Chapter 6
National Status Reports

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J. Jones et al. (eds.), *Advanced GNSS Tropospheric Products for Monitoring Severe Weather Events and Climate*, https://doi.org/10.1007/978-3-030-13901-8_6

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Abstract In this section a summary of the national progress reports is given. GNSS4SWEC Management Committee (MC) members provided outline of the work conducted in their countries combining input from different partners involved. In the COST Action paticipated member from 32 COST countries, 1 Near Neighbour Country and 8 Intrantional Partners from Australia, Canada, Hong Kong and USA. The text reflects the state as of 1 January 2018.

6.1 COST Countries

6.1.1 Austria

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GNSS-Met activities at TU Wien: Atmospheric monitoring is an active research field at the Department of Geodesy and Geoinformation at TU Wien. Fostered by various nationally funded projects but also due to the excellent exchange within the COST action GNSS4SWEC, significant progress can be reported in research fields like GNSS tomography, multi-GNSS data analysis, atmospheric modelling or tropospheric mapping (see Möller et al. 2015; Möller 2017 or Landskron and Böhm 2017).

Within COST action GNSS4SWEC, TU Wien actively contributed to the real-time demonstration campaign. Therefore, the PPP software developed within the research project PPPserve (Hinterberger 2016) was further modified for estimation of real-time tropospheric parameters. Since March 2017, TU Wien acts as an analysis centre for near real-time GNSS data processing. Near real-time ZTDs are provided on a routine basis for selected GNSS reference sites in Austria and neighbouring countries to the ZAMG (https://www.zamg.ac.at) and EGVAP (http://egvap.dmi.dk/) for data assimilation purposes. For more details, the reader is referred to Chap. 3.

GNSS-Met activities at ZAMG; ZAMG was invited to participate in the homogenisation activity of this COST action, due to the experience gathered during the COST action ES0601 on the homogenization of surface data. Homogenisation is an essential topic for climate research and different methods are available and used in different countries. At ZAMG the software HOMOP (Gruber et al. 2009), combining PRODIGE (Caussinus and Mestre 2004), SPLIDHOM (Mestre et al. 2011) and INTERP (Vincent et al. 2002), is used for daily homogenization. It's a relative homogenization method, therefore relying on highly correlated reference series. Break detection is done on an annual/seasonal basis. For the calculation of adjustments, a homogeneous sub period of about 5 years is usually recommended.

The dataset available on integrated water vapour are very different to the time series usually homogenized in climate research: The stations are sparsely distributed over the whole globe and the time series are of short duration only. Therefore, it is necessary to use reference stations, which are not located within the same climate zone and have low correlation. This is somehow circumvented by using differences between model output and stations data under the assumption that the model shows the same skill over the whole globe. Moreover, a higher precision of break detection would be of advantage. Workshops helped to understand the problems of the GNSS-community and supported the exchange of experience gathered by the two groups (ES0601 and ES1206) on homogenization. The testing of different homogenization methods initiated in the framework of the COST action ES1206 is still work in progress.

6.1.2 Belgium

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Belgium partners from the Royal Observatory of Belgium (ROB), the Royal Belgium Institute for Space Aeronomy (BIRA), and the Royal Meteorological Institute of Belgium (RMI) have contributed to most topics addressed by the WG1, WG2 and WG3 during the whole period of the COST action ES1206 (GNSS4SWEC). Their main contributions are listed below and refer to the proper section in this final report.

Contributions to WG1:

- Contribution to advanced GNSS processing techniques by BIRA and ROB (Chap. 3; Pottiaux et al. 2014; Douša et al. 2015, 2016a, 2017).
- Contribution to Benchmark campaign by BIRA and ROB (Sect. 3.2.1; Dick et al. 2016; Douša et al. 2016b).
- Contribution to the Real-time PPP demonstration campaign by ROB (Sects. 3.2.2; Douša et al. 2016c).
- State-of-the-art of GNSS meteorology by BIRA and ROB (Sect. 2.1, Brenot et al. 2015; Guerova et al. 2016).
- Coordination of sub-WG1 ASYM by BIRA and contribution to ASYM by ROB (Sect. 3.3).
- Comparison of horizontal gradients and investigation on their information content and physical meaning by ROB (Sect. 3.3.2; Morel et al. 2015a, b).
- Investigation of the use of residuals and implementation of new indicator of tropospheric activity by BIRA (Sect. 3.3.4; Brenot et al. 2014a).
- Contribution STD validation by BIRA and ROB (Sect. 3.3.5; Kačmařík et al. 2017).
- Investigation of the use of residuals and their information content to reconstruct STD by ROB (Sect. 3.3.5; Kačmařík et al. 2017).
- Multi-GNSS troposphere modeling for improved monitoring and forecasting of severe weather by ROB (Pottiaux et al. 2014).
- Assessment of GNSS ZTD errors and correlations using UKV model by ROB (Bennitt et al. 2017).
- Development and evaluation of ultra-fast tropospheric products (sub-hourly and real-time) and their dissemination by ROB (Sects. 3.4.4 and 3.7.4, Pottiaux et al. 2015).

- Development of new solutions contributing to E-GVAP (sub-hourly and worldwide solutions) by ROB (Sect. 3.7.4; Pottiaux and Bruyninx 2016).
- GNSS tropospheric products for climate by ROB (Sect. 3.6.3; Pottiaux and Pacione 2016; Pacione et al. 2017a, b).
- STSM at ROB of Pavel Václavovic on developing a processing prototype for real-time tropospheric products over dense network in Belgium (Chap. 7).

Contributions to WG2:

- Co-chairing of WG2 by ROB (Chap. 4; Jones et al. 2014, 2015a, b, c, d, e, 2016a, b, c, 2017a, b, c).
- Development of a GNSS-based toolbox for non-numerical nowcasting and severe weather in Belgium by ROB (Sect. 4.2.4).
- Improvement of forecast skill of the GLAMEPS Model based on data assimilation of GNSS products by RMI and ROB (Sect. 4.3.3).
- Contribution to sub-WG TOMO (Sect. 4.4):
  - GNSS tomography using of dense network by BIRA (Brenot et al. 2014b).
  - Cross-validation of GNSS tomography models by BIRA (Brenot et al. 2018).
  - Optimal geometrical setting of water vapour density tomography retrievals by BIRA and RMI (Brenot et al. 2014c).
  - Interest of GNSS tomography for nowcasting by BIRA (Brenot et al. 2017b).
  - STSM at BIRA of Riccardo Biondi (INGV) in summer 2014 about GNSS atmospheric water vapour detection for extreme events using GNSS tomography and radio occultations (Chap. 7).
- Contribution to the 1st GNSS4SWEC Summer School in Varna by ROB, BIRA and RMI with lectures about Extreme weather & Interactive session about Nowcasting.
- Characterisation of tropical cyclones in the South Indian Ocean by BIRA (Nogherotto et al. 2017).
- Monitoring of water cycle with reflectometry, contribution by ROB (Simeonov et al. 2017).

Contributions to WG3:

- Coordination of sub-WG3 IWV intercomparison by RMI (Sect. 5.6).
- Literature study of past IWV intercomparison studies (Sect. 5.6.1).
- Multi-site inter-comparison of IWV observations for climate change analysis by RMI, BIRA, and ROB (Sect. 5.6; Van Malderen et al. 2014).
- STSM at BIRA of Karina Wilgan (ETHZ) in summer 2016 about the implement of lookup tables of refractivity coefficients using 10 year of outputs from ERA-Interim (Chap. 7).
- GNSS tropospheric products for climate by ROB (Sect. 4.5.3; Pottiaux and Pacione 2016; Pacione et al. 2017a, b).
- Using GNSS to validate climate model runs used for climate impact studies in the CORDEX.be project by ROB (Sect. 4.5.3; Gobin et al. 2016; Termonia et al. 2016, 2018; Van Schaeybroeck et al. 2017a, b).

