bernese GPS Software 5.0, including all Lageos-1 and Lageos-2 data. In view of an inter-technique combination it is a big advantage that any inconsistencies between the techniques due to different models and parameterizations are completely avoided, although the SLR-only solution is probably not of highest quality.

Table 1 summarizes the temporal resolution and the type of parameterization that were chosen for the estimated parameters and the results are presented in the following. This results in a large amount of parameters, especially due to the hourly estimation of Earth rotation parameters and tropospheric zenith delays (ZD). The corresponding number of parameters for each technique and each parameter type is given in Table 2 together with the number of observations that are available for the two weeks. The original number of parameters includes, among others, phase ambiguities (GPS) and orbit parameters (GPS and SLR). Let us point out that the number of GPS observations exceeds that of the other techniques by orders of magnitude, but so does the number of parameters that have to be estimated from these observations. At the beginning of the CONT02 analysis, a lower temporal resolution, i.e., two hours, was chosen for the ERP and tropospheric zenith delays. The corresponding analyses and results are documented in Thaller et al. 2005 and Krügel et al. 2004. Based on these results, the temporal resolution was doubled in order to allow also fast changing features to be grasped, especially in the tropospheric delays.

Table 1. Temporal resolution and parameterization

Station coordinates	daily	constant
ERP	1 hour	piece-wise linear
Nutation angles	daily	piece-wise linear
Tropospheric ZD	1 hour	piece-wise linear
Tropospheric gradients	daily	constant

Table 2. Statistical information for a 14-days solution

	VLBI	GPS	SLR
# stations	8	153	23
# observations	46682	5935760	5088
# parameters (original)	3942	104584	1114
# station coordinates	24	459	69
# tropospheric parameters	2879	2929	-
# EOP	1015	1015	1015

3. Combination Results

Let us now discuss each of the three types of parameters that were estimated from VLBI, GPS and SLR. To begin with the Earth orientation parameters, the most important contribution of VLBI is UT1-UTC as well as the nutation offsets, because VLBI is the only technique to determine these two parameter types. The satellite techniques can only determine the corresponding rates. As an example, the hourly UT1-UTC values estimated by VLBI and GPS w.r.t. the official C04-series and the IERS2000 sub-daily model are shown in Figure 1. In spite of the big drift in the GPS estimates the combined UT1-UTC is aligned to the VLBI estimates. The RMS of the remaining differences to C04/IERS2000 can even be reduced from 0.015 ms for the VLBI-only solution to

0.011 ms for the combined solution, clearly demonstrating the advantage of an inter-technique combination. This improvement of the RMS due to an inter-technique combination can be seen for the x- and y-pole components as well, summarized in Table 3.

Table 3. RMS values of the remaining differences to C04/IERS2000 (offset removed).

	GPS	VLBI	Combination
X-pole [mas]	0.143	0.259	0.120
Y-pole [mas]	0.144	0.253	0.130
UT1-UTC [ms]	-	0.015	0.011

The capability of VLBI to determine UT1-UTC and the nutation offsets is sustained in the combination and is not disturbed by the satellite techniques as people are often worried about. The reason must be seen in the a posteriori formal errors of the estimated parameters that are displayed in Figures 2a and 2b for UT1-UTC and the nutation in obliquity, respectively. Whereas the VLBI estimates are more or less of equal accuracy during the entire time span, the UT1-UTC and nutation estimates from the satellite techniques heavily degrade with time. Daily values for UT1-UTC were generated for these two figures in order to show reasonable SLR results as well. Comparing GPS and VLBI only, the same behavior is visible for the hourly estimates.

