

Troposphere: Signal or Noise?

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BIOGRAPHY

Dr. Ulrich Vollath received a Ph.D. in Computer Science from the Munich University of Technology (TUM) in 1993. At Trimble Terrasat - where he is working on GPS algorithms since more than ten years - he is responsible for the algorithm development team. His professional interest is focused on high-precision real-time kinematic positioning and reference station network processing.

Dr. Elmar Brockmann works since 1992 in the area of GPS. 1996 he finished his PhD at the University of Berne (Astronomical Institute). From 1996-1999 he was active in the research and development group of Leica, Heerbrugg. Since 2000 he is responsible for geodetic bases and permanent networks at the Swiss Federal Office of Topography (swisstopo), Berne.

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ABSTRACT

The motivation for studying the non-dispersive part of the atmosphere, also known as troposphere, is manifold. Meteorologists study the atmosphere to learn about its physical properties and to do weather predictions. For GPS positioning the modeling of the troposphere is essential for unbiased coordinate results.

One of the common interests for both parties is the zenith total delay (ZTD) of troposphere. GPS networks can serve as an array of sensors to provide continuous tropospheric zenith total delay for numerical weather prediction applications. Several research institutes work actively in this area to derive more accurate estimates for ZTD in near real time (normally with one or two hours delay). In this paper, we will show that ZTD estimation in real-time can give comparable results as in postprocessing.

Since 1999 the Swiss Federal Office of Topography has been active in the European project COST-716 (exploitation of ground-based GPS for climate and numerical weather prediction application). After a

successful benchmarking (van der Marel et al., 2001), swisstopo has been contributing zenith total delay (ZTD) estimates in near real-time (NRT-ZTD) since December 2001. In addition to the 29 Swiss AGNES sites, 20 EUREF sites are processed on an hourly basis. Furthermore, about 12 sites from other networks, mainly in France, are being used in order to improve the station distribution in the western part of Europe. This area is important because the dominating weather conditions from the Atlantic Ocean usually pass over France before they reach Switzerland. Real-time availability of the zenith total delays is an interesting alternative to the post-processing values if the same quality of the estimates is guaranteed. As reference also post-processing ZTD values using the final IGS orbits are generated with a time delay of 21 days.

Networked reference station software for GPS processing must estimate tropospheric delays to provide a reliable network solution of the error models. The aim is to provide the field users with information about their local errors to improve productivity and accuracy of the positioning. In addition to the tropospheric delay, ionospheric delays and satellite orbit improvements are applied.

Since January 2003 ZTD values can be extracted for the Swiss AGNES network using the real-time network RTK software GPSNet 2.0. This is possible with accumulation intervals of 1 minute and a negligible time delay. A comparison of the postprocessing and real-time results proves to be interesting for meteorology as well as for networked RTK. Therefore the GPS networking software benefits from the additional know-how provided by the meteorology data, and the meteorologists gain access to real-time data.

This paper assesses real time ZTD estimation with postprocessing results. For the AGNES network, the absolute ZTD as well as the differential values between the reference stations were compared. The analyses show that 1 cm accuracy for absolute ZTD and 7 mm for relative ZTD can be achieved in real time.

Finally it can be said that coordinating both the needs and

the efforts of meteorology and GPS networking leads to better stochastic models for the networked GPS and real-time availability of absolute tropospheric zenith delays for meteorology.

TROPOSPHERE IS SIGNAL

Water vapor is one of the most highly variable atmospheric quantity, both spatially and temporally, present within the lower troposphere (0-5km). The distribution of water vapor is traditionally monitored on an operational basis by balloon soundings and surface stations (Bock et al, 2001). From last decade, GPS technique has been successfully applied to the remote sensing of integrated water vapor (IWV).

Parallel to the validation activities within the COST-716 project the necessary algorithms were developed in order to directly assimilate the GPS ZTD estimates as additional observations in the numerical weather prediction (Guerova et al., 2002).

Several test periods with different weather conditions were selected. For all these periods of about 1 month of data the numerical weather prediction was recomputed - once with using GPS, once without GPS.