- Coordination of homogenisation activity of GNSS IWV time series by RMI and ROB (Bogusz et al. 2016; Klos et al. 2017a, b; Van Malderen et al. 2017a, b, Sect. 5.5)
- World-wide analysis of the time variability of IWV by RMI, ROB and BIRA (Sect. 5.7.2), Van Malderen et al. 2017c).
- GPS water vapour and its comparison with radiosondes and ERA-Interim reanalysis in Algeria by RMI, IRA and ROB (Namaoui et al. 2017).
- Validation of climate model IWV fields by reprocessed European GNSS dataset EPN Repro 2 (Sect. 5.7.4; Berckmans et al. 2017).
- STSM at ROB and RMI of Anna Klos (MUT) on the homogenisation and characterisation of IWV time series from IGS repro1 and its comparison to ERA-Interim (Sect. 5.5 and Chap. 7).

Eric Pottiaux (ROB) and Roeland Van Malderen (RMI) are editors of the Special Issue "Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC) (AMT/ACP/ANGEO inter-journal SI)".

6.1.3 Bulgaria

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Application of GNSS tropospheric products in Bulgaria/Southeast Europe was initiated in 2011 with the project titled "Exploitation of ground-based Global Navigation Satellite Systems (GNSS) for Meteorology and Climate studies in Bulgaria/Southeast Europe" (2011–2014, http://cordis.europa.eu/result/rcn/164029_en.html). Within this project the Sofia University Atmospheric Data Archive (SUADA, http://suada.phys.uni-sofia.bg) was developed and used to study short and long-term variation of Water Vapour (WV) in the region. The GNSS4SWEC was very beneficiary for sustaining and further advancing the GNSS meteorology in Bulgaria. A summary of the GNSS4SWEC work in Bulgaria is given below.

Contribution WG1: A collaboration with University of Luxembourg resulted in establishment of the Sofia University GNSS Analysis Centre (SUGAC). SUGAC is the first Analysis Centre in Southeast Europe targeting atmospheric monitoring with the tropospheric products from the ground-based GNSS networks. The SUGAC first processing campaign took place in 2014 with processing seven Bulgarian GNSS stations for 1 year and deriving tropospheric products with very high temporal resolution (5 min). Further detail is available in Chap. 3.

Contribution WG2: In collaboration with the Operational Weather Prediction department of the National Institute of Meteorology and Hydrology case studies of fog, foehn, convective and frontal precipitation and hails storms in Bulgaria were conducted (see Chap. 3). A comparison of diurnal cycle of GNSS derived WV and WRF model simulations for Bulgaria indicate a negative model bias in the range 0.5–1.5 kg/m^2 (Simeonov et al. 2016). Collaboration with Aristotle University of Thessaloniki resulted in production of two dimensional WV map covering Bulgaria and Greece.

Contribution WG3: In collaboration with Hungarian Meteorological Service the WV anomalies from GNSS, regional climate model (ALADIN-Climate) and ERA-Interim reanalysis during the 2007 heat wave in Bulgaria were compared. The observed with GNSS (black line in Fig. 6.1) annual WV cycle at Sofia was found to be well captured in the ERA-Interim reanalysis (blue line in Fig. 6.1) while the ALADIN-Climate model peak in 2007 was 1 month earlier (red and green line in Fig. 6.1).

The early career researchers from Bulgaria participated actively in the GNSS4SWEC working group meetings and workshops. In total six MSc and five PhD students from Sofia University attended the GNSS4SWEC summer schools (2014, 2016). In 2014 the GNSS4SWEC summer school and WG meeting took place in Bulgaria (http://suada.phys.uni-sofia.bg/?page_id=2466). One early career researcher (Tzvetan Simeonov) conducted a STSM to the University of Luxembourg. Peter Szabo from the Hungarian Meteorological Service visited Sofia

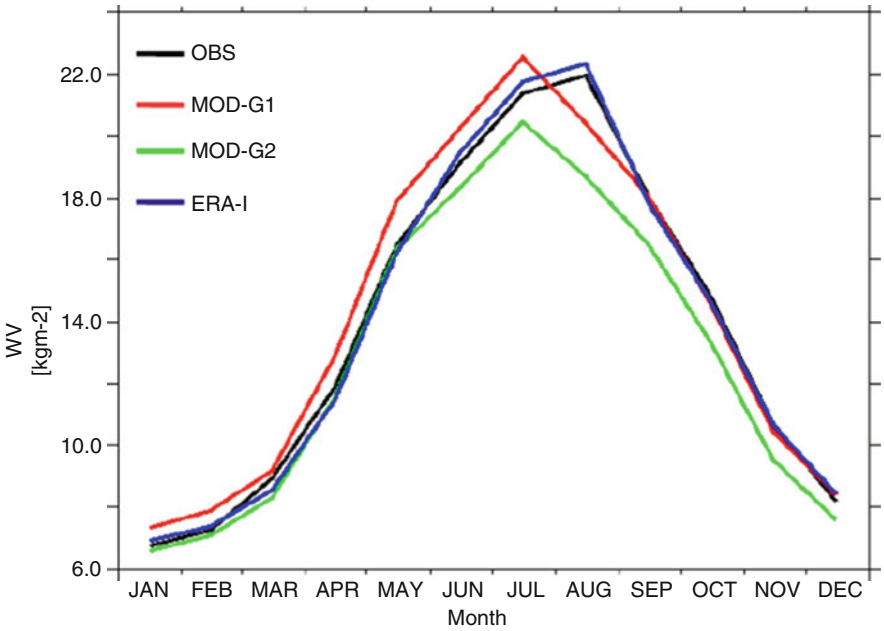

Fig. 6.1 Monthly mean WV for 2007 from GNSS (black line), ERA-Interim (blue line) and ALADIN-Climate (green and red line) at Sofia, Bulgaria. (Courtesy to P. Szabo)

University for a STSM. Published were four peer-review journal papers and two papers are in preparation. Established was close collaborations with colleagues from Cyprus and Greece, which will continue in the framework of the regional project "BalkanMed real time severe weather service" (BeRTISS, 2017–2019).

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Cyprus has not been particularly active on GNSS meteorology in recent years. This has been partly due to a lack of an operational GNSS network on the island. Although the situation has improved in recent years with the deployment of the CYPOS network (seven GNSS stations), activities related to GNSS meteorology did not change until last year when the Frederick Research Centre (Cyprus) along with two more countries from the COST Action GNSS4SWEC (Greece and Bulgaria) submitted a joint proposal in the frame of the Transnational Cooperation Programme (TNCP) "Balkan-Mediterranean 2014–2020". The proposal BeRTISS "BalkanMed real time severe weather service" was successfully evaluated and its 2-year implementation started in September 2017. The geographical scope of the related existing network is shown in Fig. 6.2 and the network under deployment in Fig. 6.3.

The objective of the project is to develop and implement a pilot transnational severe weather service based on GNSS tropospheric products for the Balkan-Mediterranean area to improve the safety and quality of life and the protection of the environment, through the timely information regarding severe weather events and the long-term monitoring of climate change in the region.

In particular, the technical aims of the project are:

1. Integration of national networks of GNSS stations located in the three countries in a united system
2. Collection, processing and analysis of GNSS tropospheric data through the establishment of GNSS Analysis Centres,
3. Calculation of the meteorological parameter PWV for more accurate short-term prediction of severe weather events, following the innovative approach of exploiting GNSS satellite products
4. Creation of a dedicated website to provide in real-time the National Meteorological Services and the public with PWV data and warnings of severe weather events.