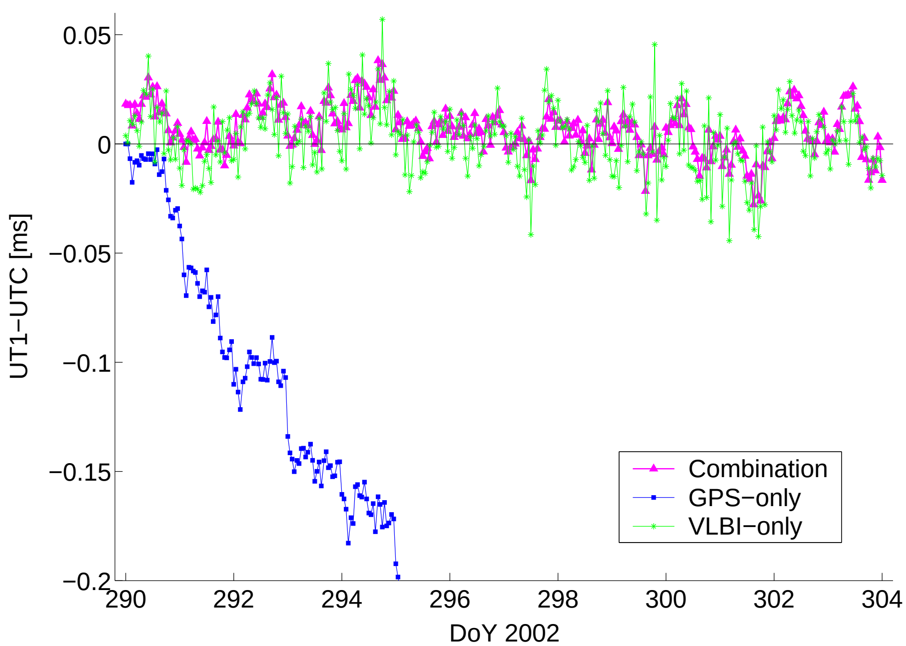

Figure 1. Hourly UT1-UTC estimates w.r.t. C04/IERS2000 derived from VLBI, GPS and a combined solution.

Analyzing the station coordinates gives an impression of the quality of the network. As far as the VLBI network of CONT02 is concerned, the distribution of the eight stations is obviously not perfect, especially in north-south direction. This imbalance between northern and southern