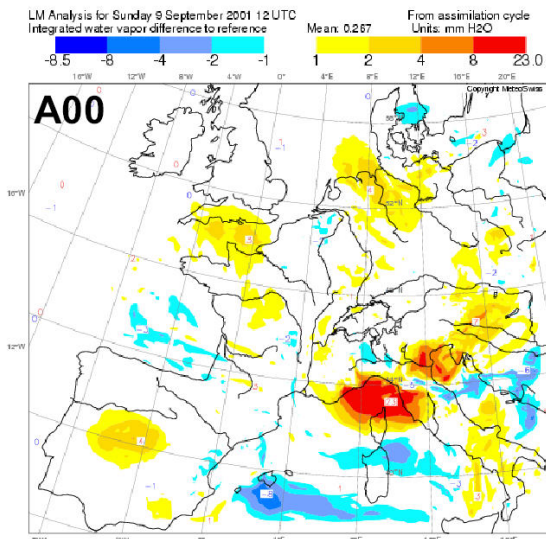


Figure 1: Differences between IWV values derived from numerical weather prediction models with and without using GPS (September 9, 2001, 12:00 UTC)

The differences in terms of the integrated water vapor, which can be computed from the ZTD with known pressure and temperature, are given in Fig. 1. It is a special situation in September 2001, where bigger differences between the 2 predictions were detected. Discrepancies are obvious mainly in the Genoa region. Fig. 2 shows the IWV estimates from the numerical weather prediction model without using GPS and with

using GPS for the GPS site GENO. This example shows quite nicely that the numerical weather prediction model without using GPS predicts a considerable drop in IWV, which was not realistic when comparing with the actual weather situation. The use of the GPS ZTD values was able to stabilize the numerical weather prediction model.

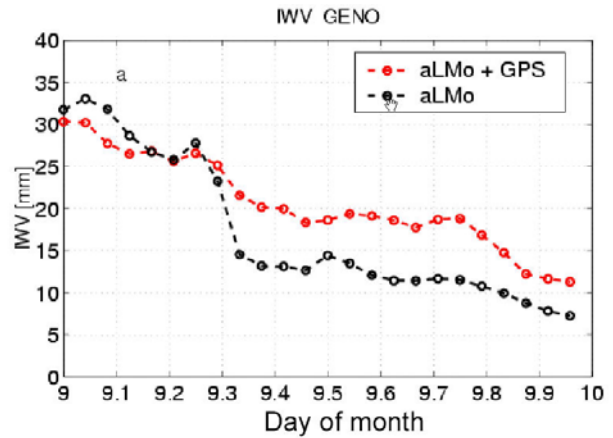


Figure 2: IWV estimates from the numerical weather prediction model without using GPS (aLMo) and with using GPS (aLMo + GPS) for the GPS site GENO.

The results of the assimilation tests can be roughly summarized:

- GPS has a significant influence on the prediction up to 6 hours
- Positive impact of GPS ZTD estimates on numerical weather prediction was found mainly in summer time.

TROPOSPHERE IS NOISE

In GPS positioning, tropospheric delay is treated as systematic error. It mainly affects the height component. Uncorrected tropospheric residuals will cause systematic biases in the height component of the position. This kind of effect can be easily seen from the long-term height variation when processing a static baseline using kinematic post-processing. Fig. 3 shows the rover height error versus time for a 32 km static baseline (Germany, Hoehenkirchen to Neufahrn, Nov. 22, 2001 0:00-6:00). The dataset was processed by the Trimble Total Control (TTC) kinematic processor using the ionosphere free observable with default tropospheric model (modified Hopfield, standard met conditions). It can be seen clearly that the height is biased up to 10 cm from 3 to 6 o'clock. However, if tropospheric scaling (it is a measure equivalent to ZTD estimation, it equals to estimated ZTD divided by ZTD from tropospheric model) is applied to the rover (Table. 1) in the processing, the height is almost flat as shown in Fig. 4.

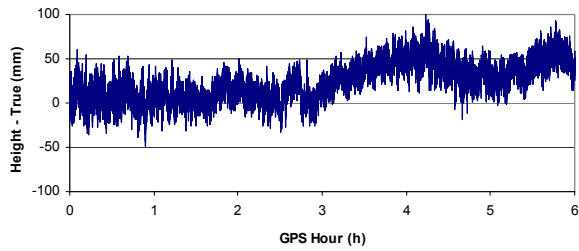


Fig. 3 Height – True height for Neufahrn (No Scaling)

Table 1. Tropospheric scaling

Time (hour)	Tropospheric scaling(%)
0	0
3	0
3.5	-0.7
4	-0.6
4.5	-0.6
5	-0.5
6	-0.4

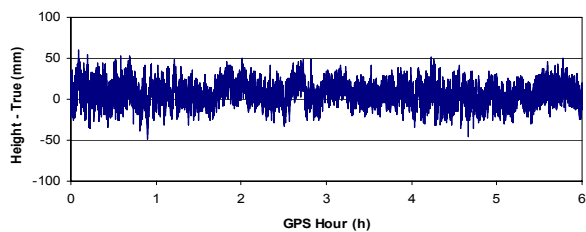


Fig. 4 Height – True Height for Neufahrn (tropospheric scaling applied)

Tropospheric delay is also very important for ambiguity resolution. Fig. 5 shows the base 2 logarithms of the expected ratios of variance as standard criterion for successful ambiguity resolution as a function of residual error in the ionosphere ambiguity and the troposphere ambiguity with fix position. It indicates that tropospheric model should reduce the tropospheric error down to less than 5 cm to get ratio larger than 2 (log 2 above 1).

