

## Near real-time Zenith Wet Delay estimation

A. Karabatic(1), R. Weber(1), S. Leroch(2), T. Haiden(2)

(1)Vienna University of Technology, Institute of Geodesy and Geophysics (IGG), Research Group Advanced Geodesy, Vienna, AUSTRIA

(2)Central Institute for Meteorology and Geodynamics, Vienna, AUSTRIA

e-mail: anna@mars.hg.tuwien.ac.at

### 1. INTRODUCTION

High resolution meteorological analysis of the humidity field is an important precondition for a better monitoring of local and regional extreme precipitation events and for forecasts with improved spatial resolution. The availability of real-time or near real-time tropospheric data derived from GNSS measurements to be assimilated in existing meteorological models represents an important issue.

Due to the interest of meteorologists in the wet component of the troposphere as an additional data source for Numerical Weather Prediction, several regional projects were initiated in Europe and abroad to derive the zenith wet delay from ground based GNSS observation data. While the zenith hydrostatic delay of GNSS microwave signals is usually well sizeable, the wet component, describing the rapid variable water vapour content of the troposphere (also one of the limiting error sources in GNSS precise point positioning) has to be estimated from the observation data.

In this presentation we present the project GNSS-MET which makes use of continuous measurements of a regional network consisting of 8 GPS/GLONASS reference stations, located in Carinthia, Austria. The network has been extended with surrounding stations of the IGS and EUREF-network. The aim of the project is to provide GNSS based measurements of the tropospheric water vapour content with a temporal resolution of one hour and a temporal delay of less than one hour to use them within the INCA (Integrated Nowcasting through Comprehensive Analysis) system, operated by the Austrian Meteorological Service (ZAMG). Additional requirement was an accuracy of 1mm for the Precipitable Water (PW) estimates.

### 2. STATION NETWORK 'KELSAT'

GNSS-measurements are taken in the 8+1 GPS/GLONASS reference station network KELSAT in Carinthia (Fig.1.) extended with surrounding stations of the IGS and the EUREF network (Wetzell, Graz, Zimmerwald). The network is characterized by a spacing of 50-80 km with differences in height of up to 2500 m. Some stations are equipped with pressure sensors; the others are located close to the network stations of the Austrian Meteorological Service (ZAMG). The network is situated in the Austrian alpine area, which is well known for rapidly changing and hard to predict weather conditions. The KELSAT stations provide observations of both GPS and GLONASS signals. To include the GLONASS data positively impacts the determination of zenith wet delays in terms of accuracy and time resolution of the estimates.