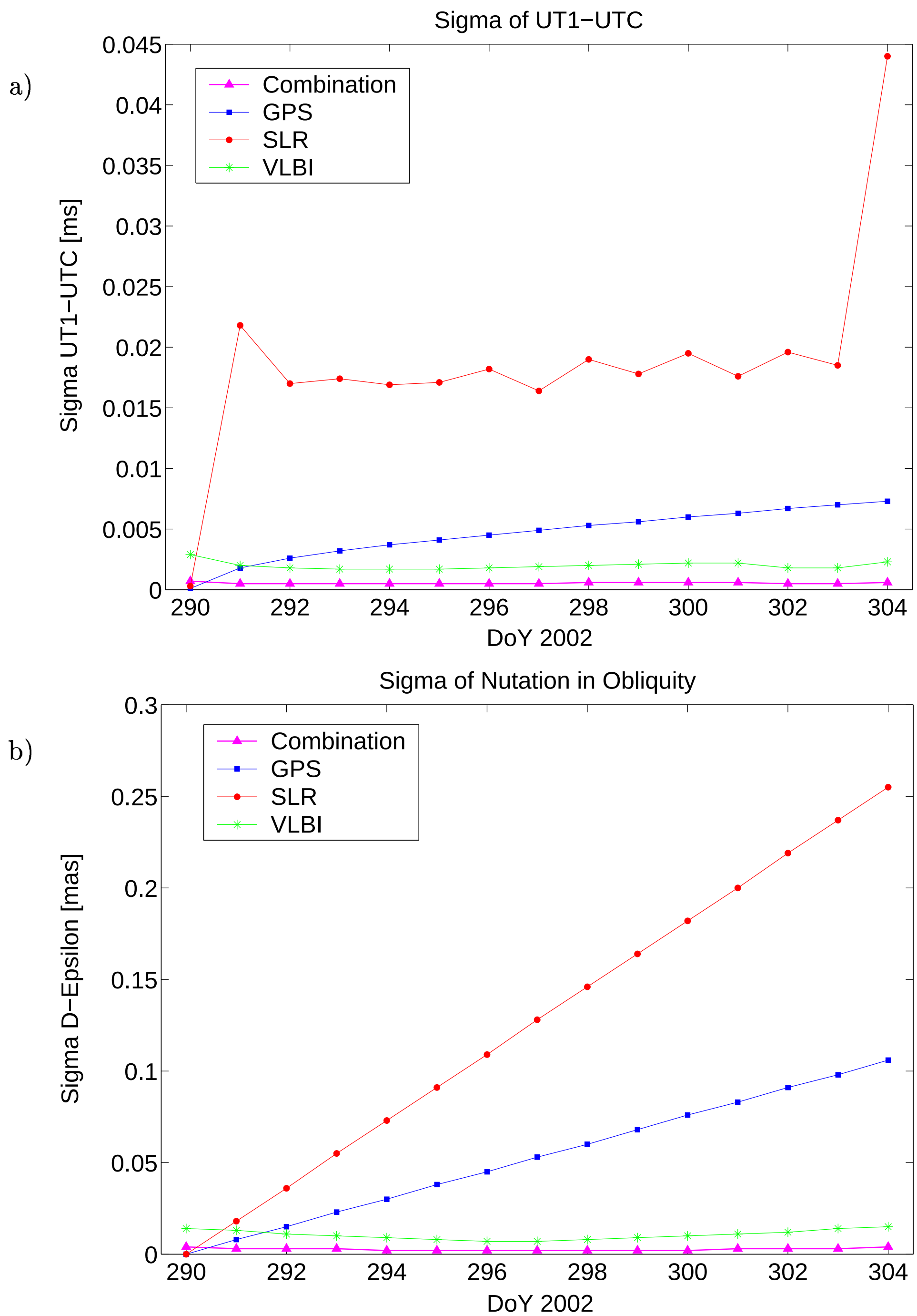

Figure 2. Formal errors of daily EOP estimates: (a) UT1-UTC, (b) Nutation in obliquity

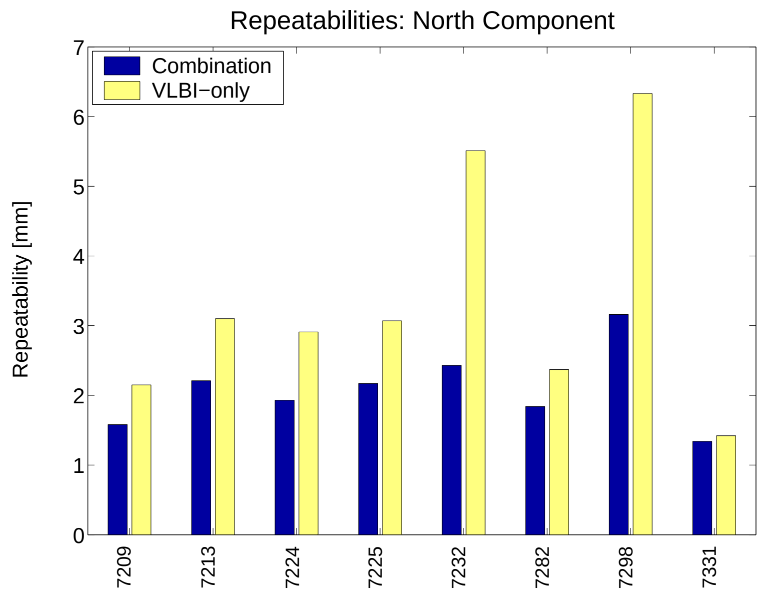

Figure 3. Repeatability of VLBI station coordinates before and after the combination with GPS (north component only).

hemisphere is reflected in the repeatability of the station coordinates. The mean repeatability for a VLBI-only solution is: 3.71 mm (north), 1.97 mm (east), 7.66 mm (height). In comparison, the mean repeatability for the more homogeneous GPS network of 150 stations is: 1.97 mm (north), 1.95 mm (east), 5.93 mm (height). This deficiency of the VLBI network can be compensated by the combination with GPS, where the datum definition is realized by a no-net-rotation condition for a subset of about 90 good and stable GPS stations and where the VLBI network is integrated through the eight local ties. Figure 3 shows the repeatability of the north component for the eight VLBI stations for a VLBI-only solution and for a combination with GPS. The improvement is clearly visible. However, an improvement of the RMS values due to the combination is not only achieved for the north component of the VLBI stations. Most of the station coordinates of both techniques improve in a combination, although this improvement is less pronounced (see Krügel et al. 2004).