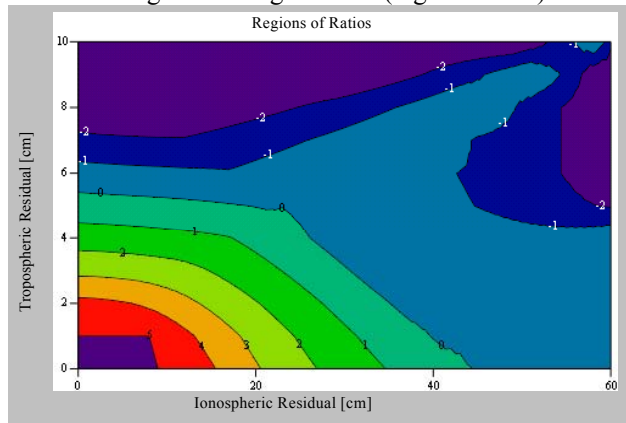


Fig. 5 Ratio Regions for Network Fixes

TRIMBLE NETWORK RTK SOFTWARE - GPSNET

The use of reference station networks has become the ubiquitous solution for high precision satellite positioning applications (Vollath et al, 2002b). The use of a network of reference stations instead of a single reference station allows to model the systematic errors in the region and thus provides the possibility of an error reduction (Vollath et al, 2000, 2001, 2002a; Landau et al, 2001). This allows a user not only to increase the distance at which the rover receiver is located from the reference, it also increase the reliability of the system and reduces the RTK initialization time (Landau et al, 2002).

Trimble GPSNet software is an infrastructure software providing network RTK service. It is an integrated system of GPS hardware, software and communication links that utilizes data from permanent reference stations to model errors throughout the region. One byproduct of this system is the real time ZTD estimation for all reference stations.

THE SWISS PERMANENT GPS NETWORK AGNES AND ITS APPLICATIONS

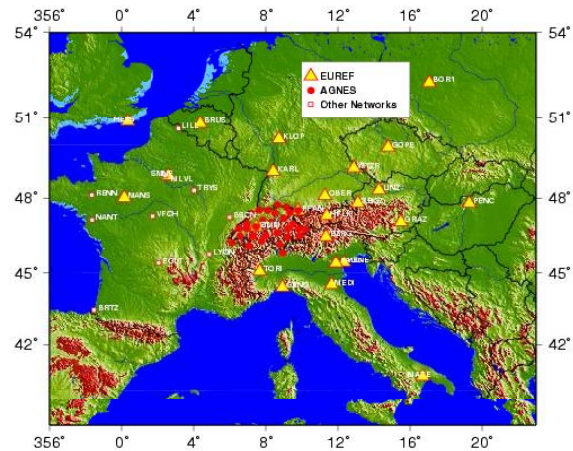


Fig. 6: Station location of the 67 stations used for ZTD estimation in near real time and postprocessing.

The Swiss Federal Office of Topography (SwissTopo) operates the Automated GPS Network for Switzerland (AGNES) consisting of 29 permanent stations. AGNES is a multipurpose network serving scientific applications (geodynamics and atmospheric research) as well as surveying applications (reference frame maintenance, densification of the reference frame) (Brockmann et al., 2002 b). In addition, a positioning service is offered on a commercial basis under the product name *swipos-GIS/GEO* (Swiss Positioning Service for GIS and Geodetic Applications) (Brockmann et al., 2001 b). The

entire network, together with approximately 20 additional IGS/EUREF sites, is analyzed for reference frame purposes with a time delay of about 2 weeks using the final IGS orbits. Hourly zenith total delay estimates (ZTDs) are a by-product of this processing and serve as a reference for solutions derived with shorter time delays (see Fig. 6).

Since the end of 2001, SwissTopo contributes hourly zenith path delay estimates with a time delay of 1:15 hours to the European COST-716 project and to the Swiss Meteorological Institute (MeteoSwiss) as additional information for numerical weather prediction. Since the beginning of 2003, SwissTopo also contributes to the European TOUGH project (Targeting the optimal use of GPS humidity). All the mentioned products are derived with the Bernese 4.2 GPS processing software. Since January 2003, the real-time software GPSNet 2.0 is also able to compute zenith total delay estimates. Due to the fact that this software works with 1-second data and a negligible time delay, the troposphere information is already available with accumulation intervals of about 1 minute.