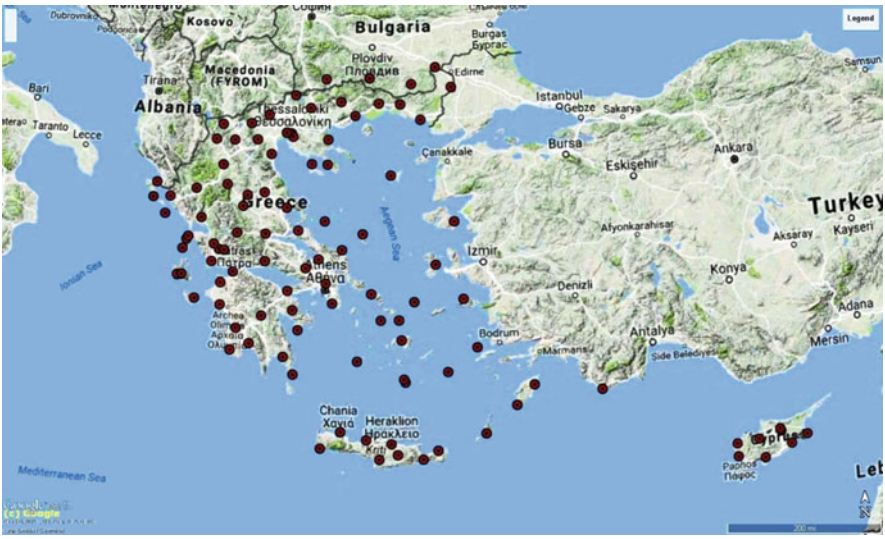

Fig. 6.2 Existing stations involved for the delivery of ZTD parameters in the frames of the BeRTISS project

Fig. 6.3 Stations to be deployed for the delivery of ZTD in the frame of the BeRTISS project

6.1.5 Czech Republic

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Three institutions participated actively in the COST Action, namely

- Geodetic Observatory Pecný (GOP), Research Institute of Geodesy, Topography and Cartography (RIGTC)
- Institute of Geoinformatics, Technical University of Ostrava (VŠB)
- Institute of Computer Science (ICS), Academy of Sciences of the Czech Republic (AS CR)

A long-term engagement of GOP in the ground-based GNSS troposphere monitoring for meteorological applications and related activities exists since 1999. GOP participated in COST-716 (2000–2003), contributed to the first NRT Demonstration campaign since the beginning in 2001, participated in EU TOUGH project (2003–2006) Targeting Optimal Use of GPS Humidity Measurements in Meteorology, and from the beginning contributed to the E-GVAP (2003–present). On a continuous basis, GOP provides several products including the first global, GPS + GLONASS combined and real-time solutions. The above experience lead to an active GOP participation during the planning, preparation and co-organization of this COST Action during which all three institutions were actively contributed to all three working groups summarized below.

Contributions to WG1:

- Chairing the working group (GOP), leading several WG1 tasks (GOP, VŠB), co-organizing workshops, group meetings, summer schools, external presentations (GOP)
- WG1 Benchmark campaign (GOP and VŠB)
  - Planning, design, coordination, data collection and provision
  - Provision and assessment of reference GNSS & NWM products
  - Assessment of tropospheric gradients in denes regional network
  - Optimizing strategy for real-time tropospheric production in simulated real-time mode

- New products for tropospheric anisotropy monitoring (GOP and VŠB)
  - Inter-comparison of slant delays retrieved from GNSS, NWM and WVR
  - Extensive comparisons of GNSS & NWM tropospheric gradients
  - Development and assessment of a fully consistent strategy for estimating ZTDs, gradients and slant-delays in (near) real-time
  - Impact of the forward filtering and the backward smoothing processing method on horizontal gradients and slant delays
  - Impacts of observation elevation weighting, gradient mapping function and multi-GNSS processing on troposheric gradients
- Ultra-fast product development (GOP and VŠB)
  - Development of in-house G-Nut/Tefnut for real-time ZTD and gradient estimation, routine provision of RT solutions since 2013
  - Development of new all-in-one strategy for a unique and optimal NRT and RT estimation of all tropospheric parameters
  - Contribution to RT Demonstration campaign with G-Nut/Tefnut software (GOP) and RTKlib software (VŠB) solutions
  - Long-term assessment of IGS RTS orbit and clock corrections
- Real-time demonstration campaign (GOP)
  - Design and coordination of the RT demonstration campaign
  - Campaign monitoring: http://www.pecny.cz/COST/RT-TROPO
  - Provision of NWM-forecasted ZTDs in RT demonstration
- Tropospheric correction models for GNSS positioning (GOP)
  - Development of accurate tropospheric parameter vertical scaling
  - Development of combined GNSS+NWM tropospheric model
  - Development and long-term assessment of tropospheric correction models in various user modes
- NWM-based data in GNSS positioning (GOP)
  - Impact of exploiting various external tropospheric corrections on hot-air baloon positioning, correlation study, multi-GNSS etc.
  - Impact of tropospheric corrections on PPP convergence time, re-convergence and pseudo-kinematic processing
  - Impact of NWM forecast length on derivation of ZTD parameters
- Support for setting up new analysis centres, transfer-of-knowledge (GOP)
  - Establishing new ACs: Trabzon (Turkey), Thessaloniki (Greece), Zolgundak (Turkey), Reykjavik (Iceland), Bucharest (Romania)
  - Development and provision of the TropNET system and transfer-of-knowledge (Poland, Netherlands, Slovakia, China).
  - Processing of national networks from Latvia and Slovakia
  - Monitoring of TropNET: http://www.pecny.cz/COST/TropNET

Contributions to WG2:

- Development of ensemble assimilation techniques (ICS)
  - Contribution to background covariance modelling
  - Initial twin experiment of assimilation of ZTD into WRF model
- Preparation of NWP data field for geodetic application (ICS, GOP)
  - Co-operation on WRF data encoding for input to PPP
  - GNSS kinematic experimental campaign supported with NWM
  - Monitoring ZTD predictions from WRF-ICS in RT-Demo

Contributions to WG3:

- GNSS re-analysis, done partly within WG1 (GOP)
  - Contribution to the EUREF GNSS 2nd reprocessing (1996–2014)
  - Assessment of seven processing variants in terms of coordinate repeatability, ZTD and tropospheric horizontal gradient estimates
  - Impact of re-processing strategy and models on ZTD trends
  - Impact of GNSS data quality on tropospheric gradients
- GOP-TropDB development and community support (GOP)
  - Evaluation of global IGS reprocessing products
  - Evaluation of individual AC + combined EUREF Repro2 solutions
  - Provision of NWM parameters for GNSS product evaluations
  - Interactive visualization of comparison statistics at the portal of the IGS Tropospheric WG: twg.igs.org/Tropo_Comp_Site
  - Online NWM-based calculation service for selected tropospheric and meteorological parameters: http://www.pecny.cz
- GNSS ZTD time-series analysis (GOP)
  - Development of the tools for time-series analysis, data cleaning, homogenization, variation and trend estimation
  - Developments and comparisons of data homogenization
  - Assessment of reference time-series from ERA-Interim
- SINEX_TRO V2.0 format design and implementation (GOP)

Finally, GOP acknowledges the national support of the Ministry of Education, Youth and Sports towards various contributions to the COST Action 1206 (LD14102, LH14089, LO1506, LM2015079).

GOP also acknowledge the Czech Hydrometeorological Institute for providing and consulting data for the Benchmark campaign.

6.1.6 Denmark

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Ground-based GNSS meteorological activities at DMI: DMI has been active in ground-based GNSS meteorology since 1998, partaking in, among other things, EU project MAGIC, EU Cost action 716, EU project TOUGH, and being part of the E-GVAP (egvap.dmi.dk) team since the start of E-GVAP in 2005, with the role of coordinator.

The first GNSS research work at DMI was related to validation of GNSS derived IWV using NWP. But most research has concentrated on the use of GNSS delays in NWP, refining assimilation algorithms and doing impact experiments. The experiments showed an increase in NWP skill from using GNSS delays. Following assimilation became operational, but stopped when access to Nordic data ceased for a period. It is now being tested again, but not yet operational. The number of GNSS sites providing ZTDs within the DMI NWP areas has increased significantly in the meantime, and the primary NWP model has changed to a non-hydrostatic model, calling for the determination of new bias corrections, observation error estimates, etc.