Fig.1. Kelsat network

### 4. RESULTS

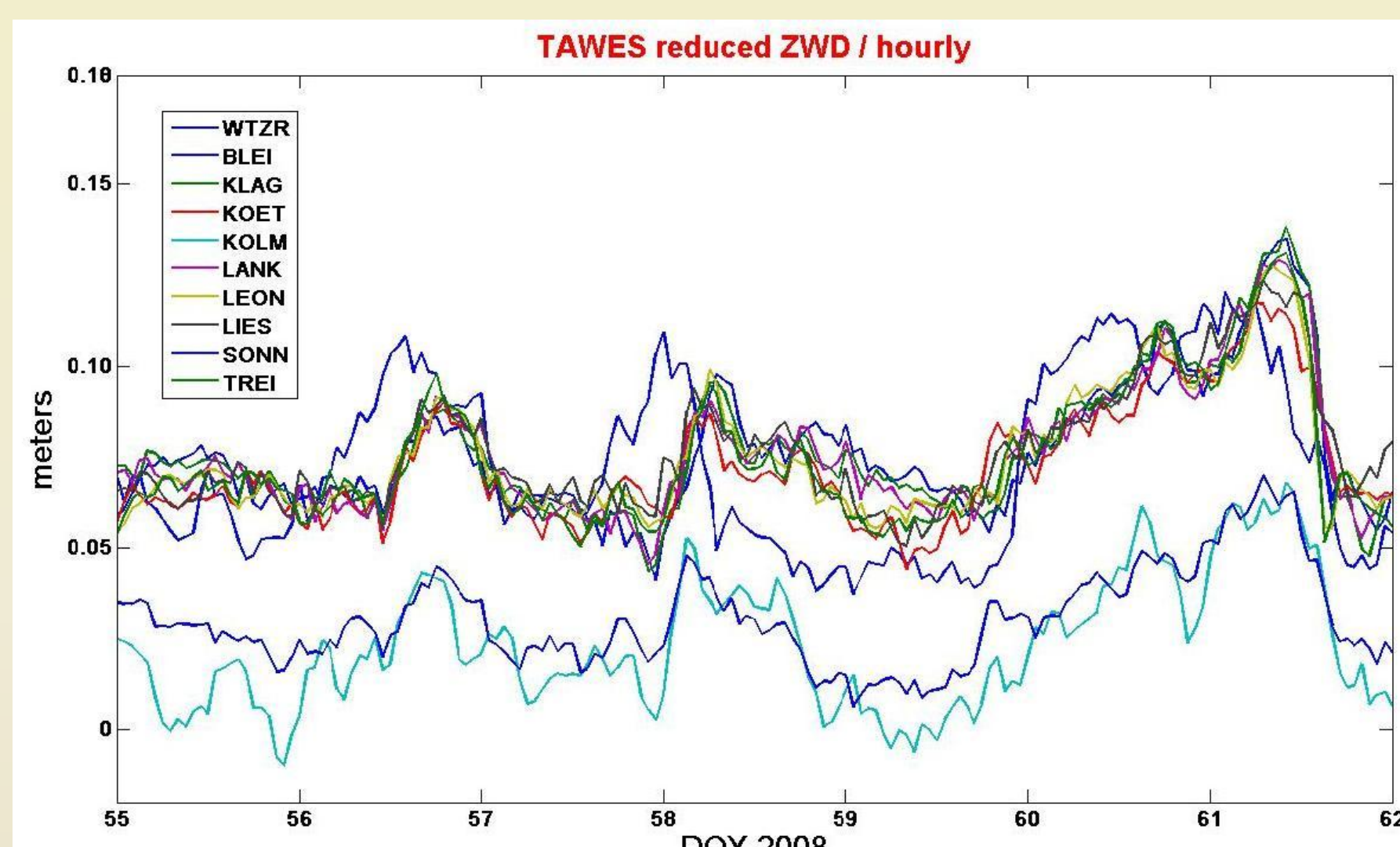


Fig.4. KELSAT network

Fig.4. presents results of a hourly processing for the time span 24.2.-1.3.2008. Each hour the data of the past 12 hours is processed and the most recent ZWD-estimate is extracted. On this plot we can clearly distinguish between two bulks of data; the upper bulk shows ZWDs for stations at about 500-700m elevation. The time series behave similar but lightly shifted due to moving atmospheric events over the area of the network (exception is the reference station Wetzell (WTZR) situated in south Germany). The lower bulk shows ZWDs for the stations Kolm and Sonnbluck situated at heights of 1600m and 3100m, respectively. For station Kolm we notice a quite noisy behavior; this is due to local obstructions. The station Kolm is situated in a very steep valley, surrounded with high mountains, and therefore obtains a significantly lower amount of observations.

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Fig.5. shows a comparison of PWs extracted from the INCA model and derived from GNSS estimates for station Graz in October 2007. Additionally, radiosonde measurements are provided and considered as a reference. In most cases, GNSS estimates show a better agreement with the radiosonde measurements (Table 1.). Fig. 6. shows humidity profiles over station Graz, and here as well, we can notice a very good agreement of the GNSS estimates with the radiosonde data.

	MAE	BIAS	CORR
$PW_{INCA}$	1.95	-1.74	0.95
$PW_{GNSS}$	1.73	-0.51	0.91

Table 1.

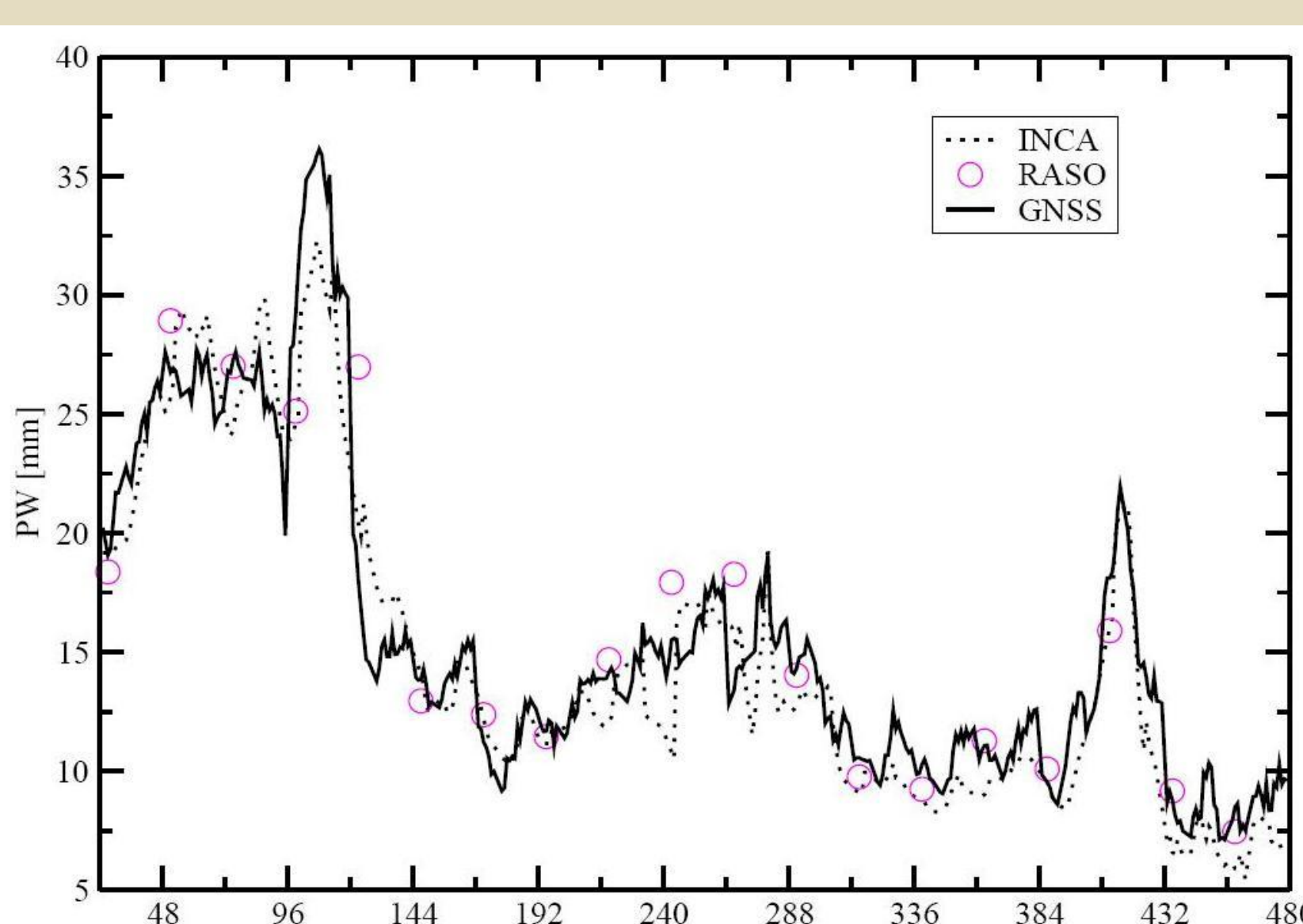


Fig.5. Station Graz (02.-20.10.2007/ in UTC)

