Improving GNSS Realtime Height Measurements in Mountain Areas – Activities of the D-A-CH Group in the Alpine Region

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Abstract

Heights are the weakest part of GNSS realtime measurements but modern applications more and more require very accurate height results at the user segment. Realtime height timeseries show short term and annual systematic signals that are connected to remaining neglected tropospheric effects. The D-A-CH group in the Alpine Region in Europe proved the correlation between height differences and differences of tropospheric zenith total delays (ZTD) between reference stations on mountain tops and in the valleys using special realtime monitoring stations. Combining near realtime ZTD values and VRS (virtual reference station) data in postprocessing showed the potential for improving the accuracy of realtime height measurements. The new concept was implemented into commercial software and is able to remove the systematic height errors in realtime systems.

Keywords: GNSS, APOS, SAPOS, SWIPOS, RTK – Monitor, RTK, Troposphere

Kurzfassung

GNSS Echtzeitmessungen sind für Höhenbestimmungen nicht besonders gut geeignet, da die erzielten Höhenresultate oft nicht die erforderliche Genauigkeit erreichen. Spielte das in der Vergangenheit eine eher untergeordnete Rolle, so erfordern neue Anwendungen doch vermehrt eine Verbesserung der erzielbaren Höhengenauigkeit. Zeitserien von mit Echtzeitsystemen gemessenen Höhen zeigen aber kurzzeitige und jahreszeitliche Schwankungen auf, welche mit der Vernachlässigung von Troposphäreneffekten in den Tälern in Zusammenhang stehen. Mit Hilfe eines speziellen Echtzeit Monitoring Konzepts gelang den Mitgliedern der D-A-CH Gruppe der Nachweis des Zusammenhangs zwischen Echtzeit Höhendifferenzen und vertikalen Laufzeitunterschieden in der Troposphäre (ZTD). Die Kombination von ZTD Werten aus „near real time" Postprozessing Analysen mit gespeicherten VRS-Daten eines Echtzeitsystems zeigte sich als sehr geeignet für die Erhöhung der Genauigkeit von Echtzeit Höhenmessungen. Dieses neue Konzept wurde in einer kommerziellen Software umgesetzt und ist in der Lage, die systematischen Höhenfehler von Echtzeitmessungen zu beheben.

Schlüsselwörter: GNSS, APOS, SAPOS, SWIPOS, RTK – Monitor, RTK, Troposphäre

1. The D-A-CH Cooperation - Introduction and Background

In the year 2003 the six German national mapping agencies (NMAs) of Bavaria, Baden-Württemberg, Hesse, North Rhine-Westphalia, Saxony and Thuringia, together with Swisstopo Switzerland and the Federal Office of Metrology and Surveying in Austria (BEV) decided to interconnect their upcoming GNSS realtime services SAPOS (Satellite Positioning Service of Germany), SWIPOS (Swiss Positioning Service) and APOS (Austrian Positioning Service) and started an intensive cooperation to benefit on different layers. The D-A-CH consortium has been founded consisting of the NMAs of the 3 adjacent countries Germany (D), Austria (A) and Switzerland (CH) in Europe. In the beginning the driving ideas behind the collaboration were simple. Costs should be reduced by using GNSS reference stations on both sides of the state borders in common and satellite data should be exchanged across borders in realtime via the internet. By coordinating the locations of the border stations the total number of required reference stations could be reduced. On the other hand the extended station distribution avoids extrapolation in the VRS (virtual reference station) generation at the borders and improves the quality of the measured realtime coordinates at border regions. Using the same reference frame ETRF89 (European Terrestrial Reference Frame) and identical coordinates in the realtime software gives the service providers the opportunity to provide a seamless and harmonised service. One of the aims of the D-A-CH providers was to set up a virtual reference system and users should be able to measure in that system with identical accuracy independently from the service provider that they may use. These early reference station networks and the first realtime services were build up mainly to be used for cadaster measurements. To achieve the required accuracy in the horizontal direction of nearly ±1 cm was the major priority of the systems. The accuracy of height results was not really important at the beginning because results have been locally transformed into projection coordinate systems and the height accuracy of the control points was at the same level of accuracy or even worse than the measured realtime height coordinates.