DMI runs a rapid update NWP model with special focus on the forecast of local, convective precipitation. These systems use 3DVar data assimilation of standard observations + additional nudging assimilation of certain types of observations obtained many times an hour and of importance for precipitation, like radar 2D precipitation estimates and satellite images of clouds. Similarly, we will consider methods enabling usage of more GNSS delay data than 3DVar, which is restricted to one observation per site per assimilation cycle.

In addition, DMI extracts radiosonde data for validation of European GNSS delays, they are made available through E-GVAP. And do statistics of the E-GVAP ZTDs wrt. UK Met Office Global model NWP ZTDs, as part of the monitoring of E-GVAP data.

GNSS4SWEC has been a big benefit to DMI. Directly, enabling us to meet other GNSS meteorological researchers, learning from them and help drive the research in directions useful to DMI. And not the least indirectly, through a very effective spread of GNSS meteorological expertise in Europe. This has both increased the rate of progress in the field regarding both GNSS data processing for NWP and climate, and use of GNSS data in NWP. And it has resulted in a much better geographical coverage as regards the GNSS observation network, which is beneficial to European meteorology at large.

Other GNSS meteorological activities at DMI: DMI is leading the EUMETSAT ROM SAF (www.romsaf.org), which process GNSS RO measurements from the EUMETSATs Metop satellites for usage in meteorology and climate monitoring.

GNSS RO data from Metop and COSMIC are assimilated into the operational AROME NWP models.

Other GNSS meteorological activities in Denmark: Two other public institutions working with GNSS, DTU Space (Danish Technical University, research oriented), and "Geodatastyrelsen" (national mapping agency, Danish reference frame), exist. None of them are active in traditional ground-based GNSS meteorology, except that the Danish GNSS ZTDs available in E-GVAP (processed by NGA and ROB) are based on RINEX data delivered by Geodatastyrelsen to DMI. That is of the order ten sites. Potentially about 50 more sites, belonging to two private networks could be included, but currently they are not available to us. DTU is involved in experiments on Greenland, testing the ability to measure sea level and ice from reflected GNSS signals. DTU operates a number of GNSS sites on Greenland that could potentially be included in the E-GVAP processing.

6.1.7 Estonia

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In frame of COST ES1206, the Estonian team (based on Tallinn University of Technology and University of Tartu) has participated in WP2 and WP3. The works under WP2 were targeted to the case studies – extreme weather events at coastal areas of the Northern Baltic Sea (Estonia and Finland). Extreme snowfalls in Merikarvia in January 2016 and its connections to the large scale water vapour transport to the Northern Europe were studied. The activities under WP3 were targeted to investigations of GNSS IPW trend analysis and issues related to harmonisation of meteorological time series. The interest in GNSS-meteorology remains basically academic. Scientific collaboration has started with FMI (modelling and analysis of extreme snow events) and the Israeli Meteorological Service. In general, there are 27 permanent GPS stations in Estonia, of what 18 were installed in 2014–2015. Thus, the possibilities in using GNSS-data for regional analysis have increased remarkably due to installation of ESTPOS RTK-network (2014–2016), owned by the Estonian Land Board (ELB). It could be a good possibility to start negotiations with ELB about delivering data (tropospheric products) for E-GVAP. The ELB has capabilities to process GNSS-data on regular basis also. Additionally, many sites are equipped with Vaisala AWS (no need for interpolating meteorological data, meteo RINEXes are archived).

6.1.8 Finland

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Finnish Meteorological Institute has participated in COST Action ES1206 WGs and MC. Main activities are listed below.

- GRUAN site Sodankylä (Fig. 6.4) provided measurements by multiple techniques, including GNSS, RS92, MWR, FTS, AERONET sun photometer data. Sodankylä is involved in several relevant networks, e.g. GNSS networks, GRUAN, NDACC, TCCON, AERONET. GRUAN data are available regarding the RS92 SGP post processing.
- SODF is a new GNSS station, established in 2015 during the COST Action. IWV data processing has been organized in cooperation with GFZ in Potsdam, Germany and GRUAN Lead centre in Lindenberg, Germany.

Fig. 6.4 Two GNSS systems at Sodankylä, Finland, 97 m vertical difference, 12 km apart. Left panel: antenna installed at Sodankylä Tähtelä. Right panel: antenna installed at Sodankylä Pittiövaara

- Detection of possible discontinuities in the ZTD and IWV time series due to changes in instrumentation (Fig. 6.5).
- Inclusion of radiosonde data from long-term operation at the GRUAN site.
- Quality control of RS data set.
- Quality control of other available IWV data sets.
- Comparison of IWV values from redundant measurements.
- Collaboration with other COST countries has included study of Severe Weather using GNSS data (Fig. 6.6).

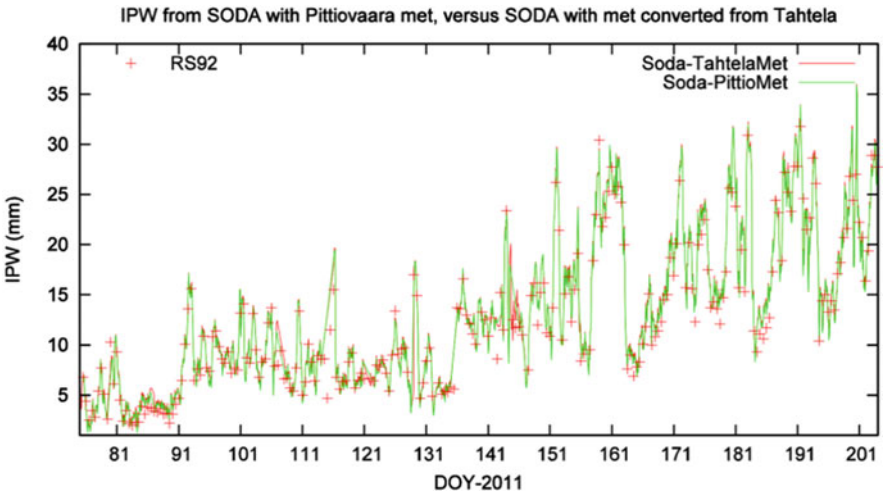

Fig. 6.5 GPS-PW from two stations in Sodankylä

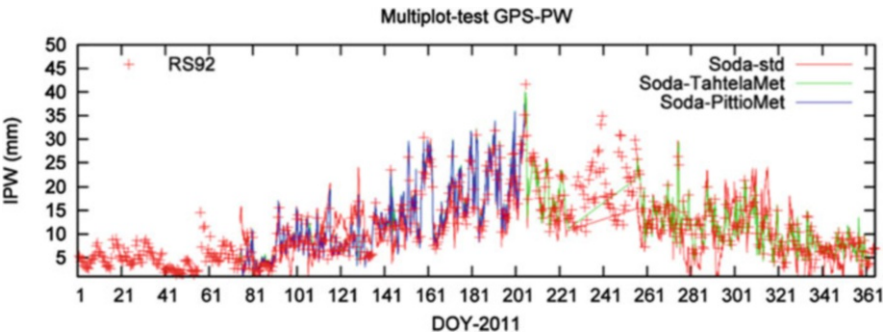

Fig. 6.6 PW in Sodankylä for the year 2011

6.1.9 France

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IGN's operational geodetic and levelling service (SGN) is maintaining the French national GNSS network (RGP) comprising more than 450 stations. The network includes a small core of geodetic reference stations as well as a large number of stations from private and public operators. The rinex data from all the stations are publicly available at a central data centre hosted by IGN. The data are processed with Bernese GNSS software in different batches using near real time (NRT), rapid, and final IGS products, with 1-hourly, daily and weekly updates, respectively. One of the NRT batches is dedicated to operational GNSS meteorology as IGN has been an official E-GVAP Analysis Centre since 2001. Similarly, one of the weekly batches is dedicated to maintain the European terrestrial reference frame (EUREF). The main activities of IGN/SGN during the course of the GNSS4SWEC project were: the inclusion of new stations, both over the metropolitan zone and overseas (namely in the Caribbean region), the switch from GPS only to GPS + GLONASS solutions, and the participation in the EUREF repro2 reprocessing campaign.