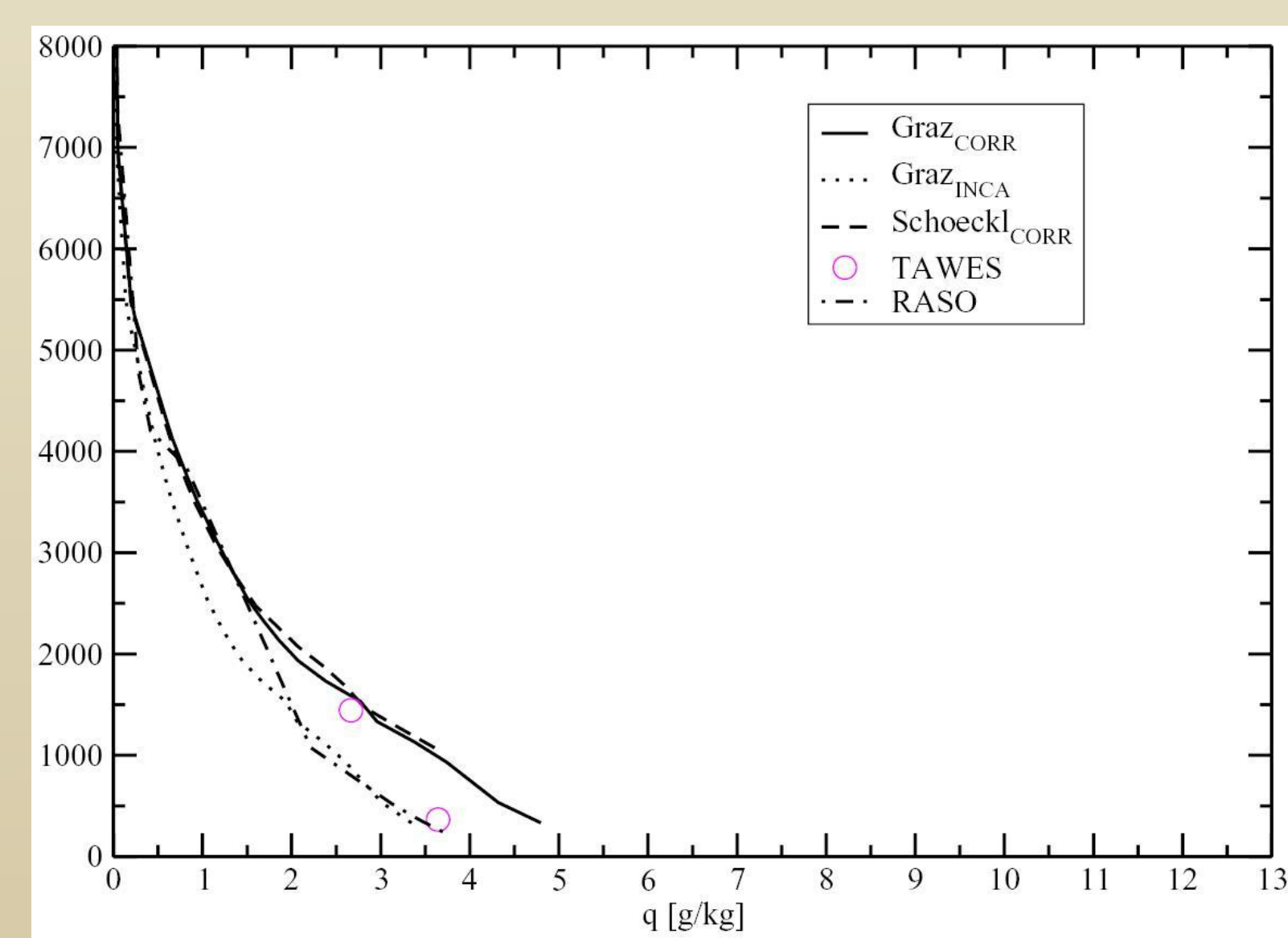


Fig.6. Station Graz – humidity profiles (20.10.07/03 UTC)

### 3. REALIZATION

Currently the ZAMG operates a network of automated stations at ~140 sites all over Austria (Fig.2.) for monitoring meteorological parameters. Temperature, air pressure and humidity are measured with a temporal resolution of 10 minutes. These surface observations, together with radar and satellite data, topography data and forecast models represent the data-base of the INCA system. The spatial distribution of the TAWES stations is in general too sparse especially in the areas with rugged topography. Therefore humidity information from GNSS analysis is absolutely valuable.

The calculation of tropospheric parameters and station coordinates is based on a double differencing (baseline) approach. For the data processing we make use of the **BERNESE V5.0** GPS/GLONASS post processing package. To separate the hydrostatic part from the non-hydrostatic contribution the exact pressure and temperature at the GNSS Sensor Stations has to be known or carefully extrapolated from nearby located Meteorological Sensor Stations (see red dots in Fig.1.). The provided TAWES data allows us to feed the Saastamoinen model with surface data and to re-calculate the hydrostatic part. This leaves us finally with the required Zenith Wet Delay (ZWD=ZTD-ZHD) with an accuracy of +/- 5mm (less than +/- 1mm in PW).

