Comparison of atmospheric parameters estimated from VLBI, GPS and microwave radiometer data

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Abstract

Very Long Baseline Interferometry (VLBI) is colocated with a permanent Global Positioning System (GPS) receiver and a Water Vapour Radiometer (WVR) at the Onsala Space Observatory (OSO). Both VLBI and GPS data are affected by the propagation delay of radio waves in the atmosphere, while the WVR is sensitive to the atmospheric emission close to the center of the 22 GHz water vapour emission line and provides wet delay estimates. We present a comparison of estimated atmospheric parameters (equivalent zenith wet delay and linear horizontal delay gradients) derived from an independent analysis of simultaneous VLBI, GPS and WVR observations. We study and compare the estimated parameters using different elevation cut off angles for the analysis of VLBI data with those obtained from the GPS and the WVR data analyses. The parameters are estimated for 90, 180 and 360 minutes long intervals, which allows us to study the averaging effect on the integrated parameters of the turbulent atmosphere.

1. Objectives

Variations in the atmospheric refractive index are a major error source for the space based geodetic techniques. Symmetry and the elevation dependence of the propagation delay are used in the VLBI and GPS processing for estimating the total zenith delay. It has been realized [*MacMillan,* 1995] that azimuthal asymmetries in the atmospheric refractive index could be present leading to errors in the horizontal and the vertical station coordinates. Including a horizontal gradient estimation into the data processing leads to an improved repeatability of the site coordinate estimates for both VLBI and GPS [*Rothacher et al.,* 1998; *Bar-Sever et al.,* 1998; *MacMillan,* 1995]. The objective of this work is to compare estimated wet delay and linear atmospheric gradients from the different techniques, study the differences and discuss the effect of the different processing strategies on the estimated atmospheric parameters. A better estimation of the horizontal gradients should lead to improved geodetic estimates.

2. Colocated techniques

The 20 m radome enclosed telescope at the Onsala Space Observatory is used for geodetic Very Long Baseline Interferometry (VLBI). In 1997 Onsala participated in 18 geodetic VLBI sessions, from the EURO, the CORE-B-100 and the RD-VLBA series [*Haas et al.,* 1999]. In our study 14 such 24 hour long sessions covering all seasons of the year 1997 were processed.

The permanent GPS site at Onsala is a part of the International GPS Service (IGS) [*Beutler et al.,* 1995] and is equipped with two receivers: a Turbo Rogue 8-channel and an Ashtech Z12 channel connected to a Dorne–Margolin B type antenna with a conically shaped radome. The receivers are connected to a 5 MHz reference frequency from the hydrogen maser which is also used in the VLBI observations.

The water vapour radiometer measures the sky emission at two frequencies – 21.0 GHz and 31.4 GHz. The sky emission (equivalent temperature) at those frequencies depends on the cosmic background emission, the amounts of water vapour, liquid water, and oxygen. By using algorithms described in [*Elgered,* 1993] the measured temperatures can be related to the wet path delay.

3. Atmospheric parameters of interest

The elevation dependencies of the wet and the hydrostatic component of the delay is used to estimate a total zenith delay (VLBI and GPS). The hydrostatic part can be estimated with good accuracy in the zenith direction based on the ground pressure measurements. Subtracting the hydrostatic component from the total delay yields the wet delay component.

The other parameter of interest is the horizontal wet delay gradient. Figure 1 displays an example of presence of a wet delay gradient in the WVR data. The first plot (1a) displays the measured delay, the second (1b) shows the zenith delay values for one scan at elevation the elevation 33.4 degrees (taken at time indicated with the vertical line in (1a)) and the third (1c) displays a 3D view of the mapped delay, where an obvious tilt in the delay values is present[1].