It is widely known that the third parameter group, i.e., the tropospheric parameters (ZD and horizontal gradients), are highly correlated with the station coordinates. First of all, it must be stated that, in general, the agreement between the two techniques is very good. Let us start with looking at the tropospheric zenith delays. The height differences between the corresponding GPS and VLBI reference points have to be corrected for, if the ZD estimates of both techniques are to be compared or combined. For the studies presented here, the Saastamoinen model with mean surface meteorological data was used for this purpose. The modeled ZD differences to be expected theoretically (Saastamoinen) are compared to the differences between the space techniques averaged over 14 days (see Table 4). For Algonquin Park, Wettzell and Hartebeesthoek the agreement between the estimation and the model is quite good. The biases for Onsala, Fairbanks and Ny-Alesund might be caused by unmodeled phase center variations of the radomes installed on the GPS antennas, whereas the biases for Kokee Park and Westford cannot be explained at the moment. Although the errors in the zenith delay estimates due to a radome seem to be systematic, a conclusive statement about this topic cannot be given because the number of eight stations is too small and not enough studies were done up to now.

Table 4. Comparison of tropospheric zenith delay differences from the Saastamoinen model and the space techniques [mm].

	Model	GPS-VLBI Δ ZD	Diff. Δ ZD - Model	Radome
Ny-Alesund	0.96	-0.50	-1.46	yes
Onsala	4.53	1.17	-3.36	yes
Wettzell	0.98	1.26	0.28	
Hartebeesthoek	0.46	-0.40	-0.86	
Algonquin Park	7.33	7.28	-0.05	
Fairbanks	3.90	0.74	-3.16	yes
Kokee Park	3.04	8.40	5.36	
Westford	0.57	4.38	3.81	

The high correlation between tropospheric parameters and station coordinates can nicely be shown by means of the horizontal gradient estimates. In general, the gradients estimated independently by VLBI and GPS match quite well as shown in Figure 4a for the north gradient of the station Fairbanks. In a first step, all available local ties are introduced into the combination, whereupon the resulting gradients for VLBI and GPS (gradients not yet combined) show a clear bias (Figure 4b). As can be seen in Figure 4c, this bias can be removed if the north component of the Fairbanks local tie is not introduced into the combination. Together with comparably large discrepancies between the coordinate differences and the local tie values, this investigation leads to the conclusion that the north component of the local tie for Fairbanks should be disregarded in a combination. A very similar effect is present in the Westford local tie (east component).

Comparable studies were also performed for the correlation between the height component of the local ties and the tropospheric zenith delay differences between VLBI and GPS. Apparently, the height differences measured by the space techniques do not always agree with the local tie values available. If these "wrong" height differences are fixed in a combination by introducing the local ties, the discrepancies are absorbed by the tropospheric ZD because of the high correlation. This means that the ZD estimates change significantly. In order to see whether such problems can be avoided, the potential of combining the tropospheric ZD instead of introducing the local ties in height was tested. On the basis of the repeatability of the station heights, Figure 5 demonstrates that this alternative combination method works. Introducing only the horizontal local ties and combining the tropospheric ZD improves the repeatability in height compared to a solution without combining the ZD. However, as expected, the combination of the zenith delays cannot fully replace the direct combination of the height components.

For the validation of the tropospheric zenith delays independent measurements from water vapor radiometers (WVR) can be used. However, such measurements are not available for all CONT02 stations. As an example, the wet tropospheric zenith delay (ZWD) from the WVR and from a combined GPS/VLBI-solution (after removing the dry delay using pressure measurements) is displayed in Figure 6 for the station Wettzell. In view of the large offset (about 20.6 mm) and