Research activities were conducted by IGN/LAREG (Laboratoire de Recherche en Géodésie), in collaboration between several partners from the Action: ENSTA, France, LATMOS, France, AgroParisTech, France, RMI, Belgium, UWM, Poland, MUT, Poland. They covered the following topics:

1. The signature of Mesoscale convective systems passing over GPS stations in West Africa was investigated in ZTD, gradients, and phase residuals, and a stochastic model parametrization method based on Bayesian model selection was proposed to optimally tune the GNSS data processing options in case of such extreme events (Nahmani and Bock 2014; Nahmani et al. 2016, 2017).
2. The impact of baseline strategy on ZTD estimates in double-difference processing of GNSS networks was investigated and a methodology was proposed to significantly reduce the number of ZTD outliers by an improved network design (Stepniak et al. 2018).
3. ZTD post-processing screening strategy has been developed to detect ZTD outliers and has been proposed as a standard method for GNSS meteorology (Bock 2016b; Bosser and Bock 2016). The method is based on range-checks and outlier checks and comprises two options: one using GNSS-results only (ZTD and formal error data) and one using an independent dataset as a reference (e.g. NWP reanalysis). It can be used both for operational and post-processed data.

4. ZTD to IWV conversion methods have been reviewed, including the uncertainty due to refractivity constants and various sources of auxiliary data (Parracho 2017). Recommendations are provided in the Final Report (WG3).
5. A reference long-term reprocessed GNSS IWV dataset was prepared for homogenization activities in WG3 (Bock 2016a; Klos et al. 2017a, b; Van Malderen et al. 2017a, b, c). It is based on IGS repro1 ZTD data, screened and converted to IWV using the aforementioned methods and ERA-Interim as auxiliary data (for surface pressure and Tm).
6. Global IWV trends and variability have been analysed based on the aforementioned GNSS IWV dataset and on reanalysis data from ERA-Interim and MERRA (Parracho et al. 2018) as well as from global climate model simulations (Parracho 2017) and regional climate model simulations Med-CORDEX project (Bastin et al. 2017).
7. Satellite IWV data from three instruments (MODIS, SCIAMACHY, and AIRS) have been evaluated against GPS IWV data in the Arctic region for the period 2001–2014 (Alraddawi et al. 2017). It was shown that surface albedo and cloudiness (in cloud-cleared data) are not enough well modelled in current satellite retrieval algorithms with MODIS and SCIAMACHY and introduce spurious seasonal and inter-annual variability in IWV retrievals.
8. Existing homogenization methods were tested for the detection of breaks in the GNSS IWV time series and it was shown that due to the non-stationarity of noise in the GNSS observations, the performance of homoscedastic and heteroscedastic methods breaks down (Ahmed et al. 2015). New methods are currently being developed in collaboration with AgroParisTech.

6.1.10 Germany

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GNSS Meteorology at GFZ: GNSS Meteorology is an integrative part of the GFZ research activities in the Helmholtz Association's Research Field "Earth and Environment" Programme "Atmosphere and Climate" (ATMO). The related scientific

work was initiated in 2000 with the GPS Atmosphere Sounding Project (GASP). GNSS ground-based observations of global networks as IGS and TIGA, of EUREF and the German SAPOS (SAtelliten-POSitionierungsdienst), as well as campaign-type networks (all-together around 1300 stations) are used for operational atmospheric sounding. The data are analysed in near-real time for the assimilation to weather models and consistently re-processed for climatological investigations in the framework of the Global Climate Observing System (GCOS). Recent investigations at GFZ focus on exploiting the potential of real-time multi-GNSS observations for atmospheric data products with improved accuracy, higher spatio-temporal resolution and immediate availability. Additional tasks like the derivation of 3D water vapour distributions and GNSS applications for climate research are also included into the GFZ developments.

GFZ contribution to GNSS4SWEC: GFZ significantly contributed to all three Working Groups of the COST Action GNSS4SWEC and especially to the Working Group 1 by the development of the next-generation data products with improved impact to forecasts in close cooperation with German Weather Service (DWD). The international cooperation within the COST action was extremely useful for these investigations. Multi-GNSS tropospheric products in real time (Fig. 6.7) were one of the main focuses of the GFZ contributions. GRDs (Fig. 6.8) and STDs were other investigation areas. Operational retrieval of slants was established at GFZ for the first time and the STDs were continuously provided to DWD for forecast experiments (Fig. 6.9) after intense validation with water vapour radiometer data. The new assimilation operator for slants was developed in close cooperation of DWD with GFZ.

Operational Weather Forecast: The application of operational atmospheric products to improve regional and global weather forecasts is an integral part of the scientific development work in GNSS Meteorology at GFZ and a significant contribution to the Working Group 2 of GNSS4SWEC. Figure 6.9 exemplarily shows a regional precipitation forecast study by the German Weather Service (DWD). More than 20% improvement was reached by additional use of the GNSS slant total delays from GFZ.

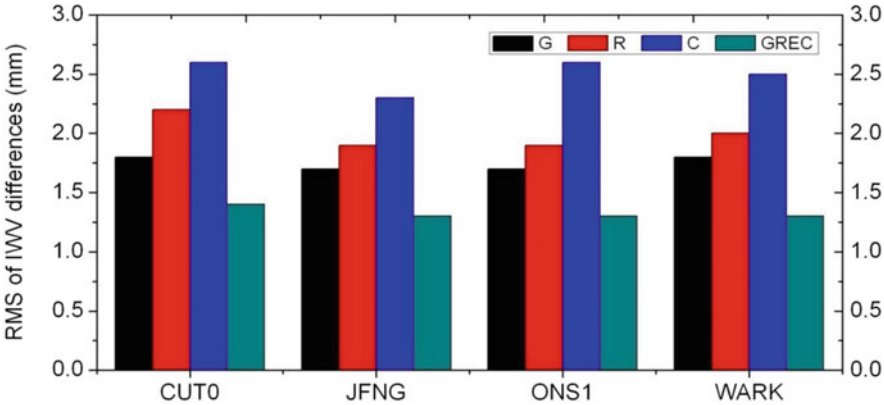

Fig. 6.7 Multi-GNSS IWV in simulated real time: Validation with radiosondes data. Results are presented for: G – GPS only, R – GLO only, C – BDS only, and GREC – all four satellite systems GPS + GLO + GAL+BDS. Time period: January–July, 2014

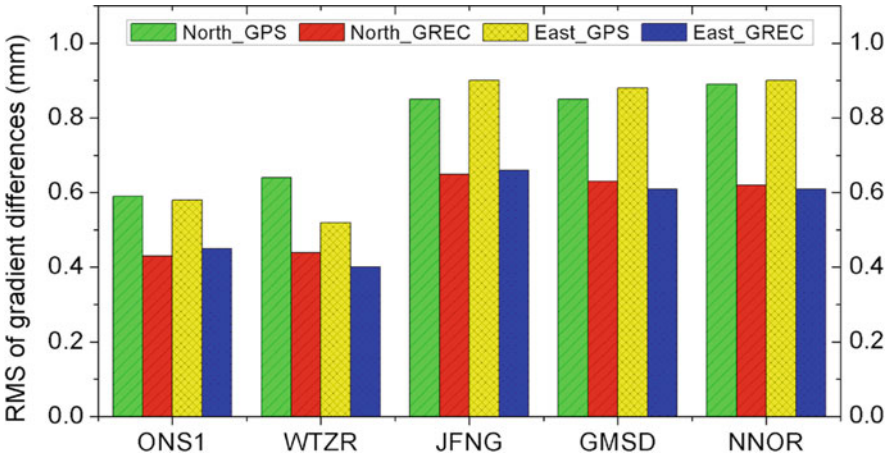

Fig. 6.8 Multi-GNSS (GREC-GPS + GLO + GAL+BDS) high-resolution tropospheric gradients compared to horizontal delay gradients from a NWM refractivity field (ECMWF analysis)