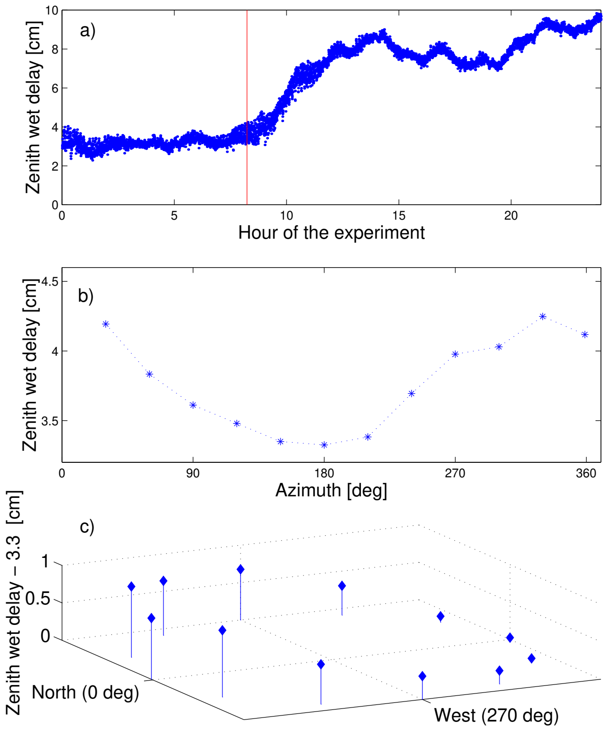

Figure 1: Example of wet delay gradient:
a) 24 hours of WVR data, August 31, 1998;
b) azimuth scan at the constant elevation 33.4 degrees at the time indicated by the line in 1a;
c) 3-D view of the wet delay for the azimuth scan.

A linear azimuthal asymmetry in the troposphere can be described using the model [*Davis et al.*, 1993]:

$$\begin{aligned}\Delta\tilde{L}^z(\epsilon,\phi,\Delta t) &= \Delta L^z + V_L\Delta t \\ &+ \cot\epsilon\left[1 - 10^{-6}N_s\csc^2\epsilon\right] \\ &\times\left[\Xi_n\cos\phi + \Xi_e\sin\phi\right]\end{aligned}$$

where ϵ and ϕ are the azimuth and the elevation angles, Δt the time (from the first epoch for which the model is derived), $\Delta\tilde{L}^z(\epsilon,\phi) = \Delta L/m_o(\epsilon)$ is the equivalent zenith wet delay, ΔL^z – mean zenith delay, V_L –zenith delay rate Ξ_i – north /east delay gradient components, $10^{-6}N_s\csc^2\epsilon$ – correction for bending (0.2^o for $\epsilon = 5^o$ at see level [*Davis et al.*, 1993]).

In our study we compare the wet delay estimates from WVR observations with the wet delay estimates from VLBI and GPS data. Note, however, that the horizontal gradient estimates from WVR are for the wet part only, whereas VLBI and GPS estimates are the total horizontal gradients. We assume that the main gradient contribution is due to the wet part, which is not completely true in situations when large pressure or temperature gradients exist at the site.

4. Data acquisition and processing strategies

The data of the three techniques were processed for 3 different time intervals 90, 180, and 360 minutes, producing estimates of delay and horizontal gradients. The VLBI data were processed using the SOLVE software. The constraints for the total delay and the delay gradients were 36 cm/day and 4 mm/day, respectively. The mapping functions derived by *Niell, [1996]* were used. Several solutions were produces using different cut-off angles of 5, 10, 15 and 20 degrees.

The GPS data at OSO are acquired in a continuous mode where a sampling frequency of 1 s is used. The data are resampled to 300 s during processing. JPL provided the orbits, the earth orientation, and the clock correction parameters. Using the GIPSY [*Webb and Zumberge*, 1996] processing package with fixed orbits, earth orientation, clock correction parameters and station coordinates provides the opportunity to use the Precise Point Positioning [*Zumberge et al.*, 1997] technique, where the zenith delay and linear gradients at the site are estimated. The Niell mapping functions and constrains equivalent to those used in the VLBI analysis were used for the specification of the Kalman filter used in GIPSY.