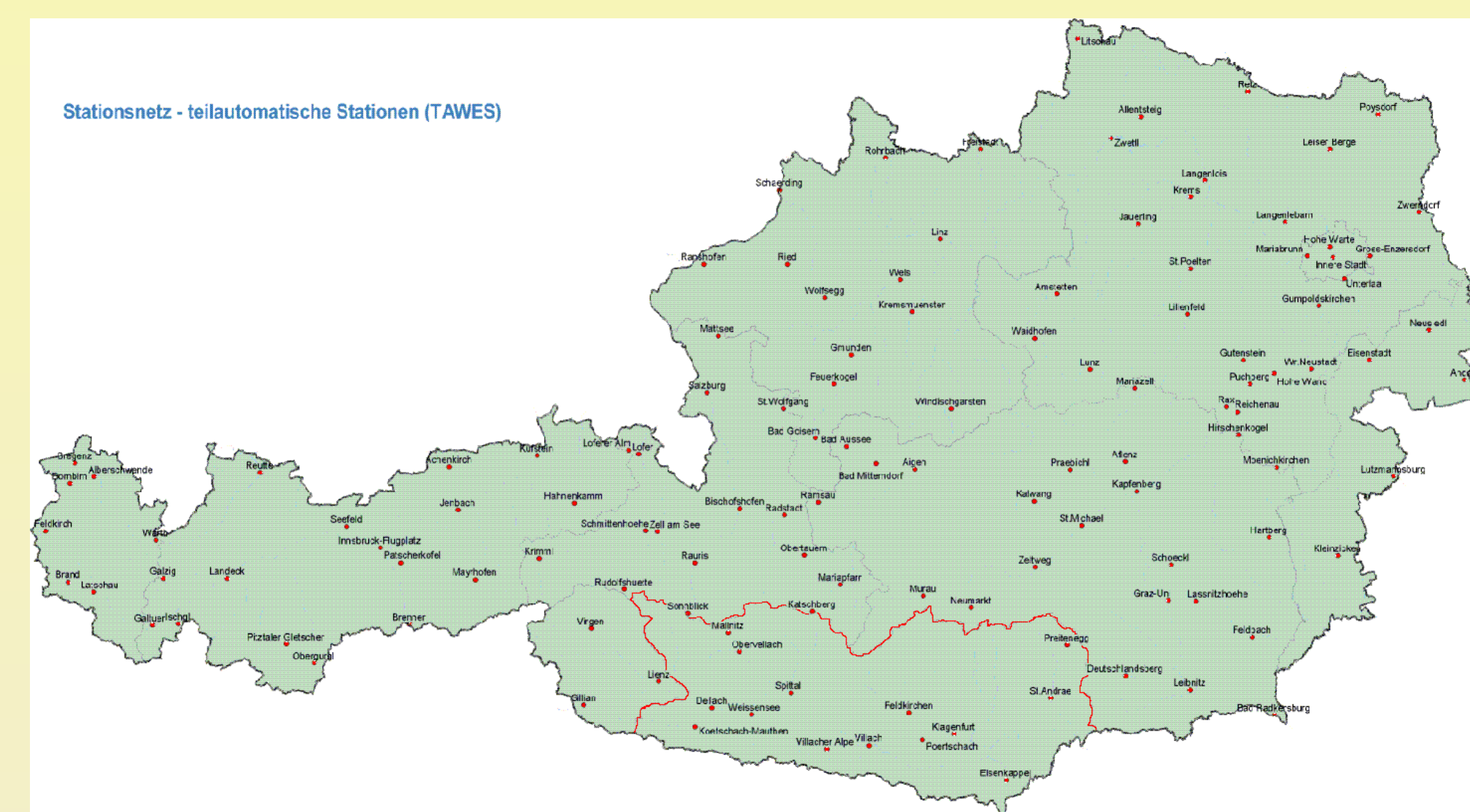
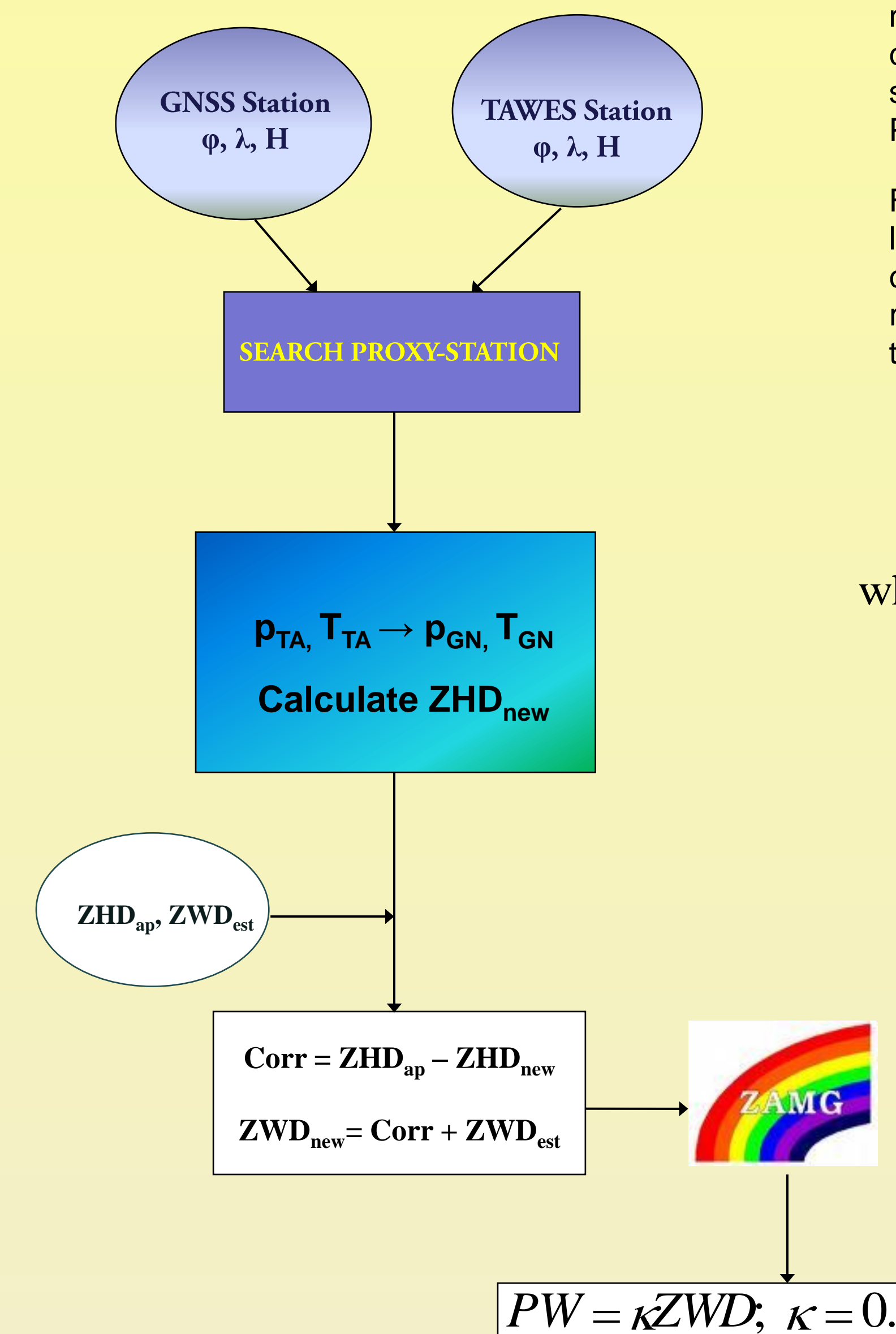


Fig.2. TAWES network



The modeling scheme (left) presents the data reduction process. ZHDs based on real meteorological observations derived from the TAWES network are used to calculate corrections, which are later applied to derive reduced ZWDs. The reduced ZWD-values are subsequently forwarded to the Austrian Meteorological Service (ZAMG), transformed into Precipitable Water (PW) and assimilated into the INCA system.