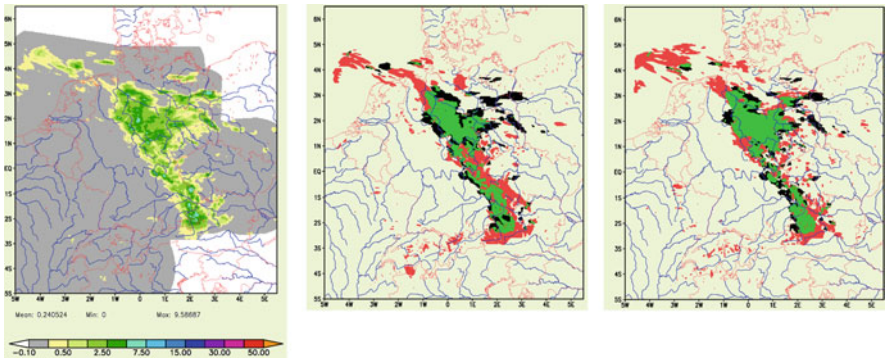

Fig. 6.9 Results of a DWD forecast experiment using GNSS slant delays from the German network on May 28, 2014, during a strong precipitation event. Left: radar observation (mm/hour; truth), middle: forecast without GNSS and right: forecast with GNSS. Green/red colour indicates good/bad agreement of forecast and radar data. The assimilation of GNSS slant data improves the forecast more than 20% indicated by larger green and smaller red areas. (Figures provided by K. Stephan, DWD)

Climatological Investigations: GFZ contributed to the Working Group 3 with re-processing of GNSS data of about 800 globally distributed stations within IGS TIGA project. Precise trends of water vapour can be derived from such long-term data sets (Fig. 6.10).

An additional contribution is GFZ's activity within the GCOS Reference Upper Air Network (GRUAN, www.gruan.org) of the World Meteorological Organization (WMO). GFZ was selected as the central GRUAN GNSS Data Processing Centre of WMO.

GNSS Meteorology activities at DWD: The Data Assimilation Group of DWD has integrated the assimilation of GNSS ZTD data into the global ICON model (13 km resolution) and its two-way nested area over Europe (6.5 km resolution),

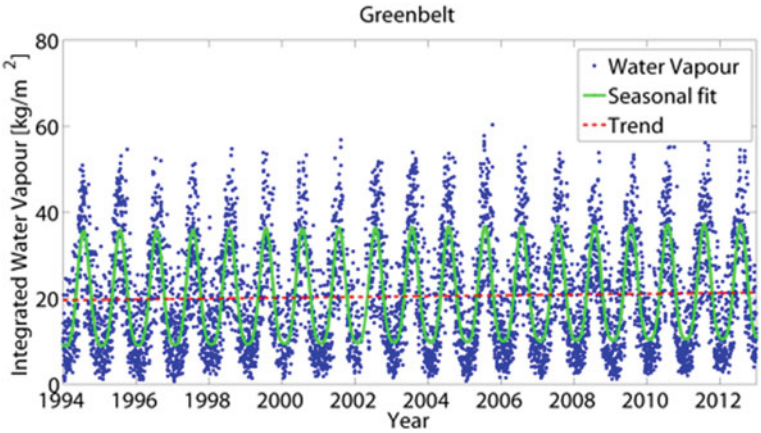

Fig. 6.10 Integrated water vapour at the GNSS station Greenbelt (U.S.). Trend of 0.94 mm/year was derived, based on the re-processed data set of ~800 TIGA stations for 20 years

based on the Local Ensemble Transform Kalman Filter (LETKF) and Ensemble Variational Data Assimilation EnVAR. The assimilation of ZTD shows a slightly positive impact on upper air verification in the global forecasting system. However, the GNSS data lead to some spin-up effect on precipitation in the ICON model for the first 24 h, which is under investigation currently. ZTD assimilation is in preoperational testing state waiting for the remaining issues to be resolved. For the convection-permitting COSMO-DE and COSMO-DE-EPS the assimilation of GNSS STD has been developed based on the Kilometre-Scale Ensemble Kalman Filter (KENDA), with a sophisticated GNSS-STD forward operator includes ray tracing (Bender et al., in preparation). Initial experiments (compare Fig. 6.9) show a positive effect on the localization of precipitation. More intense testing is being carried out currently, with the need of careful tuning of localization and thinning in the LETKF to reduce the influence of correlated errors and spurious correlations in the 40 member KENDA ensemble. We expect to enter a preoperational state for the KENDA-STD system in the near future.

GNSS Meteorology activities at University Cologne: Near-real time IWV estimates from GFZ are used as at University of Cologne to investigate the performance of a new high-resolution reanalysis (Bollmeyer et al. 2015) with 6 km resolution (COSMO-REA6) on the European scale and 2 km over Germany (COSMO-REA2). Their suitability for this for temporal scales of 15 min and longer has been shown Steinke et al. (2015) using comprehensive instrument comparisons and high resolution modelling during the HOPE campaign (Macke et al. 2017). The comparison of reanalyses revealed the benefit of the high resolution which show standard deviation with observed of about 1.5 mm and thus significantly lower than ERA-Interim (2.5). This improvement compared to global reanalysis also holds for daily mean IWV values but disappears than monthly means are considered. Figure 6.11 shows that the improved standard deviation is observed over all seasons and that both bias and standard deviation differ much less between different stations than for ERA-Interim.

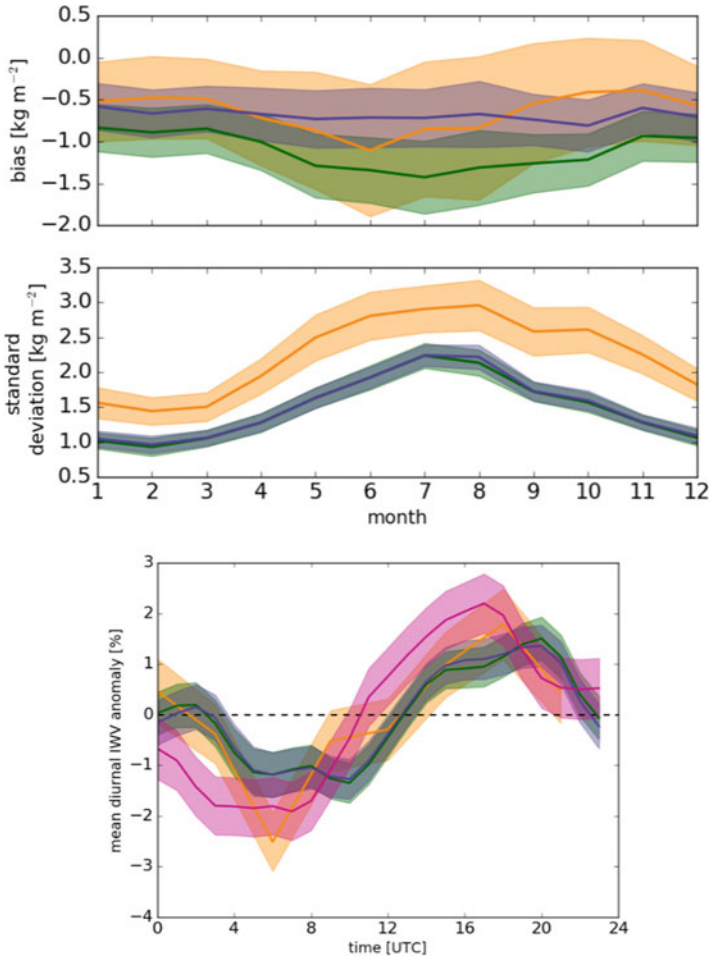

Fig. 6.11 IWV monthly mean of bias (top) and standard deviation (bottom) simulated with COSMO-REA2 (green), COSMO-REA6 (purple) and ERA-Interim (orange) compared to 133 GPS station observations for 2007–2013. The standard deviation of the respective error is shaded

A major improvement of COSMO-REA compared to ERA-Interim which only is available every 6 h (forecasts every 3 h) is the availability to resolve the diurnal cycle of IWV. In general COSMO-REA reproduces the observed diurnal cycle (Fig. 6.11) but shows some phase shift and reduced amplitude. This evaluation already helped to identify an issue with the surface vegetation information in COSMO-REA which will be fixed in later versions. Because the surface is the source for water vapour and the water vapour content of the boundary layer contributes roughly half of the total IWV, the observations are well suited to analyse land surface exchange processes and could reveal differences in the diurnal cycle for different circulation weather types and surface elevations (not shown).