REAL TIME ZTD VALIDATIONS

Within project COST-716, tremendous experiments have been done to prove the excellent agreement of GPS ZTD estimation from post-processing and near real time processing with Radiosonde/water vapor radiometer (WVR) measurements. In this paper, real time ZTD estimation will be validated by using postprocessing results from Bernese software version 4.2 as a reference.

Data from the Agnes Network (GPS Week 1226, July 6-12, 2003) is used in the analysis. Two network scenarios are presented:

- Only 29 AGNES stations are used in ZTD estimation (abbreviate as AG in later figures).
- 29 AGNES stations plus 5 IGS global stations-KIRU, MOBN, MATE, GOPE and MADR, which are 500 – 2000 km away from AGNES network (abbreviate as GL in later figures) to assess the impact remote station on the estimation of ZTD. High rate data of the IGS stations are downloaded from CDDIS website (see Fig. 7).

The data are processed by a postprocessing version of GPSNet, which enables us to process with different settings in order to verify the impact of:

- satellite orbit
- elevation angle cutoff

on real time absolute and relative ZTD estimation for the small and large network. Niell mapping function is used in the process.

In postprocessing, 67 stations are used. Elevation cutoff sets to 10 degree, the mapping function is Niell, and precise orbits are used.

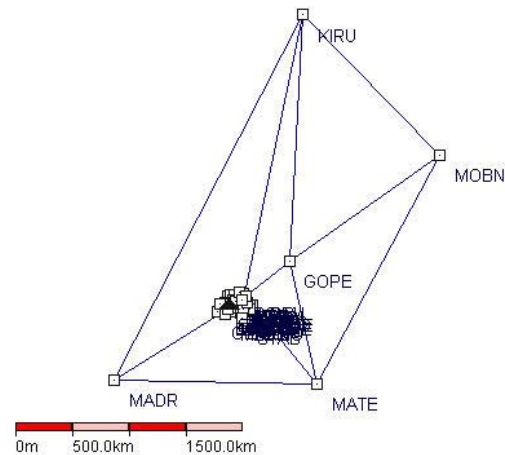


Fig. 7 Agnes Network with global stations (GL)

IMPACT OF SATELLITE ORBIT

Satellite orbit accuracy is very crucial to ZTD estimation. However, for a small network like AGNES, it is almost impossible to estimate orbit in high precision in real time. An alternative is to use ultra-rapid orbits from IGS. Normally, ultra-rapid orbit accuracy is within 50 cm, which is already quite good for estimating ZTD. Fig. 8 shows the estimated ZTD for station STCX when using precise and ultra-rapid orbit computed from AGNES station only. In Fig. 8, the red line represents the ZTD estimation by using satellites with precise orbit and yellow line represents the result calculated by using satellites with ultra-rapid orbit. The blue dotted line is the post-processing result from Bernese software. It shows very clear that the ZTD difference caused by using precise or ultra rapid orbit is within millimeter for a network with size like AGNES. For larger size network, the same magnitude orbit error certainly has more impact on ZTD estimation as shown in Fig. 9. It shows the ZTD estimation for station STCX using AGNES and 5 global stations. The ZTD estimations using precise and ultra rapid orbit diverge for about 1 cm at around day 2.5 to day 3. This is caused by the large difference between precise and ultra rapid orbit for SV 24. Fig. 10 shows the RMS and maximum difference between precise and ultra rapid orbit for all satellites in week 1226. The RMS and maximum of SV 24 are significantly larger than other satellite. Besides this, both are matched quite well except at the beginning - caused by the filter startup and at the end - caused by satellites missing in ultra rapid orbit files.

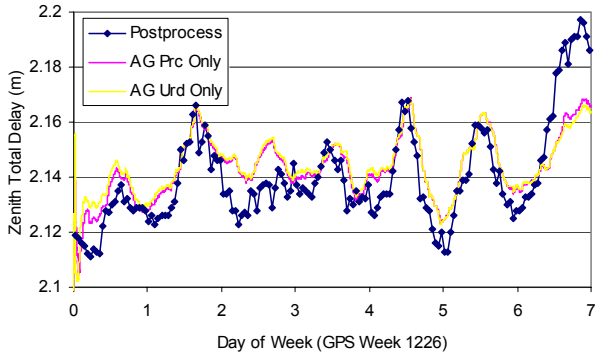


Fig. 8 ZTD estimation comparison for Station STCX computed from AGNES stations

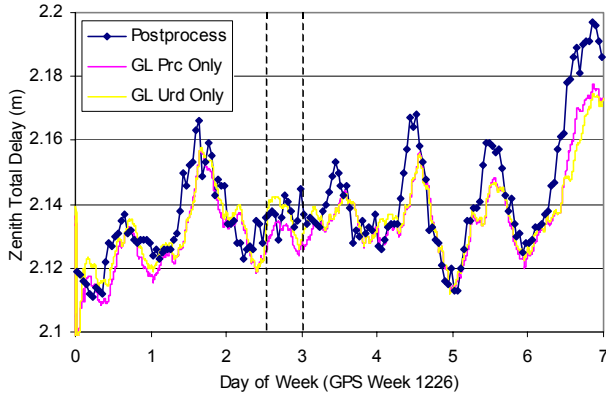


Fig. 9 ZTD estimation comparison for station STCX computing from AGNES+Global stations