The members of the D-A-CH group meet annually in Munich. Up to now the cooperation evolved to a very close collaboration and exchange of information and experiences with the focus on the following common topics:

- Dataformats and open standards (RTCM, RINEX, NTRIP, NMEA)
- Quality checking and monitoring
- Reference systems and local transformations to cadaster systems
- New satellite systems and signals (GLONASS, GALILEO, BEIDOU)
- Service improvements
- Coordination of support meetings with software producers
- Development of software tools

Depending on the interests, priorities and possibilities of the colleagues involved in the D-A-CH group special working teams have been formed and the developed tools and solutions have been exchanged.

2. From Quality Monitoring to Height Improvement

GNSS realtime service providers typically want to know if their service is operating correctly. They want to see if the required or guaranteed accuracy can be reached and if the VRS generation is producing reliable results. The behavior of the service, the correct operation or malfunction of the VRS-software should be documented and be ready to be useful in support cases. The generation of alarms should be possible too by the software. All these requirements were aimed in the development of a special Rover - Monitoring Concept. Independent reference stations beside the VRS network calculation that behave like roving users should be used to evaluate the required performance and availability parameters. A special RTK – Monitor Software, developed by Martin Freitag from SAPOS Bavaria from 2006 on, fulfills all the requirements and allows visualization of timeseries and longterm analyses of coordinate deviations. The software is situated between the hardware GNSS receiver of the monitoring station and the NTRIP-caster (Network Transport of Reference station Data over the Internet Protocol) of the provider that delivers the correction data (Figure 1). By regularly interrupting the correction data stream to the GNSS receiver the RTK – Monitor forces the receiver to reinitialise the ambiguity fixing algorithm and to produce a sequence of coordinates and other information with an interval of typically a few minutes. Comparing these coordinates to high precision reference coordinates calculated by using postprocessing methods allows the production of residual coordinate timeseries and the calculation of statistical parameters.

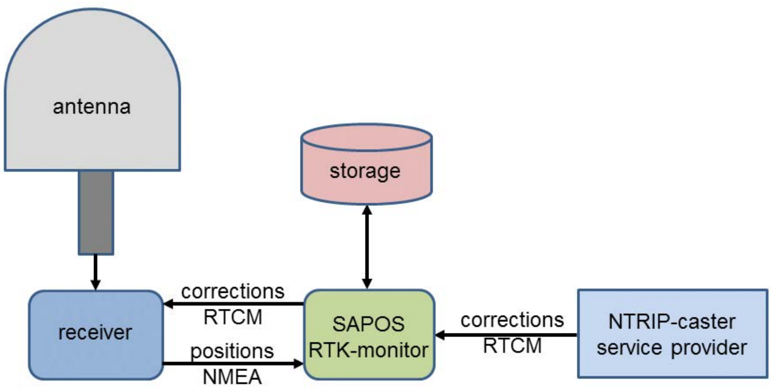

***Fig. 1:** RTK-monitor concept*

In the past each member of the D-A-CH group has established a more or less dense network consisting of up to 3 independent monitoring stations. When comparing the height timeseries of all the monitoring stations a systematic different behavior of the realtime heights could be detected depending on the location of the monitoring stations. In plain areas the accuracy requirements could be achieved and the timeseries showed a typical random behavior. In mountainous areas where height differences between rover and the surrounding reference stations are often more than 1000 m the heigths showed systematic disturbances of short term and long term characteristics. These height variations were supposed to be correlated to local troposphere variations. To analyse them in detail and to find a way to improve the achieved height accuracy in realtime systems special monitoring scenarios have been set up in the Alps. On the German-Austrian border 3 regions have been selected for further investigations (Figure 2). The Austrian monitoring station INBK in Innsbruck has been built up in 2011 especially to study the height variations (Figure 3). The height difference to the surrounding reference stations PAT2 (Patscherkofel) and HFL2 (Hafelekar) is approximately 1700 m (Figure 4).