Fig.3. displays the actual impact of the introduction of real meteo-observations. The green line shows the estimated ZWDs, based on the use of a standard atmosphere model to calculate the hydrostatic delay ZHD, and the blue line represents the ZWDs after introducing real pressure extrapolated from nearby TAWES stations to the GNSS station by means of the following expression:

$$P_{GNSS} = P_{TAWES} \left( \frac{T_{TAWES} - \gamma (h_{GNSS} - h_{TAWES})}{T_{TAWES}} \right)^{\frac{g}{R}}$$

$$\text{where } g, \phi = 9.8063 \left( -10^{-7} h \right) - 0.0026373 \cos \phi - 5.9 \cdot 10^{-6} \cos^2 \phi$$

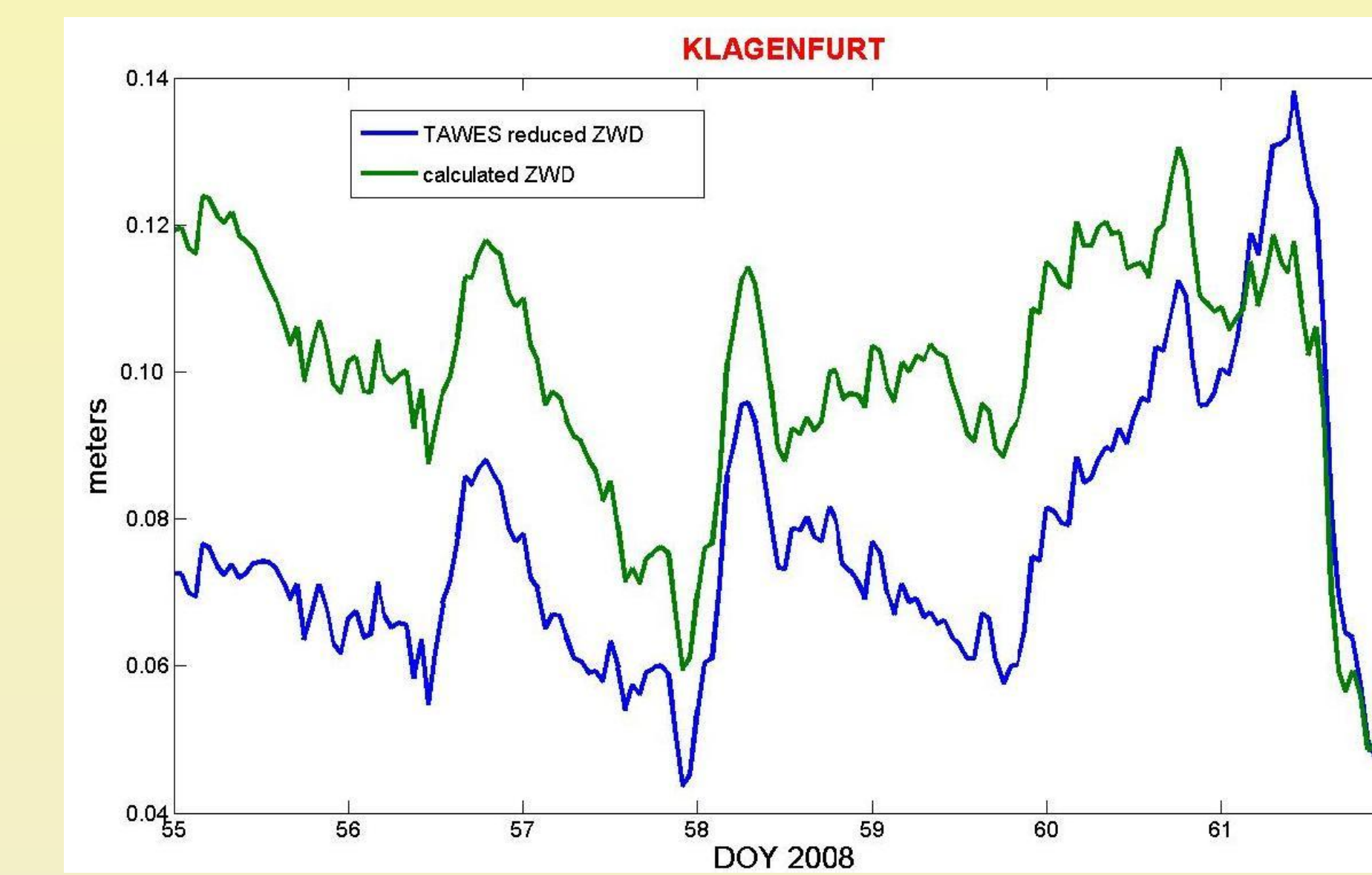


Fig.3. Comparison of TAWES reduced and calculated ZWD

### 5. ASSIMILATION

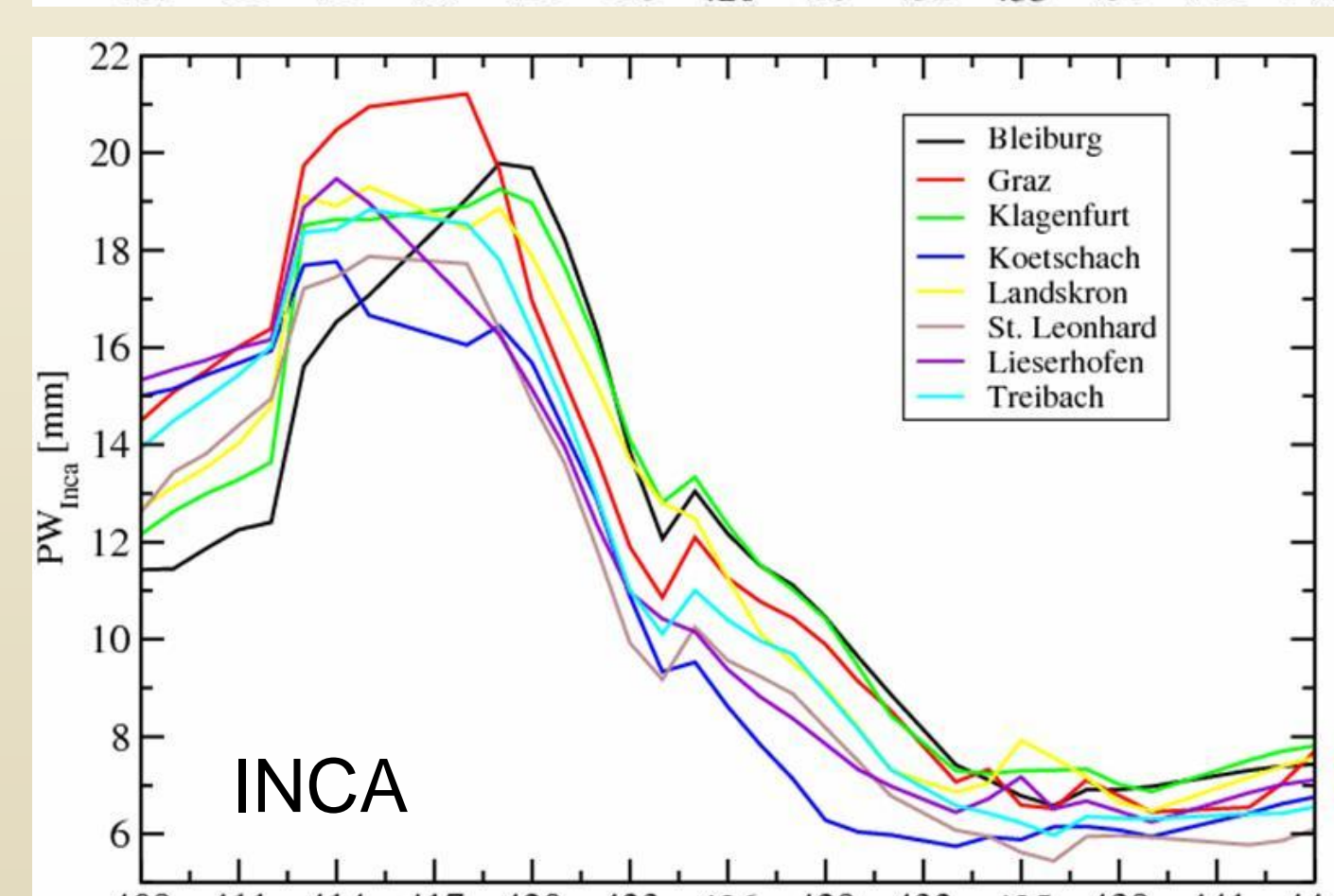
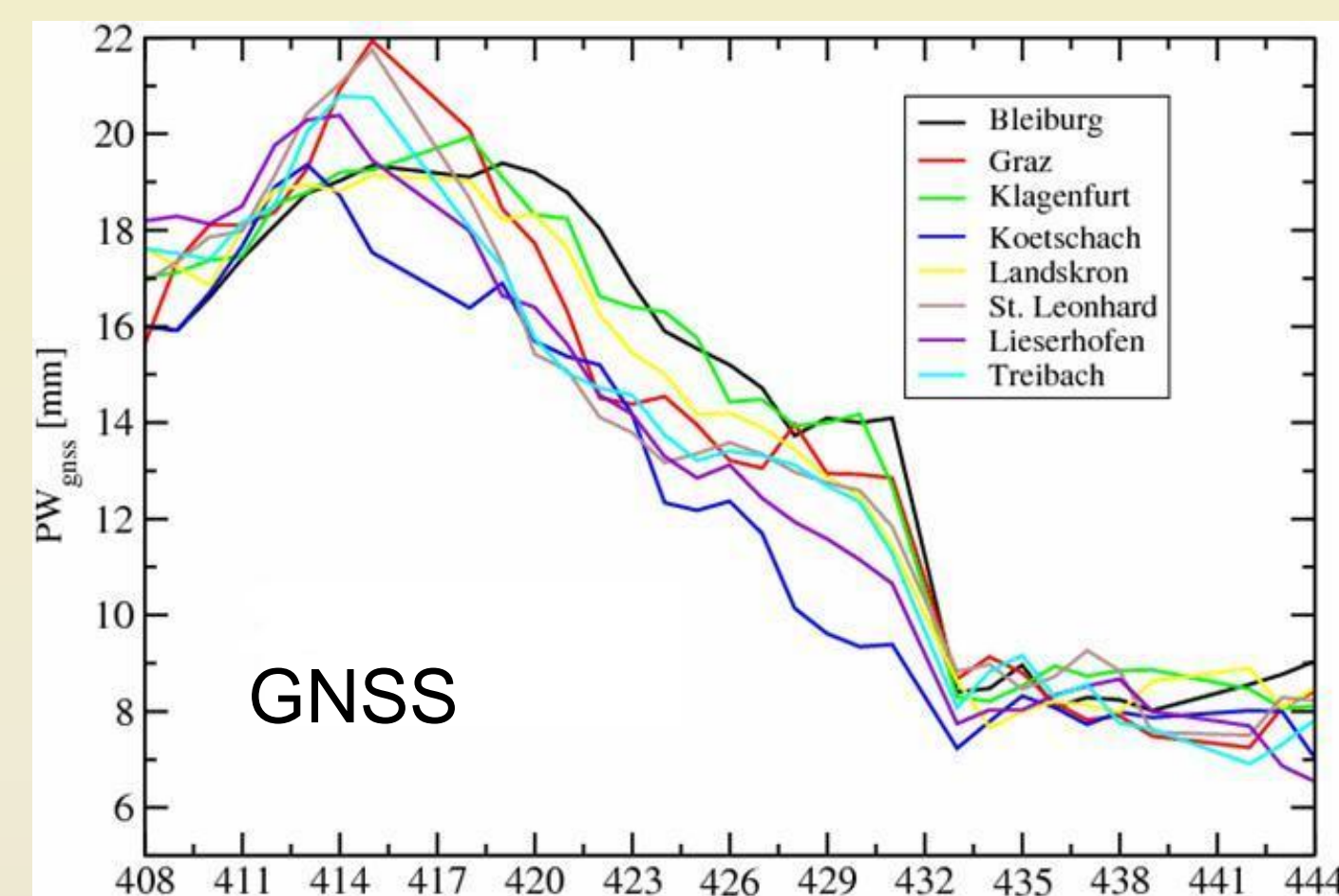