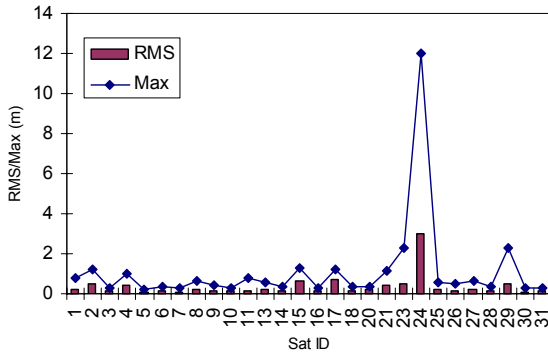


Fig. 10 Difference between precise and ultra-rapid orbit

Sometimes when some satellites are missing in the ultra rapid orbit files, it's applicable to exclude these satellites in the real time ZTD estimation. However, for network RTK, the more satellites are processed in the network, the better rover RTK performance, which means all visible satellites should add into the process if the orbit accuracy will not affect the estimation. Fig. 11 shows the RMS and maximum difference between precise and broadcast orbit for all satellites in week 1226, RMS for all satellites are below 6 m, and the maximum error is about 20 m for SV

24. This kind of broadcast orbit accuracy should still be possible to provide mm level ZTD estimation comparing with using only satellites with ultra-rapid orbit for a small network if including satellite which has only broadcast orbit information in the process. Fig. 12 shows the estimated ZTD for station FHBB by only using satellites with ultra rapid orbit and satellites with broadcast orbit and ultra rapid orbit using AGNES stations. Apparently, this is not applicable for a large network as seen in Fig. 13 where 5 global stations are included in the processing. The ZTD estimated from ultra rapid + broadcast orbit has about 1 cm difference comparing with estimation from ultra rapid orbit only in day 3.

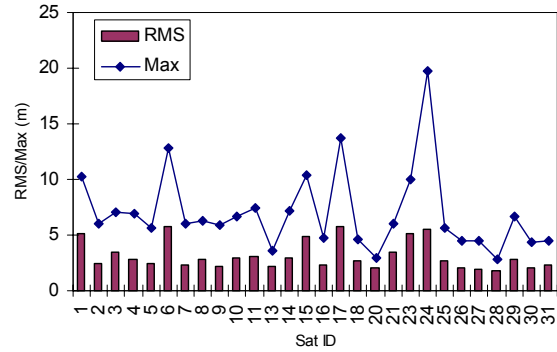


Fig. 11 Difference between precise and broadcast orbit

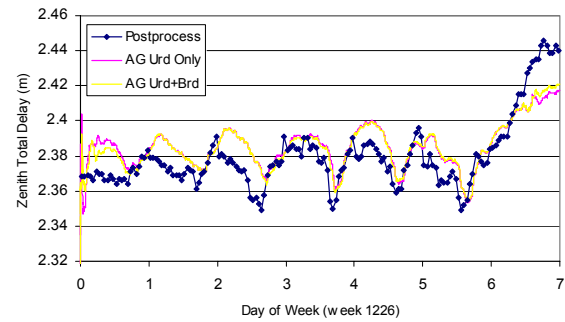


Fig. 12 ZTD estimation comparison for Station FHBB computed from AGNES stations

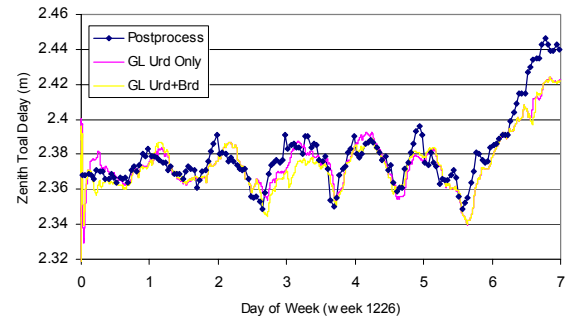


Fig. 13 ZTD estimation comparison for station FHBB computing from AGNES+Global stations