The WVR operates in a continuous sky scanning mode. The zenith wet delay estimates are obtained using an automated editing procedure

[1] *note the constant 3.3 cm wet delay subtracted from the total value for better visibility*

for th sun[2], the horizon mask[3] and rain[4]. After the wet delay was obtained the gradient model was fit to the data in a least squares sense to estimate the north and the east gradient parts.

5. Intercomparison results

Before presenting the comparisons it is worth to mention some features for each of the techniques. The VLBI estimates, especially the gradients might be affected by the source distribution on the sky. The GPS estimates will also be affected to some extend by the location of Onsala being 57^o in latitude, resulting in a poorer satellite coverage in the north. The WVR estimates are affected by rain and heavy clouds, and during those periods the data have larger uncertainties if they were not removed by the editing.

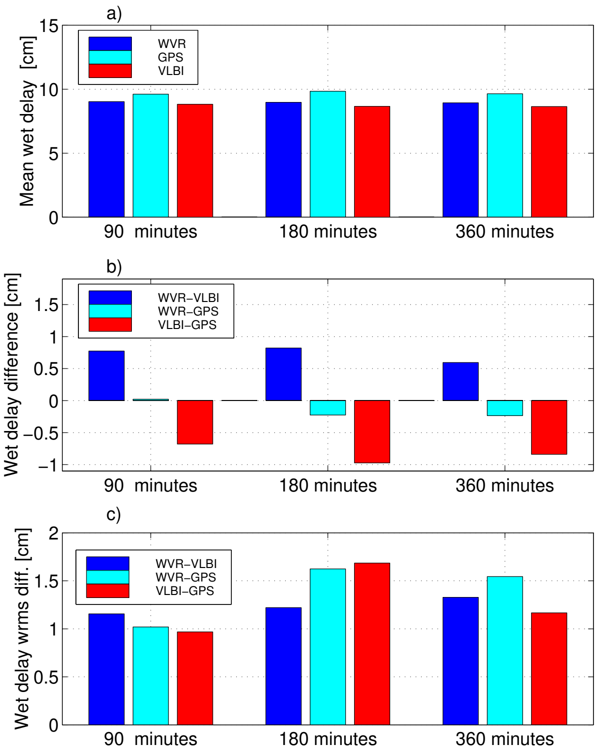

Figure 2: Wet delay statistics: a) weighted means; b) weighted differences; c) wrms differences.

First we present results for the zenith wet delay estimated from VLBI, GPS and WVR. Figure 2 displays a statistical comparison. Plot (2a) shows the weighted wet delay means. An agreement at the 1 cm level and no significant dependence on the estimation time interval is observed. The second plot (2b) shows the weighted mean difference between the different techniques. The WVR and the GPS results agree better according to this criterion while VLBI shows an underestimation of the delay. The third plot (2c) shows the weighted RMS (WRMS) differences. Some dependence on the estimation interval is present. The agreement varies between 1.0–1.5 cm for the different combinations of the techniques. Changing the elevation cut-off angle in th VLBI analyses did not affected the agreement. Given these results it is difficult to give any preferences for a better than 1 cm level agreement between any of the techniques.

