Integrating GPS zenith path-delay measurements into VLBI analysis of geodetic observations with the European network

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The aim of this work is to contribute to the effort of increasing the accuracy of VLBI geodetic parameters. We are investigating a route to disentangle the coupling between the values of the vertical coordinates and the tropospheric contributions at each site, estimated from the VLBI analysis. We present results from a novel route of analysis which implements external GPS tropospheric estimates, computed every hour, in the VLBI analysis using the CALC/SOLVE package. Our working database consists of the six European VLBI geodetic observations from 1998. We have performed repeatability tests using both standard VLBI analysis and introducing GPS tropospheric estimates. The results are very encouraging and justify a deeper investigation of the potential of a route of analysis combining the products from both geodetic techniques. Also, astronomical observations at millimetre wavelengths, with coherence times as short as a few tens of seconds, would benefit from a better modelling of the wet component of the troposphere, allowing longer integration times.

1. Introduction

The radio signals observed with telescopes at the Earth are affected by the propagation medium, and variations in the distribution of the water vapour content in the troposphere ('wet component') are still considered one of the main error sources in the geodetic measurements with VLBI. A common way to correct for the extra path delay due to the wet component of the troposphere is to assume a horizontally stratified atmosphere to estimate the equivalent zenith wet delay from the data themselves using mapping functions to estimate values at appropriate elevation angles. However, given the close functional dependence of the tropospheric and geometric contributions in the mathematical formulation of the interferometric group delay, errors in the tropospheric modelling will corrupt the least squares adjustment of the vertical component of the site position. We intend to contribute to the effort of investigating the potential of new routes of analysis to increase the accuracy of the VLBI geodetic parameters. In particular we have tried to combine the products from two different geodetic techniques, namely GPS and VLBI.

The observational strategy used in VLBI to sample the atmosphere consists of a rapid switching of the antenna between radio sources in different directions to cover the whole sky, including low elevation angles. Instead, a GPS antenna collects the radio signals arriving **simultaneously** from the observations of a number of satellites from different directions. The later observational configuration would in principle seem more favourable to estimate unknown spatial and temporal irregularities of the wet component in the troposphere. For sites with both GPS and VLBI techniques one could use the GPS tropospheric estimates in the analysis of the VLBI observations. Other authors have made attempts in that direction with no conclusive results (Carlsson et al. 1995).

2. Data Analysis and Results

Our working data set are the series of six EUROPE campaigns of VLBI observations in 1998, 24-hours long each and separated by ca. 2 months. The number of participating antennas per epoch ranges from 7 to 9, and at all epochs more than half of the sites had simultaneous GPS tropospheric estimates from the analysis of IGS data from Berna University (Markus Rothacher, priv. comm.) The VLBI experiments were processed with the least squares estimation program SOLVE. We have performed parallel analysis using two different approaches to account for the wet delay: 1) in the so called *standard route*, the wet zenith path delays at all sites were estimated from the data themselves, using continuous piecewise linear functions in segments of 60 minutes; 2) in the novel route, *hybrid route* from now on, we took GPS tropospheric estimates from simultaneous observations, wherever available, and fed them into the VLBI analysis without any further adjustment.

The strong coupling between errors in the tropospheric modelling and inaccurate estimates of the vertical components follows from the close functional dependence of the tropospheric and the geometric (in particular, the vertical component of the position of a site) contributions in the mathematical formulation of the interferometric delay. Any elevation dependent error (such as errors in modelling the atmospheric path delay) in the group delay model which correlates with the sine of the elevation will corrupt the least squares adjustment of the vertical component of the site position. Also, an error introduced into the estimate of the vertical component of the position of either site (Δr) introduces a corresponding error in the estimate of the length of the baselines between the sites (ΔD):

$$\Delta D \approx \frac{D}{2r_e}\Delta r$$

where D is the baseline length and r_e is the radius of the Earth.

Hence longer baselines are more sensitive to errors in the vertical components of any or both of the stations that form it. A first and simple diagnosis tool to make a comparison between the results from both routes of analysis is to compare the slopes of the linear fits to plots with the baseline length errors as a function of the baseline length.

Before proceeding, a few words concerning the tropospheric estimates from both techniques. Figure 1 shows the difference between wet zenith delay estimates with GPS and VLBI versus time at Onsala, for 5 epochs of observations. For all stations the agreement between the estimates from both techniques looks good, with correlation coefficients close to 1, however there is a mean bias of the order of some millimetres which changes from site to site and between epochs. This same effect has also been found by other authors in different data sets. Very likely part of the difference is related to the height difference between the GPS and VLBI antennas. A rough estimate of the contribution to the observed delay from an extra layer of troposphere 10 meters long, is ca. 10 picoseconds or 3 millimetres. This is very close to the differences shown in figure 1 for Onsala, and for other sites.