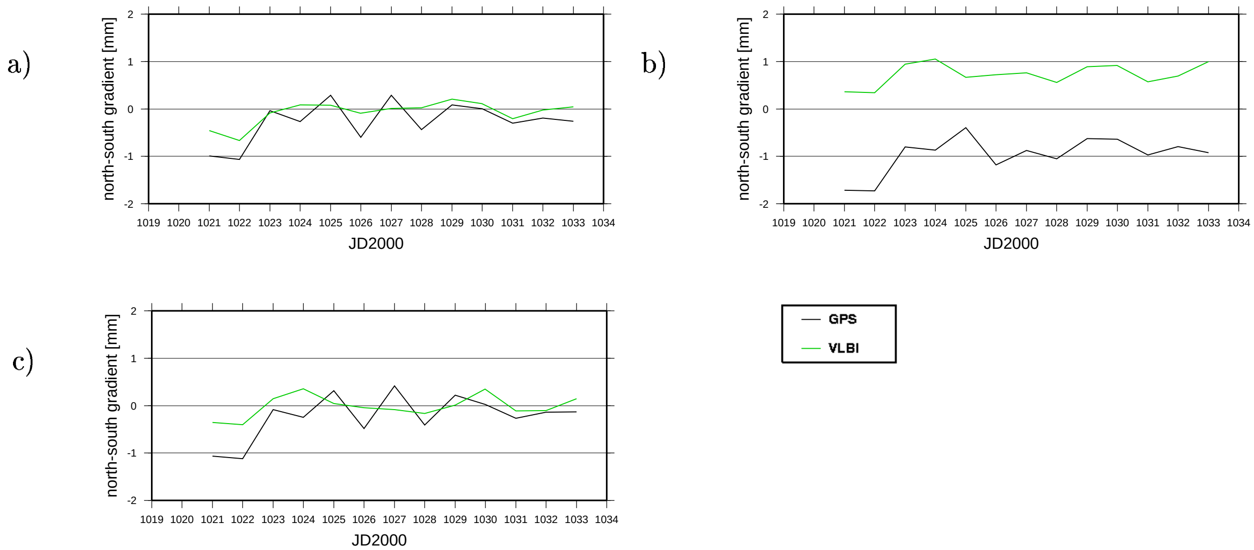

Figure 4. North gradient of Fairbanks from VLBI and GPS: (a) single technique solutions, (b) combination with all local ties, (c) combination with all local ties except for Fairbanks.

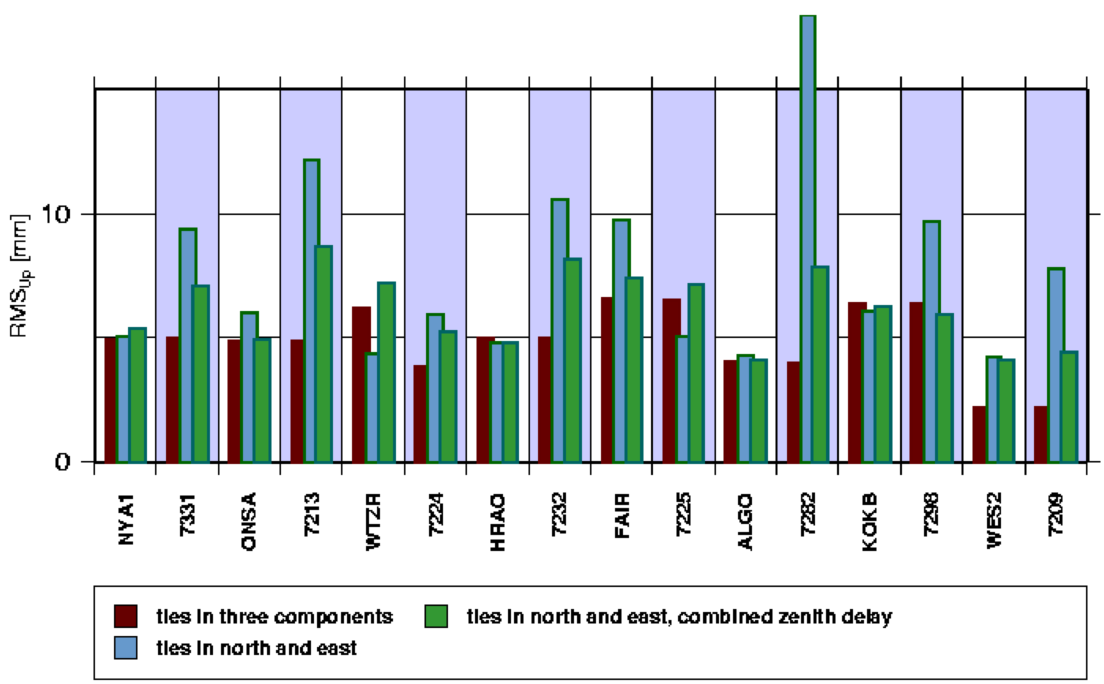

Figure 5. Repeatability of station heights for different combinations (shaded background for VLBI stations).