IMPACT OF ELEVATION ANGLE CUTOFF

For zenith total delay estimation in post-processing or near real time processing the elevation cutoff normally set at 10, 15 degree, and sometimes even 20 degree in IGS analysis centers due to the high noise in low elevation satellites. But for network RTK, low elevation satellites should also be included in the process in order to fix ambiguities earlier and thus provide more network corrections for the rover. Fig. 14 and Fig. 15 show the influence of different elevation cutoff setting to ZTD estimation for station BOUR from different size networks. In Fig. 14, only AGNES stations are used in the process. In Fig. 15, 5 global stations are also included in the process. There is about 1 cm bias between the ZTD estimations using 5 and 10 degree elevation cutoff in AGNES only network. However, there is no significant difference between 5 and 10 degree elevation cutoff if some remote stations are included in the process as shown in Fig. 15. This is due to the big elevation angle difference for the same satellite at different sites for a large network which makes the absolute ZTD estimation more accurate and stable.

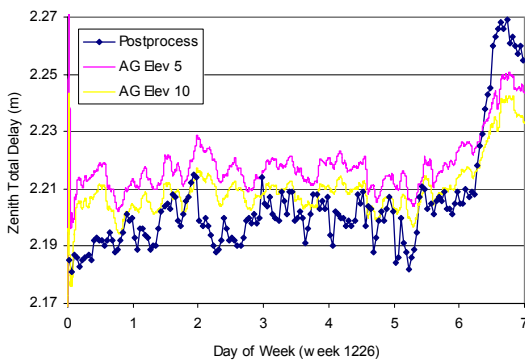


Fig. 14 ZTD estimation comparison for station BOUR using different elevation cutoff from AGNES stations

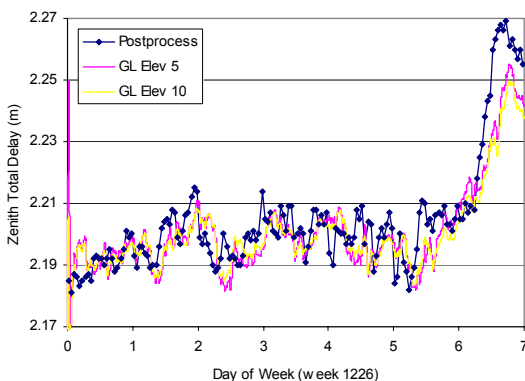


Fig. 15 ZTD estimation comparison for station BOUR using different elevation cutoff from AGNES+GLOBAL stations.

ABSOLUTE OR DIFFERENTIAL ZTD

For meteorology and numerical weather prediction, absolute ZTD is preferred. On the other hand, for network RTK, precise differential ZTD between stations is more important especially for small networks.

Comparing Fig. 8 and Fig. 9, Fig. 12 and Fig. 13, we can find that there is about 1 cm absolute ZTD bias between estimations from AGNES and AGNES+Global stations (Fig. 16). But if compare the differential ZTD (using ZIMM as reference), there is virtually no difference (Fig. 17). Table 2 gives statistics of real time absolute ZTD estimation from all AGNES stations. With remote stations, the absolute ZTD estimation is about 2 mm better. Table 3 gives statistics of real time differential ZTD estimation (ZIMM as reference station). There is almost no difference between the estimation with/without remote stations.

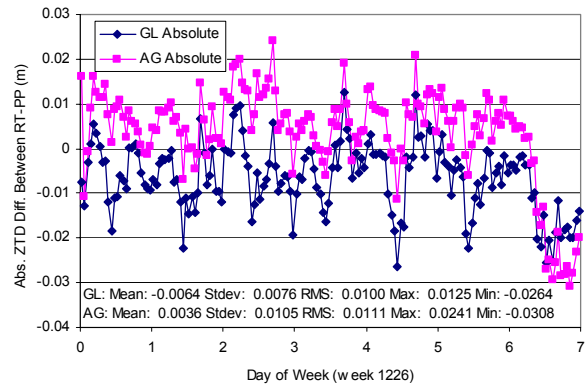


Fig. 16 Absolute ZTD difference for station STCX with/without global stations

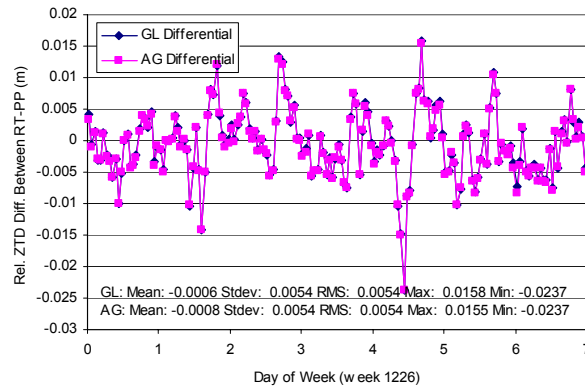


Fig. 17 Differential ZTD difference for station STCX with/without global stations