6.1.11 Greece

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In the frame of a Short Term Scientific Mission on October 2014, a new analysis centre (AC) for near real-time GNSS tropospheric monitoring in Greece was established at the Department of Surveying Engineering of the Aristotle University of Thessaloniki (AUTh). Since then the AUTh Analysis Centre contributes to the EGVAP hourly ZTDs from over 90 permanent GNSS stations in Greece using the Trop-NET Engine. The AC provides a unique contribution of tropospheric products to the meteorological community for the E-GVAP project that cover the whole of Greece. Also as a direct result of Greece's participation in this COST action, in collaboration with two other COST participating countries, Bulgaria and Cyprus, the AUTh Research team received funding under the frame of the European Territorial Cooperation Programme "Interreg V-B Balkan-Mediterranean 2014–2020" for the project BeRTISS (Balkan-Meditteranean Real Time Severe weather Service). More information on the new AC activities in Greece can be found in Sect. 3.6.7 of this report.

6.1.12 Hungary

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Within the frame of the project the Budapest University of Technology and Ecomics (BME), the Hungarian Meteorological Service (HMS) and the Satellite Geodetic Observatory of the Institute for Geodesy, Cartography and Remote Sensing (SGO) worked closely together to improve the coverage of the near-realtime ZTD estaimations in central and eastern Europe.

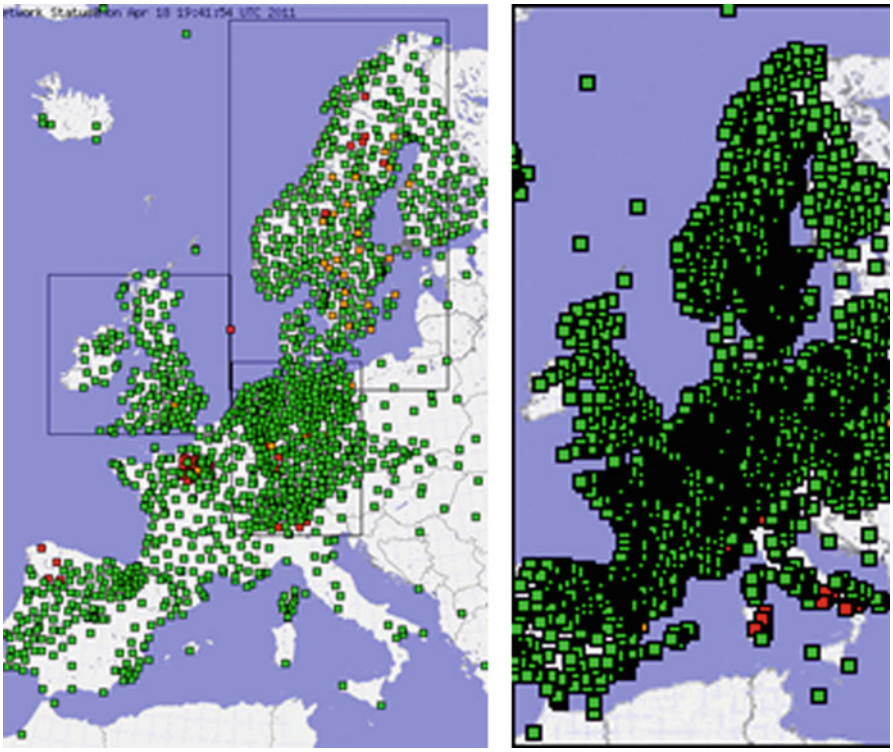

Fig. 6.12 The E-GVAP coverage in 2011 (left) and 2013 (right). Observe the significant improvement in Central and Eastern-Europe

In order to achieve this goal, a new near real-time GNSS processing centre has been established with the cooperation of BME and SGO and the estimations were automatically transferred to the E-GVAP data centre for testing and validation purposes. The centre (SGOB) processed the following GNSS stations:

- Hungarian GNSS network (GNSSNet.hu)
- additional GNSS stations from the neighbouring countries including E-GVAP supersites for validation
- As a result of this activity altogether 54 new Hungarian and Central-European GNSS stations were added to the E-GVAP coverage (see Fig. 6.12).

Since the GNSS observations must be processed within the premises of the SGO due to legal restrictions, the SGOB processing centre has been transformed to the SGO1 processing centre by the Satellite Geodetic Observatory and the original SGOB centre has been abandoned.

After the validation of the ZTD estimates, some preliminary tests were done in the assimilation of ZTD data in numerical weather models. The colleagues at the Hungarian Meteorological Service assimilated the near real-time ZTD estimates in

a test run of the AROME 3DVar numerical weather model. The tests were done with the pre-selection of the GNSS ZTDs from SGO1 E-GVAP network. The estimates were tested and tuned with static and variational bias correction in 3DVar. The preliminary results showed promising impact on the ARTOME analyses and forecasts. The RMSE and the bias of the parameters MSLP and Rh2m of the analysis and the forecasts are depicted on Fig. 6.13. It can be seen that the bias of both of the parameters were significantly improved by the assimilation of the ZTDs in the model runs. Moreover, the RMSE of the short-term forecasts of these parameters improved, too.

6.1.13 Iceland

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There are approximately 100 GNSS sites in Iceland (Fig. 6.14), mainly for geodetic purpose. Jan Douša and Benedikt established the IMO processing centre in March 2016 with approximately 60 ZTD processed stations. There were just two ZDT processed stations in Iceland before that. Then IMO became one of the analysis centres in E-GVAP and is in charge of the data processing for the GNSS stations in Iceland. Benedikt extended it with six well spread coast stations (GUSK, ISAF, SIFJ, HEID, AKUR, MYVA) in January 2017. One near real-time ZTD product (IMOA) is currently provided. The IMOA product is obtained from using the GOP's Trop-NET system (http://www.pecny.cz/gop/index.php/trop-net) which utilizes BSW52 software. The time resolution is 60 min.

Sigurdur has started and plans to continue to do assimilation impact studies with the above mentioned GNSS ZTD data as well as from four GNSS sites in Greenland gotten from EGVAP in HARMONIE on the 2.5 km IGB grid domain. New decision regarding the common operational system between IMO and the Danish Meteorological Institute (DMI) is to extend the domain to cover the whole Greenland and Iceland and its surrounding islands, termed IGB domain.

The HARMONIE tools and the Icelandic processing GNSS ZTD centre that we have developed in COST ES1206 to monitor convective clouds and severe weather conditions will become useful for IMO.