the high variability of the difference between the two techniques (14.5 mm), the usefulness of WVR for validating the tropospheric zenith delays of the space techniques is limited. In comparison, the RMS of the differences between GPS and VLBI zenith delay estimates is only about 6.9 mm, which means that these results are more stable by a factor of two. We have to add that analyses of the WVR data at Onsala were performed, yielding more encouraging companion results (see Elgered & Haas 2003).

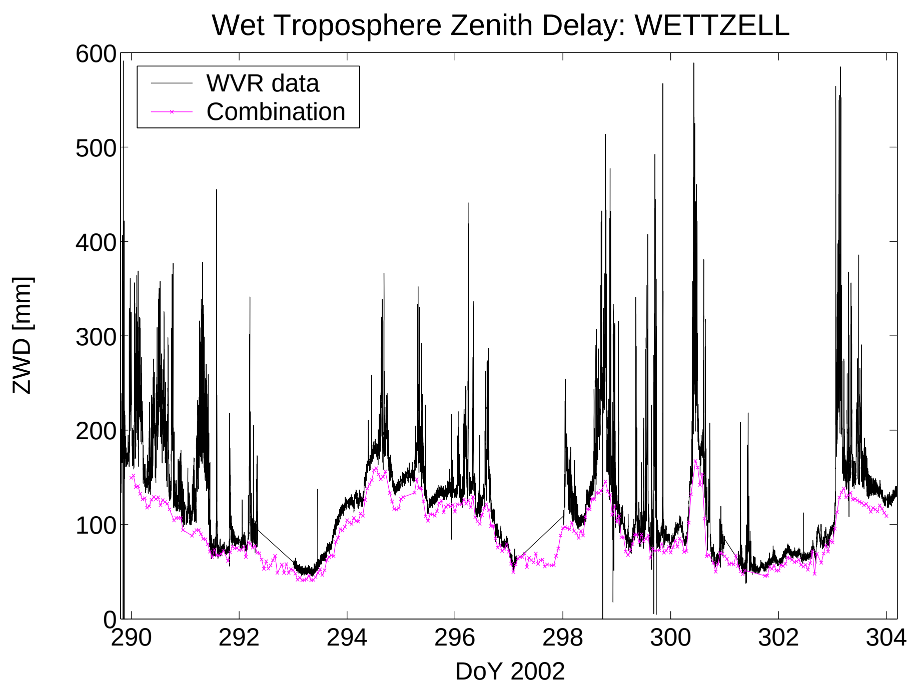

Figure 6. Comparison of wet zenith delays (ZWD) from space techniques and WVR at Wettzell.

4. Conclusions

The data of the continuous VLBI campaign CONT02, together with the data of the global GPS and SLR networks, has proved to be an excellent and unique data set to test rigorous combination algorithms and strategies. The combination of the CONT02 VLBI and GPS data has led to promising results for all parameters common to both techniques considered here, i.e., station positions, tropospheric parameters and Earth orientation parameters. As an important result, it could be demonstrated that the systematic effects present in LOD and nutation rates derived from satellite techniques do not necessarily result in a deterioration of UT1-UTC estimates and nutation offsets contributed to an inter-technique combination by VLBI. It was shown that tropospheric parameters are useful to detect problems in the local ties due to their strong correlation with station coordinates. When troposphere parameters are pre-eliminated before a combination, important inconsistencies between the techniques may hide in these parameters and go undetected. The analyses also showed that the combined solution can be improved by combining the tropospheric parameters. However, the remaining offsets in the tropospheric parameters for some of the stations still have to be analyzed in more detail.

5. References

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