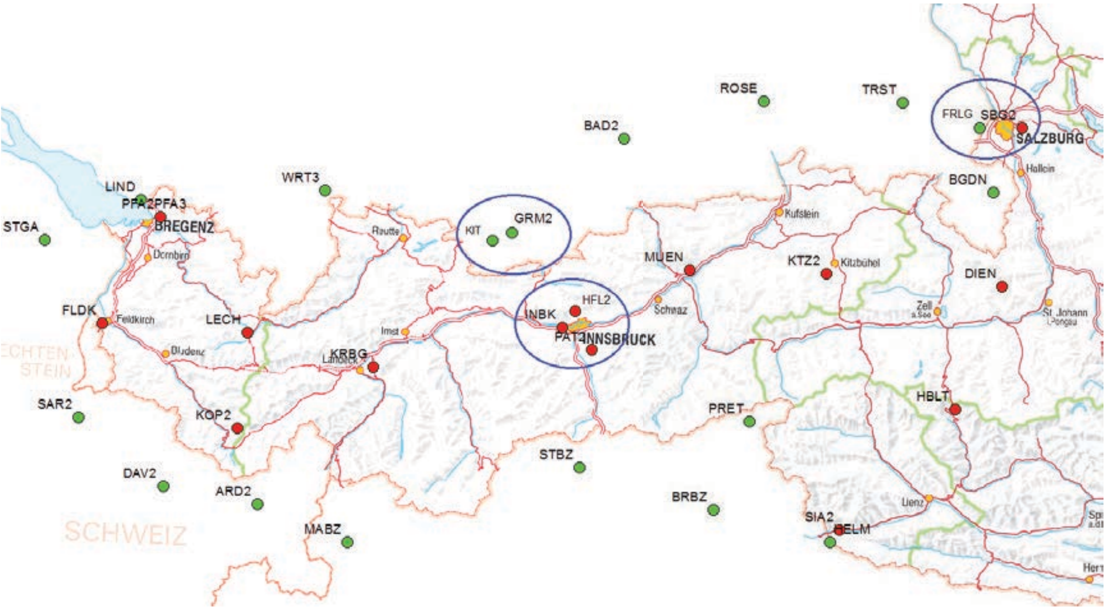

Fig. 2: *Monitoring station distribution for studying the height variations*

Fig. 3: *The monitoring station INBK in Innsbruck (H = 664 m, ellipsoidal height – ETRS89)*

Fig. 4: *The APOS reference station PAT2 at Patscherkofel (H= 2298 m, ellipsoidal height – ETRS89)*

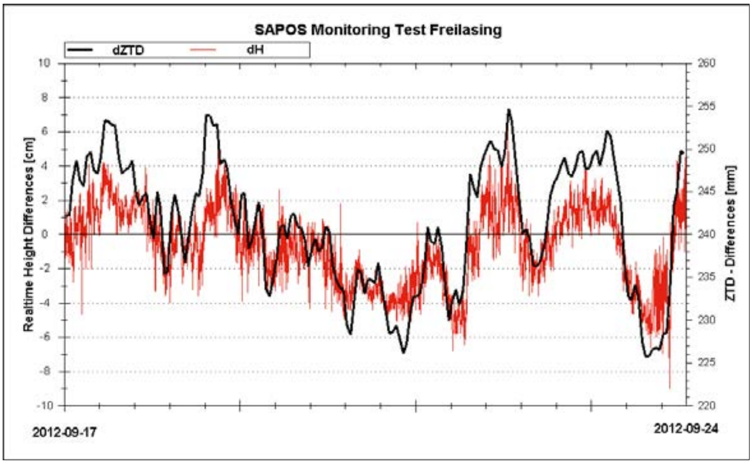

Fig. 5: Realtime height deviations and Zenith Total Delay (ZTD) differences at the monitoring station FRLG Freilassing [1]

3. Chronology of the Activities on Improving Realtime Height Measurements

3.1 Proof of the Correlation between Realtime Height Differences and ZTD-Differences

The height difference of the ellipsoidal heights (ETRS89) between the Bavarian reference station FRLG Freilassing (H = 481 m) and the Austrian reference station SBG2 Salzburg/Gaisberg (H = 1323 m) is 842 m. The horizontal distance between the two stations is only 11 km. These two nearby stations fulfill the requirements for an ideal testbed for first investigations in the analyses of height variations in the mountains. A special GNSS receiver with a so-called monitoring option has been temporarily installed at Freilassing in September 2012. The station Freilassing excluded from the VRS calculation in a test environment allowed the use of Freilassing as an independent realtime monitoring station. The measured realtime height differences of one week of testing (September 17, 2012 – September 24, 2012) were stored using the SAPOS RTK Monitor software and are shown in Figure 5. Systematic height variations of a few centimetres can be easily realised (see dH in Figure 5). Neglected remaining tropospheric effects in the VRS calculation as well as in the rover software were assumed to be the reason for that.