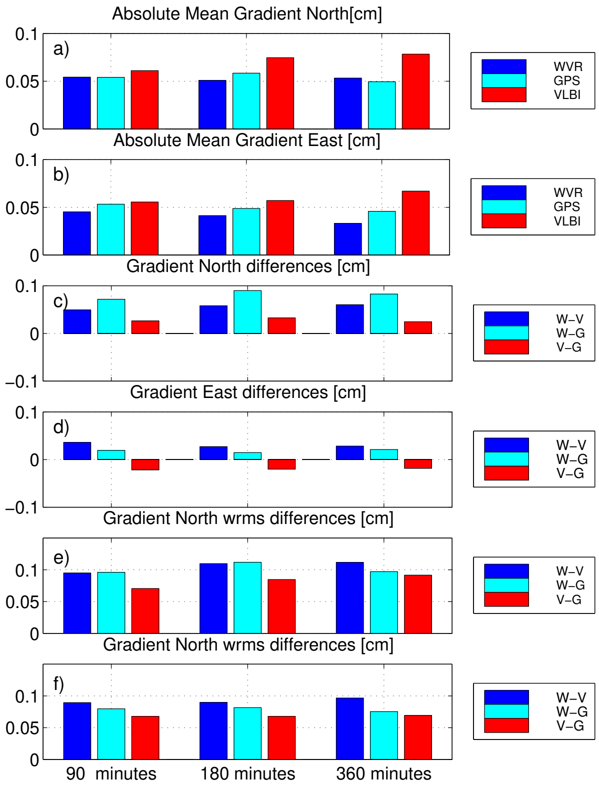

Figure 3: Gradient statistics: a) and b) absolute mean north and east; c) and d) differences north and east; e) and f) RMS differences north and east.

Figure 3 presents the results for the north and the east gradient components. The first two rows are the weighted absolute means of the gradient components. The WVR estimates decrease for increased time intervals, which is according to the expectations. The GPS esti-

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[2] *points obtained within 15^o of the sun are removed*

[3] *the 20 m antenna radome obscures the horizon between NE and E*

[4] *the wet delay algorithm brakes down during rain*

mates do not show a trend, while VLBI is estimating larger gradients for larger time intervals. This last feature is not physically reasonable and is up to now unexplained. It can be mentioned that looking at the time series of the VLBI gradient estimates shows that in general the VLBI results show less gradient variability, compared to WVR and GPS.

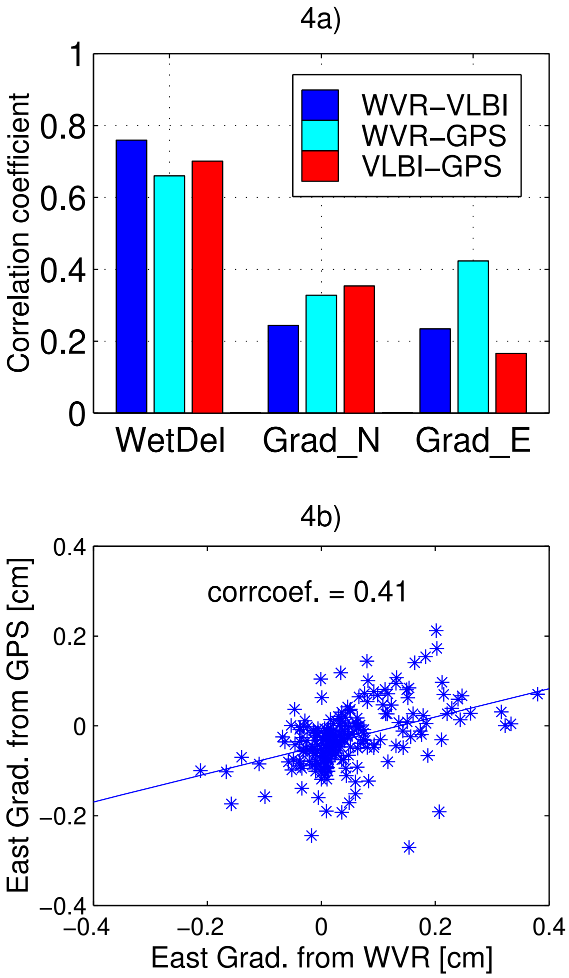

Figure 4: a) Cross-Correlation results for the 90 minutes intervals; b) Correlation plot WVR v/s GPS having the largest correlation coefficient.