Fig.7. Weather front

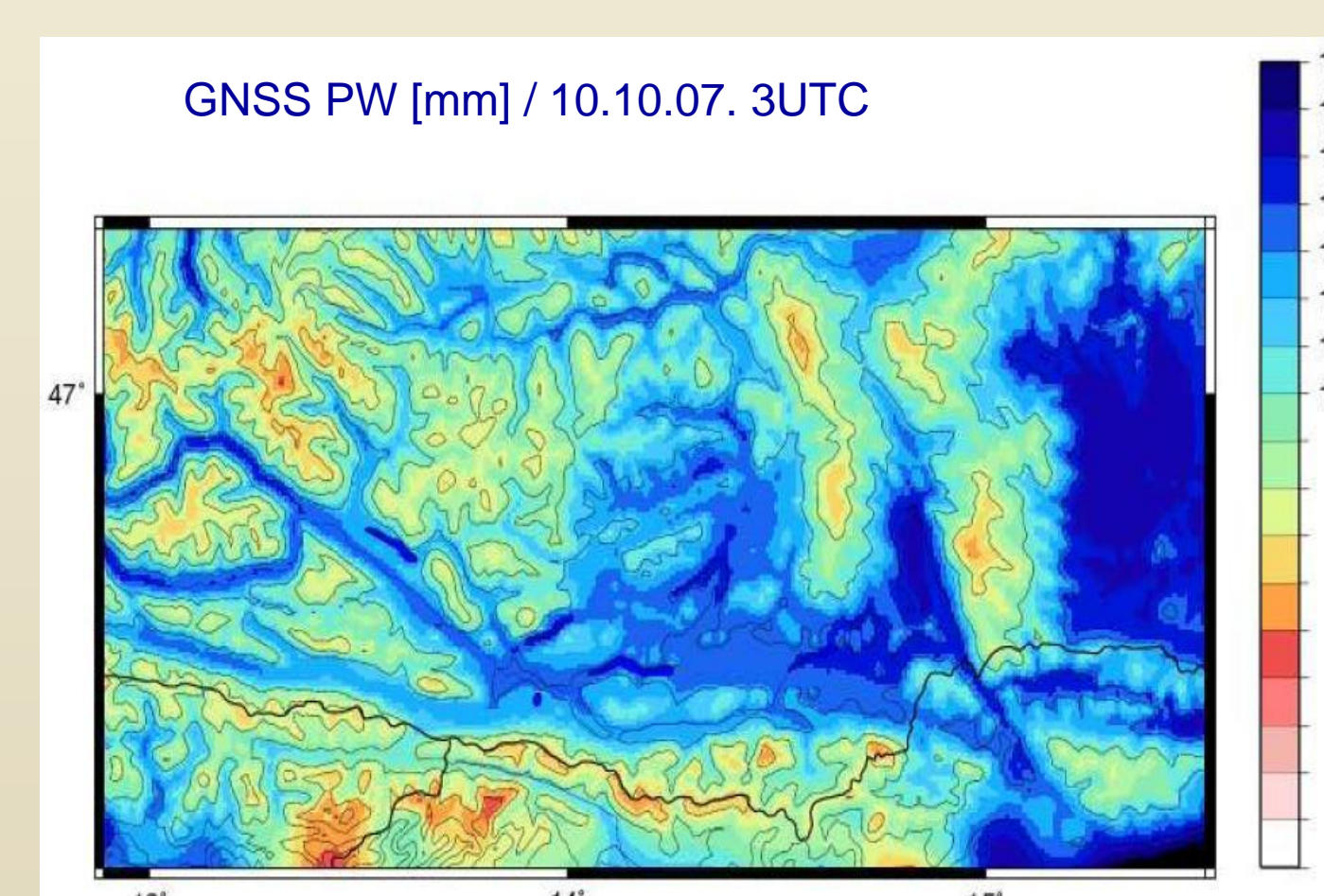
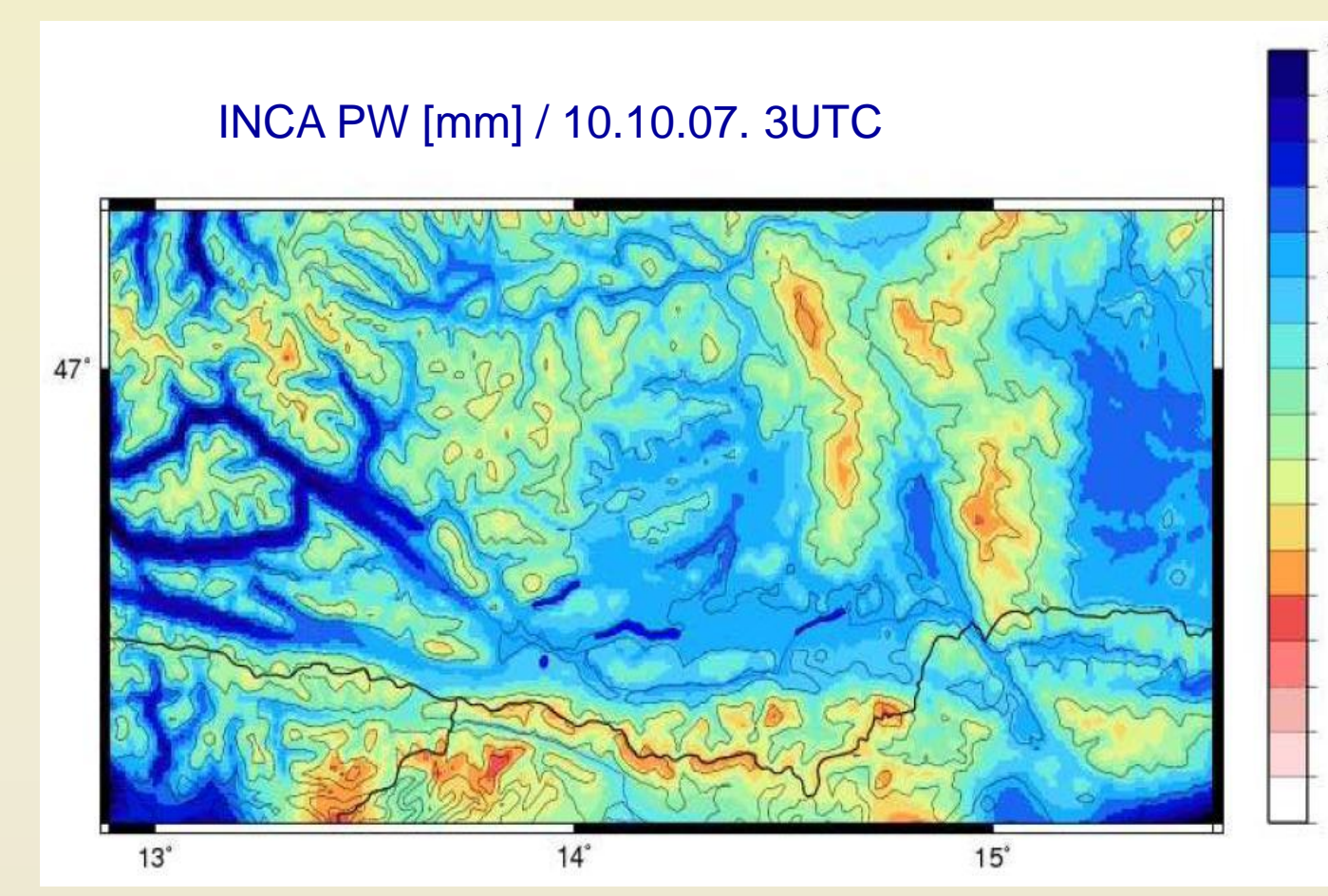