The BEV calculates coordinates and troposphere parameters routinely using stored raw measurements of all APOS sites. These results are produced using the Bernese GNSS Software and are saved in daily and weekly files. To verify the relation between height deviations and the actual troposphere status the hourly zenith total delay (ZTD) parameters calculated for both stations have been used. The differences between the ZTD values between the stations Freilassing and Salzburg/Gaisberg were meant to possibly be a value for the neglected tropospheric influence on the rover height variations and are shown in Figure 5 together with the height differences (see dZTD). Comparing the two curves in Figure 5 shows the very strong correlation between the realtime height differences and the differences of the hourly calculated zenith total delays (ZTD). Deviations of the troposphere status in the height layer between the nearest reference station of the network and the rover station from the implemented troposphere models may therefore lead to systematic height effects in the realtime solutions.

3.2 Detection of an Annual Signal at the Monitoring Station INBK (Innsbruck)

For more systematic studies of the influence of neglected tropospheric effects in realtime measurements the BEV decided in 2011 to build up a new GNSS permanent station at the Leopold Franzens University in Innsbruck (Figure 3). Innsbruck is situated in a deep valley called Inntal at the height of 664 m. The surrounding APOS reference stations that are used in the realtime system are nearly 1700 m higher on top of the mountains (Figure 6).

Fig. 6: Height profile through the Inntal at Innsbruck

Using the SAPOS RTK – Monitor Software the station was used for realtime monitoring from 2012 on. The height differences of the stored realtime measurements compared with high precision coordinates from a longterm postprocessing solution for the period of the year 2013 are shown in Figure 7. An annual signal of up to 16 cm can easily be seen. The figure shows the influence of the variation of atmospheric water vapour. The dry air in the cold winter has nearly no influence on the heights. Maximum height differences due to neglected tropospheric effects can be recognised in summer.

Height measurements in mountainous areas therefore may be time dependent.

3.3 Improving the Realtime VRS Computation by using Near Realtime Troposphere Parameters

It is possible to store VRS data streams as files and to use these files for the calculation of rover coordinates in standard postprocessing applications. This is useful for example in cases, when an online connection to a realtime service provider is impossible. These VRS-RINEX-files may be corrected for ZTD differences to get improved height accuracies. This can easily be done in postprocessing if the required reference stations are available.

Nearby the German SAPOS station GRM2 in Garmisch-Partenkirchen the Karlsruher Institute of Technology (KIT) which is part of the Geoforschungszentrum Potzdam (GFZ) operates a GNSS-teststation in the valley. The height difference to the SAPOS station is 1034 m, the horizontal difference is only 8 km. High accurate ZTD values with 15 minutes interval were calculated for a two day test period on August 25, 2014 – August 26,

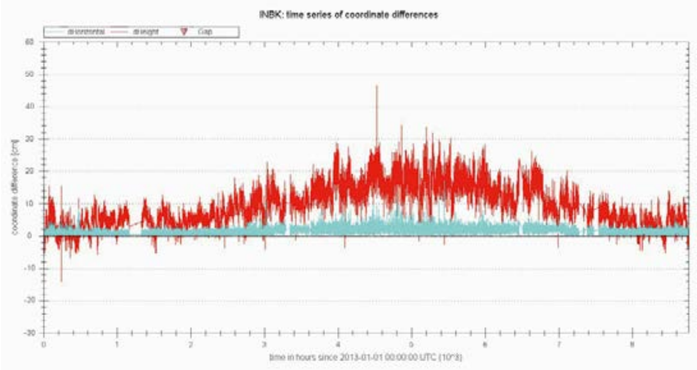

Fig. 7: Realtime height differences at the monitoring station Innsbruck during the year 2013

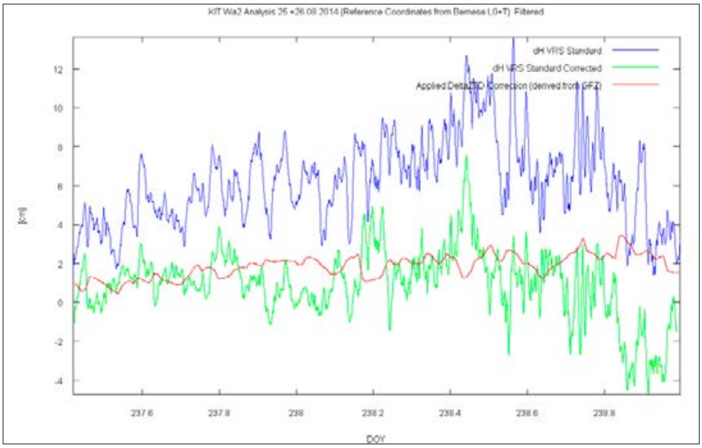

Fig. 8: ZTD corrected VRS postprocessing height results processed by SAPOS Bavaria and KIT [2]