Back to the analysis, we have computed the baseline length repeatabilities from the analysis of the 6 experiments in 1998, and used them to quantify the errors in the

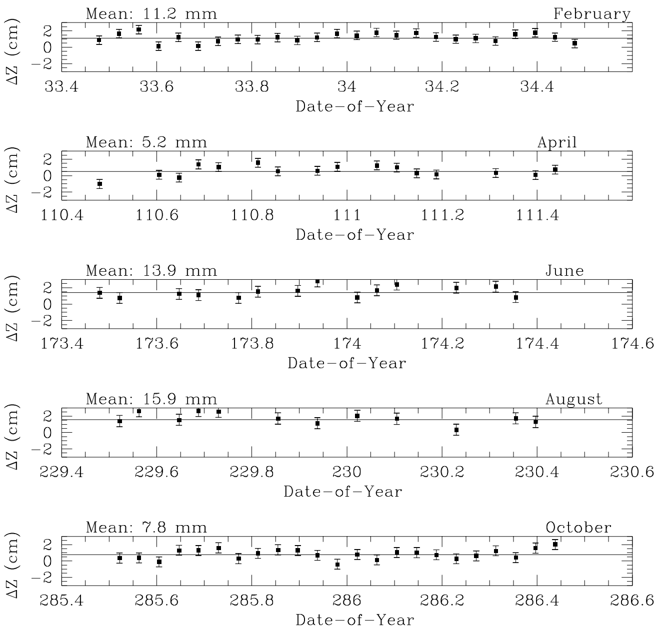

FIGURE 1. Differences between the estimated tropospheric wet zenith delays for the Onsala site from GPS and VLBI, as a function of time, at 5 epochs of observations in 1998.

baseline length estimates. Then, figure 2 displays the baseline length errors (baseline repeatabilities) as a function of baseline length for all participating sites, using the two different methods to correct the wet zenith path delay. The best fit of a straight line to the estimates from the *standard route* is : $1.8 + 0.64 * 10^{-9}D$; for the second type of VLBI solution, with GPS tropospheric estimates, the best fit of a straight line is: $1.8 + 0.37 * 10^{-9}D$. The comparison of results from both analysis shows an improvement in the overall performance of the VLBI solution using the *hybrid route*.

3. Results and Conclusions

We can summarise the current status of the project as follows:

• We have established a working interface that integrates external tropospheric data in the analysis of VLBI observations with SOLVE.

• We confirm the evidence also found by other authors, that the inferred wet delay contributions estimated from GPS and VLBI exhibit similar short term variations but with an apparent long term bias.

• Our results from repeatability tests indicate a promising perspective for the combination of both geodetic techniques. Figure 1 shows an overall improvement of the network in the VLBI solution using the *hybrid route* of analysis, which implements external GPS tropospheric estimates into the VLBI analysis, as an alternative option to the auto-calibration from the VLBI data themselves.

This is a report from a work which is still in progress. The results shown in that contribution are very encouraging to investigate further in detail the potential of this new route of analysis. We are currently investigating the effects of decreasing the solution interval of GPS tropospheric estimates, testing new strategies in the analysis, and trying to understand the meaning of the bias between tropospheric estimates.

Astronomical observations with VLBI would also benefit from an improved modelling of the troposphere using GPS estimates in the analysis. Nowadays, phase reference and/or astrometric observations are becoming nearly standard at centimetre wavelengths, and a detailed modelling of the atmospheric contribution could help to increase the angular separation across which the phase connection is possible. Certainly, if GPS could provide tropospheric estimates every few minutes or shorter time intervals, would be of great interest for millimetre astronomy, increasing the coherence time. The short coherence time, of the order of some tens of seconds at most, limited by unknown fluctuations in the wet component of the troposphere, sets a main constraint in the sources reachable at millimetre wavelengths with VLBI.

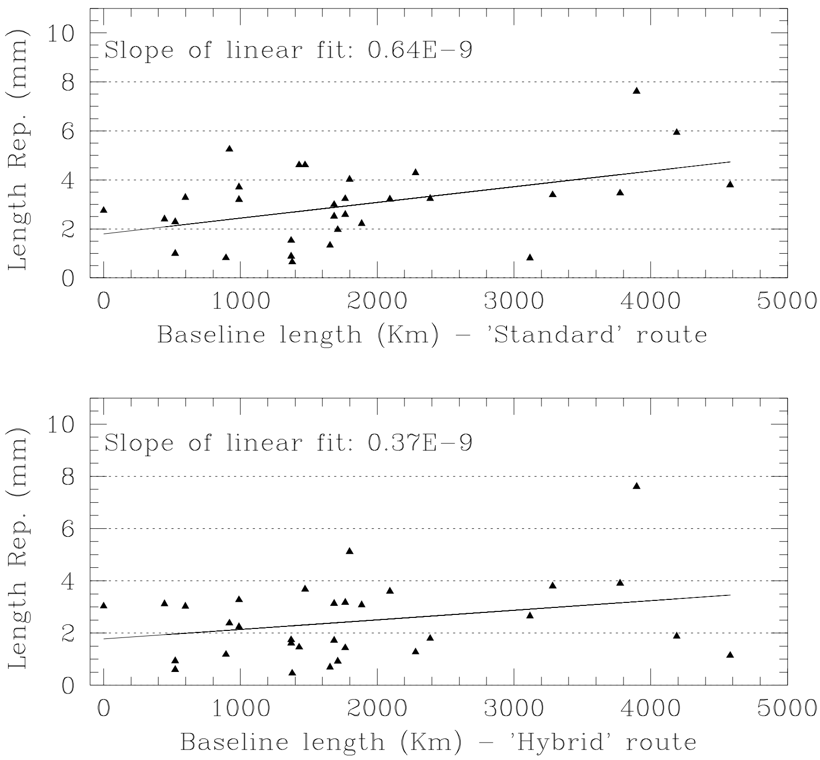

FIGURE 2. Baseline length repeatability as a function of baseline length, computed with the estimates from the *standard route* (*Upper plot*), and the hybrid route (*Lower plot*) which combines VLBI and GPS products. The slopes of the best fit of straight lines are indicated in each plot. The slope is proportional to the magnitude of elevation dependent errors in the analysis.

REFERENCES

CARLSSON, T.R., ELGERED, G., & JOHANSSON, J.M. 1995 *Proc. 10th Working Meeting on European VLBI for Geodesy and Astrometry*, p. 148.