Fig.8. Humidity maps over Carinthia

The left hand graphics (Fig. 7) display a weather front passing the area of the KELSAT network as seen by the GNSS reference stations (top panel) and by the INCA forecast model (bottom panel). The horizontal axis resolution is hours. The event occurs in both cases in the same sequence of stations but shows a steeper decrease of the humidity in the forecast model. The right hand formulas display the applied weighting scheme to assimilate the GNSS estimates in INCA. The right panels (Fig.8) provide humidity maps of the KELSAT area. The top panel gives the raw INCA model and the lower panel INCA plus assimilated GNSS PW estimates.

$$f_k \langle \phi, \phi \rangle = \frac{PW_{GNSS}}{PW_{INCA}}$$

$$f_{ij} = \sum_{k=1}^N w_{ij}^k f_k \langle \phi, \phi \rangle$$

$$w_{ij}^k = \begin{cases} \frac{1}{r_k^2} & \text{when } r_k \leq 100km, \\ 0 & \text{when } r_k > 100km. \end{cases}$$

$$PW_{ij} = f_{ij} PW_{ij}^{INCA}$$

### 6. CONCLUSIONS & OUTLOOK

- We deliver Zenith Wet Delays for a regional network located in alpine area with an hourly resolution and a time delay of 30min (best case)
- The accuracy of our estimates is in most cases better than +/-1mm PW
- The hydrostatic part is calculated from ground meteo measurements nearby the GNSS stations
- ZAMG assimilates the ZWD values for test purposes into the real-time forecast system INCA
- GNSS corrected humidity profiles match radiosonde measurements quite well
- Improvements of INCA humidity profiles are visible in general during summer (GNSS constraints during periods of high humidity more tight) and in special in times of passing weather fronts.

In the near future we plan to further investigate the inclusion of GLONASS data, which will help to achieve a better coverage of the sky with observations. In addition further investigations aim at monitoring of rapid water vapour changes with an extremely high time resolution around the station Sonnbluck and at the installation of an GALILEO-IOV (In Orbit Validation) receiver for studying the potential impact of the new European Satellite Navigation System on the accuracy of water vapour estimates. New signals (E5) would allow to model higher order terms of ionospheric refraction and subsequently improve the ZWD accuracy. Additional observations to GLONASS and GALILEO satellites would allow for an increased temporal resolution of the ZWD estimates and for a spatial resolution (tomography).

It is planned to extend the GNSS network over the whole territory of Austria. This will of course imply a larger number of stations, and therefore tests to estimate the ZWD with PPP are performed. We may note the PPP dual frequency

ionospheric-free functional model for code and phase which is given by following formulas:

$$P_{if} = \rho + c(dt_s - dt_r) + \Delta_{up}$$

$$\Phi_{if} = \rho + c(dt_s - dt_r) + \Delta_{up} + \lambda_{if} N_{if}$$

Fig. 9. shows first results of PPP tests (blue line). The processed data covers the period 24.2.-1.3.2008, and the results are compared with results obtained from double differencing approach for the same time span (green line).

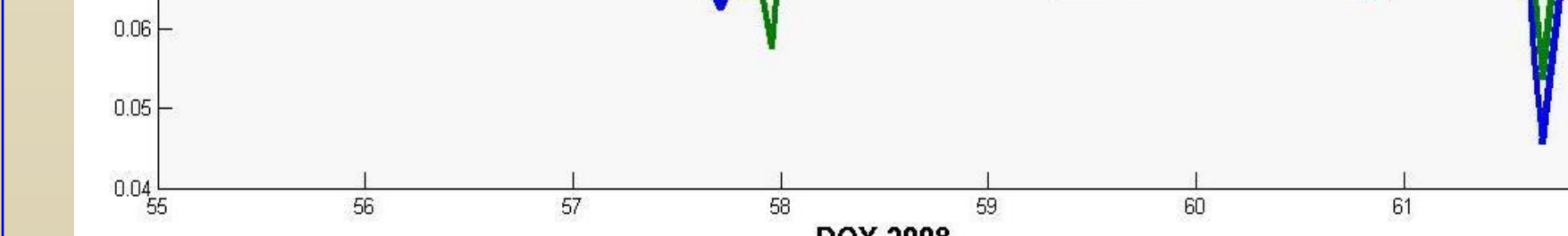


Fig.9. Comparison of DD and PPP approach in ZWD estimation

#### REFERENCES:

- Dach,R., Hugentobler,U., Friedz,P., Meindl,M.: „Bernese GPS Software, Version 5.0“, January 2006
- Klaffenböck,E.: „Troposphärische Laufzeitverzögerung von GNSS-Signalen – Nutzen aktiver Referenzstationsnetze für die Meteorologie“, Geowissenschaftliche Mitteilungen, Heft 76, TU Wien, 2007