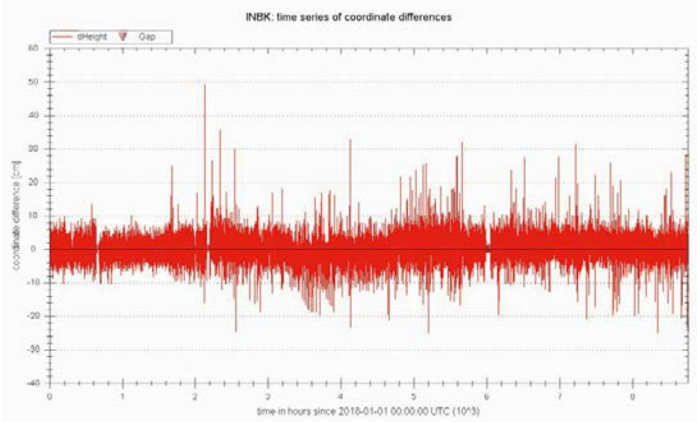

Fig. 9: Height deviations at the APOS monitoring station in Innsbruck in the year 2018 using the 3D troposphere interpolation model

2014. During a project cooperation of the KIT and SAPOS Bavaria a prototype software has been developed that allows the ZTD correction of stored VRS files. These corrected files may then be used in standard software to calculate rover positions in postprocessing. A simple ZTD correction model is used. Slant GNSS observations are corrected by using the Dry Neill Mapping Function for the ZTD values and ZTD differences are calculated by a simple linear height dependent function of the original ZTD values.

This simulation project showed that the realtime height measurements could benefit from the introduction of externally calculated troposphere parameters into the realtime VRS creation. It could also have been proved that a simple linear interpolation algorithm is able to deliver improved height accuracies and that due to the spatial correlation of the troposphere parameters good height results are obtained within a radius of 15 km to the KIT station. Nevertheless an interface to feed near realtime ZTD values into existing realtime software is not available.

3.4 Implementing the new concept into commercial software

The idea of using externally computed near realtime ZTD values in commercial realtime software has been discussed with different software developers. The use of these ZTDs seemed to be problematic because of quality and availability concerns. Nevertheless the 2D tropospheric model that represents the height layer of the included reference stations was not sufficient for achieving centimetre level accuracy in the height component at the user locations. A new 3D interpolation approach should be developed to improve the height measurements. Based on a set of raw datastreams of selected SAPOS- and APOS- stations the new concept includes an extended realtime troposphere calculation. To allow interpolation in the height direction reference stations on different height levels were requested. The simple linear interpolation function was replaced by a more complex prediction function to get representative ZTD values. First tests of the new concept have started in 2015. Figure 9 shows the results obtained at the APOS monitoring station in Innsbruck in 2018.

From January 1, 2018 to December 31, 2018 there have been 391018 realtime measurements registered. The achieved mean accuracy has been ± 1.5 cm in the horizontal direction and ± 4.0 cm in the vertical direction. Systematic height variations especially the annual signal could be successfully removed.

4. Summary and Outlook

The D-A-CH consortium consists of a high-grade group of experts that work together very successfully and share information, experiences and tools on various topics related to GNSS realtime systems on a routinely basis. The SAPOS RTK – Monitor software is an excellent tool for service providers to check the quality and the operational status of their realtime systems. Systematic height variations could be detected and analysed using the RTK – Monitor and the correlation between realtime height deviations and neglected tropospheric effects in mountainous areas has been proved. A new and improved concept of handling these unmodelled tropospheric influences in the realtime processing has been developed and has been implemented into commercial software. This leads to better height results and the remaining systematic height errors could be removed.

For further testing of algorithms and to establish a test environment for the future, Innsbruck has been equipped with a second GNSS receiver connected to the same antenna as the existing one using an antenna splitter in August 2018. This will allow the comparison of two different tropospheric approaches in parallel in the future.

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