Table 2. Statistics of real time abs. ZTD estimation (mm)

	Mean	Std. dev.	RMS
AG	4.6	12.4	13.2
GL	-5.2	10.0	11.3

Table 3. Statistics of real time dif. ZTD estimation (mm)

	Mean	Std. Dev.	RMS
AG	-0.8	6.6	6.6
GL	-0.9	6.6	6.6

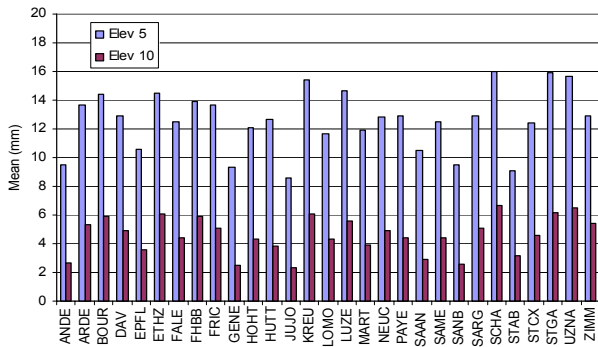


Fig. 18 Mean of absolute ZTD for all stations

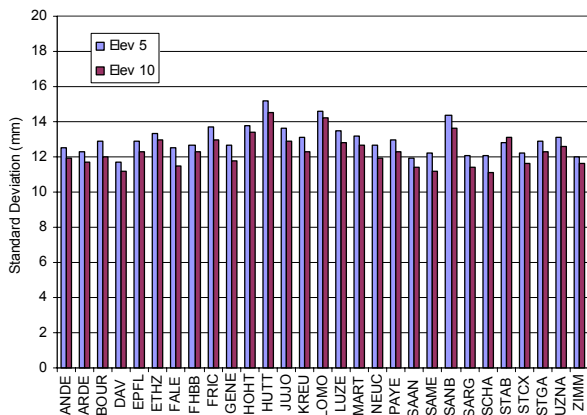


Fig. 19 Standard deviation of absolute ZTD for all stations

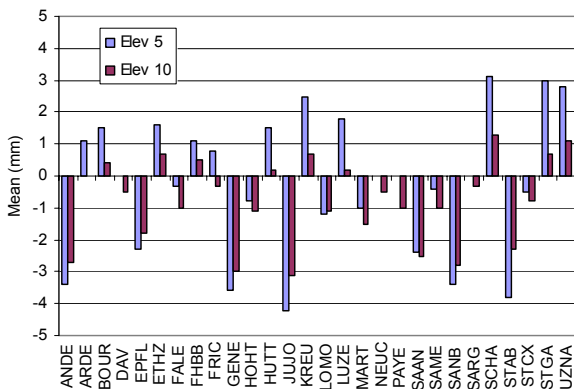


Fig. 20 Mean of differential ZTD for all stations

This is true for different elevation cutoff settings as well. It can be seen from Fig. 14 that there are some biases in ZTD estimation between 5 and 10 degree elevation cutoff when only using AGNES stations. Fig. 18 and Fig. 19 show mean and standard deviation of ZTD (to post-processing results) for all stations. The standard deviation is very similar for 5 and 10 degree elevation cutoff, but

the mean values are differed for about 1 cm for all stations. However, looking at the differential ZTD (mean and standard deviation shown in Fig. 20 and Fig. 21), the difference to the differential ZTD estimation from post-processing is much smaller.

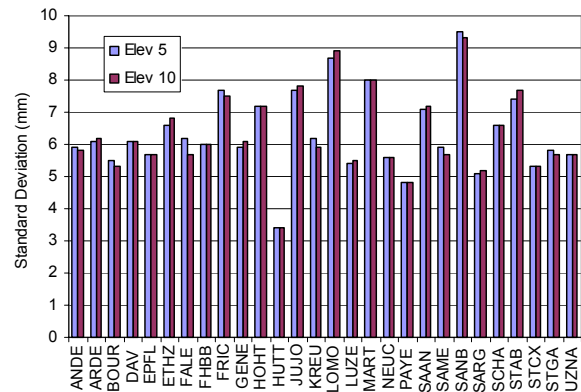


Fig. 21 Standard deviation of differential ZTD for all stations

GPS ZTD VALIDATION WITH FORECAST AND RADIOSONDE

The zenith total delay estimates are validated by comparing them to additional information, such as forecast models and radiosonde values of MeteoSwiss. That the GPS-derived ZTD values are a signal of the atmosphere can easily be verified from Fig. 22. Different ZTD estimates are plotted for the time interval of GPS week 1209 (March 9-15, 2003; day of the year 68-75). The different estimates are:

- (1) “Post-processed (24 hours)”: The best possible GPS solution type (24 hours, ambiguity fixing, IGS precise orbits, no ZTD weights) derived from Bernese 4.2. The solution is only available after 3 weeks due to the delay of the precise GPS orbits.
- (2) (3): “Near real-time (1 hour and 7 hours)”: The NRT estimates are derived from the analyses of GPS observations in 1-hour intervals using Bernese 4.2 (1 hour, no ambiguity fixing, IGS ultra rapid orbits, no absolute ZTD constraints, relative ZTD constraints between consecutive hours of 1.2 mm in the case of the 7 hour solution type).
- (4) “Real real-time”: GPSNet solution. It provides ZTD estimates with a time delay of just 1 minute. Only the GPS data of the 29 AGNES sites are used in the processing.
- (5) “Local Model (LM)”: It is a numerical weather prediction model of MeteoSwiss which predicts the weather of the next 48 hours. Only the first 3 hours of the day are based on meteorological observations. The conversion of this model to ZTD is routinely provided to swisstopo since beginning of 2003.

- (6) “Assimilation”: This meteo model from MeteoSwiss is available with a time delay of 2 days. The assimilation model purely consists on measured meteorological data. The data are available since March 6, 2003.
- (7) Radiosonde: The GPS station Payerne (PAYE) is collocated with the radiosonde observations of MeteoSwiss. Twice a day a radiosonde measures a profile of pressure, temperature and humidity.

The above mentioned different ZTD estimates are updated every hour on the web page http://www.swisstopo.ch/en/geo/pnac_results.htm.

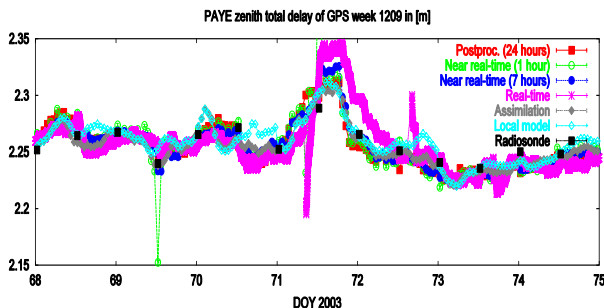


Figure 22: Different ZTD estimates for site Payerne for GPS week 1209.

Table 4: Comparisons of different ZTD estimates with the 24-hour postprocessing GPS solution (average of 29 sites in the time interval January-March 2003).

Statistics of the differences to the post- processing (all sites)			
(2) - (1)	Near real-time (1 hour)	# differences [-]	50489
		offset [mm]	-0.3
		std [mm]	8.5
(3) - (1)	Near real-time (7 hours)	# differences [-]	51466
		offset [mm]	-0.1
		std [mm]	5.7
(4) - (1)	Real-time	# differences [-]	43153
		offset [mm]	2.5
		std [mm]	12.2
(5) - (1)	Local model	# differences [-]	36135
		offset [mm]	4.0
		std [mm]	8.1
(6) - (1)	Assimilation	# differences [-]	5244
		offset [mm]	8.9
		std [mm]	7.8
(7) - (1)	Radiosonde	# differences [-]	20
		offset [mm]	-5.0
		std [mm]	8.7

Results of a validation for the period January – March 2003, where the post-processed solution type was used as the reference, is shown in Table. 4. We may conclude that:

- All ZTD estimates (GPS-derived ZTD and derived from meteorological models) agree within about 1 cm ZTD.
- The hourly estimates (2), (3) are almost bias-free compared to the post-processed solution (1).
- The forecast models LM (5), the radiosonde in Payerne (7), and the assimilation models (6) perfectly agree with the GPS-derived ZTD estimates (1, 2, 3, 4).

CONCLUSIONS

Several impacts, which affect real time ZTD estimation, both absolute and differential, are addressed in this paper. Results from the analysis of one week AGNES data show that:

- Orbit accuracy mainly affects the ZTD estimation for large network. Estimation for small networks is less sensitive to the orbit. Ultra-rapid orbit + broadcast orbit can be used for network RTK purpose without degrade the accuracy in case of small network.
- Absolute ZTD estimation is sensitive to elevation cutoff setting for small network. For a large network, the impact of the elevation cutoff setting is not significant.
- Network size and elevation cutoff have very small effect on relative ZTD estimation, which is a good news for network RTK.
- 10 mm accuracy of absolute ZTD and 7 mm of differential ZTD is achieved from real time process comparing with Bernese postprocessing results.
- GPS ZTD estimation has positive influence on numerical weather prediction. Coordinating both the needs and efforts of meteorology and GPS networking leads to better stochastic models for networked GPS and real time availability of absolute tropospheric zenith delays for meteorology.

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