A possible reason for that might be that the used constraints are too tight. Gradient differences – plots (3c) and (3d) – show that the best agreement is between VLBI and GPS results and that there are larger discrepancies with the WVR results. One possible explanation is that both VLBI and GPS are sensitive to the total gradient. In the eastern component this is not that obvious. The agreement between VLBI and GPS is also best for the WRMS differences (Fig. 3e and 3f). The dependence of the averaging time is again week. Since there is no consistent trend we may be seeing random variations due to the limited data set. It is interesting to mention that choosing higher cut-off angles increased the differences due to larger estimated gradients from the VLBI data. This is in agreement with the expectation of larger tropospheric inhomogeneity for smaller scales.

Finally the correlation coefficients for the 90 minutes estimates were calculated and the results are shown in Figure 4a. As expected the wet delay correlation is high (at the 0.7 level), while the estimated horizontal gradients are less correlated, which again shows the difficulty of comparing the small gradient components. Figure 4b shows one example correlation plot for the east 90 minutes gradients from the WVR v/s the GPS data set. This was the highest (0.4) correlation coefficient.

6. Conclusions and future work

From the presented comparison a good agreement between estimated wet delays from VLBI, GPS and WVR data was shown. The agreement is independent of the averaging time and the VLBI cut-off angle and the WRMS differences are at the 1–1.5 cm level, with correlation coefficients at the 0.7 level. The gradient comparison showed WRMS differences at the level of 1–1.5 mm. This is comparable to the magnitude of the gradients. Week dependence on the estimation time was present and a slightly better agreement between VLBI and GPS on average was evident, possibly related to the fact that both VLBI and GPS data are sensitive to the total gradients. Another possibility is the fact that a major error source of the WVR gradients is the presence of rain or heavy clouds. In the future processing of GPS data with elevation dependent weighting and different cut-off angles might be included. Different tropospheric parameters constrains will also be used. Finally we conclude that the typical size of the estimated horizontal gradient is less than 1 mm. Given that the differences between the estimates using different methods are at the same order, larger data sets are needed in order to study systematic effects.

References

Bar-Sever, Y. E., P. M. Kroger, J. A. Borjesson: Estimating horizontal gradients of tropospheric path delay with a single GPS receiver, *Geophys. Res. Lett.,* , **103(B3)**, 5019-5035, 1998

Beutler, G., I. I. Mueller and R. E. Neilan: The International GPS Service for Geodynamics (IGS): The story, in *GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, **115**, 3-13, Springer, 1996

Davis, J. L., G. Elgered, A. E. Niell and C. E. Kuehn: Ground-based measurements of gradients in the "wet" radio refractivity of air, *Radio Science*, **28(6)**, 1003-1018, 1993

Elgered, G.: Tropospheric radio-path delay from ground-based microwave radiometry, in Janssen, M. A. (ed), *Atmospheric Remote Sensing by Microwave Radiometry*, pp.218-258, Wiley & Sons, Inc, 1993

Haas, R., L. P. Gradinarsky, J. M. Johansson and G. Elgered: The atmospheric propagation delay: A common error source for Colocated Space Techniques of VLBI and GPS, *Poster paper at GEMSTONE*, Tokyo 1999

MacMillan, D. S.: Atmospheric gradients from very long baseline interferometry observations, *Geophys. Res. Lett.,* , **22(9)**, 1041-1044, 1995

Niell, A.: Global mapping functions for the atmosphere delay at radio wavelength, *Journal of Geophysical Research*, **101(B2)**, 3227-3246, 1996

Rothacher, M., T. A. Springer, S. Schaer, G. Beutler: Processing strategies for regional GPS networks, *International Association of Geodesy Symposia*, **118**, 1998

Webb, F. H. and J. F. Zumberge: An introduction to GIPSY/OASIS-II, *JPL Publication D-11088*, Jet Propulsion Laboratory, Pasadena, California, 1993

Zumberge J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins, F. H. Webb: Precise point possitioning for the efficient and robust analysis of GPS data from large networks, *Geophys. Res. Lett.,* , **102**, 5005–5017, 1997

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