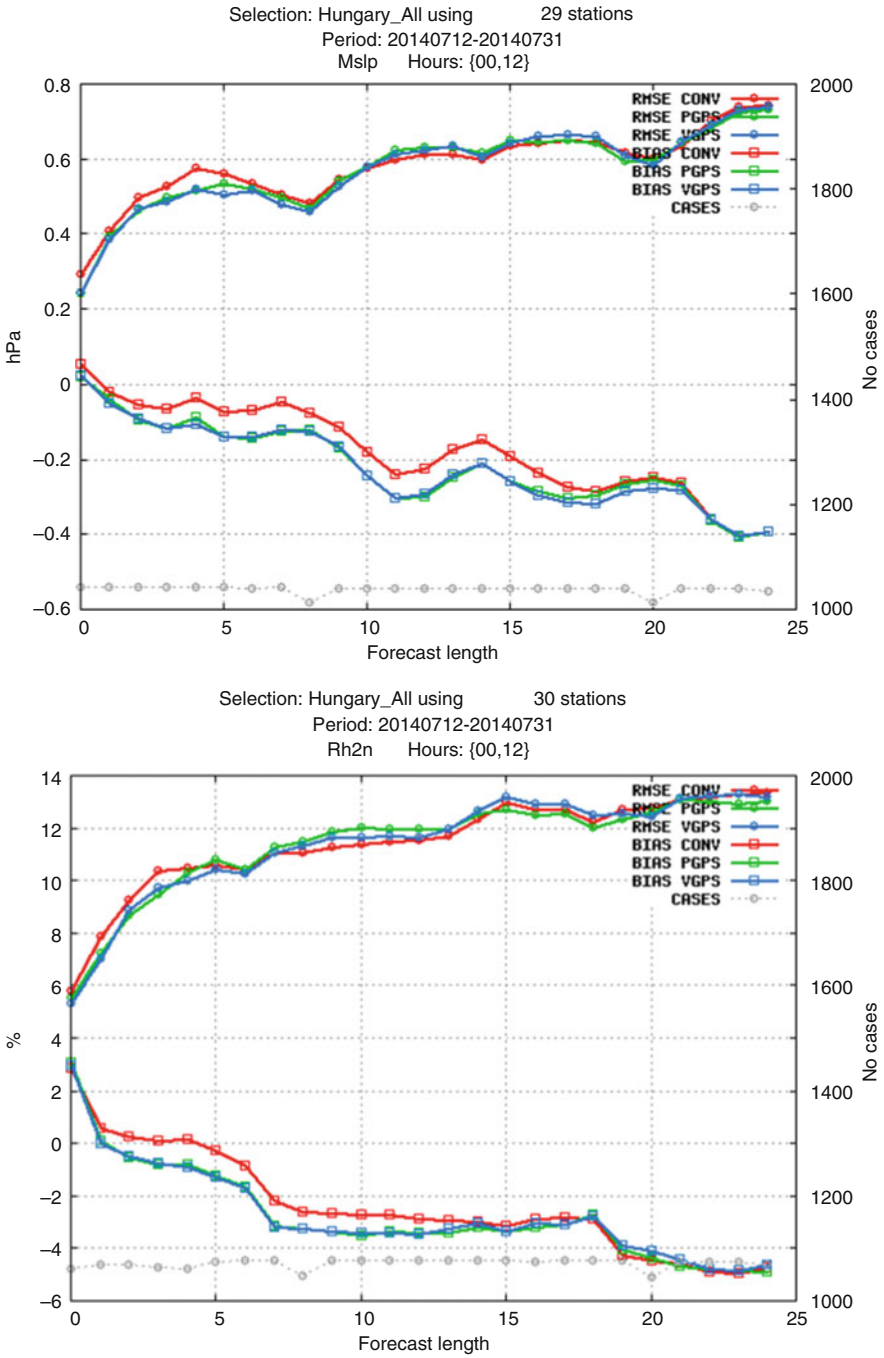

Fig. 6.13 The RMSE and the bias of MSLP and Rh2m parameters of the model runs. (AROME CONV: operational AROME model run without ZTD assimilation; AROME PGPS: operational AROME model with ZTD assimilation using static bias correction; AROME VGPS: operational AROME model with ZTD assimilation using variable bias correction)

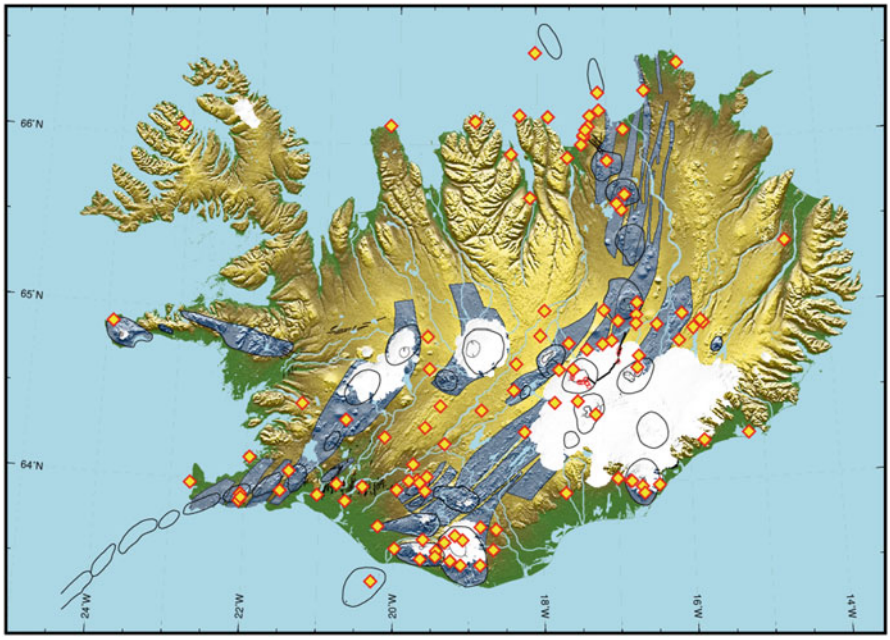

Fig. 6.14 Approximately 100 GNSS sites are in Iceland, mainly for geodetic purpose. So far we ZTD process approximately 60 of these stations

6.1.14 Israel

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The operational GPS network in Israel is consisted of 24 permanent stations and is operated by the Survey of Israel (SOI). Currently, we have near real-time RINEX data from all the stations, while hopefully in the near future SOI will partner with E-GVAP to allow real-time access with 1-h latency. Other data sources which are being used for on-going GNSS-meteorology R&D in Israel are METEOSAT-10 real time data (mainly 7.3 and 10.8 μm channels), IMS radiosondes and surface temperature data from about 80 permanent stations. We have presented for the first time the use of Israel's dense regional GPS network for extracting tropospheric zenith path delays combined with near-real time METEOSAT-10 Water Vapour (WV) and surface temperature pixel intensity values (7.3 and 10.8 μm channels, respectively) in order to assess if it is possible to obtain absolute IWV (kg/m^2) distribution. The

results show good agreement between the absolute values obtained from our triangulation strategy based solely on GPS ZTDs and METEOSAT-10 surface temperature data compared with available radiosonde IWV absolute values. The presented strategy can provide high temporal and special IWV resolution, which is required as part of the accurate and comprehensive observation data integrated in modern data assimilation systems, and is required for increasing the accuracy of regional Numerical Weather Prediction (NWP) systems forecast. Furthermore, constructing WV maps using only interpolated GPS zenith wet delay (ZWD) estimations has a main disadvantage: it doesn't take into account clouds, which are situated outside the integrated GPS paths when interpolating the IWV estimations from a network of GPS stations. Recently, we have developed a new and upgraded strategy, which combines our initial approach for WV estimations by using the mathematical dependency between GPS ZWD and Meteosat-10 in order to estimate the IWV amount, while also taking into account the spatio-temporal cloud distribution when performing the interpolation between adjacent GPS station inside our network. This modified approach increases the accuracy of the estimated regional IWV maps distribution and could potentially increase the accuracy of regional NWP platforms.

6.1.15 Italy

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GNSS-Met activities at ASI/CGS: ASI/CGS is active in the GNSS-Met field since 1999 participating to several European projects:

- MAGIC (1999–2001), one of the first projects being set up to develop and test the capacity for meteorological organizations to benefit from GPS as new data source;
- COST-716 (2001–2003), a NRT demonstration campaign;
- TOUGH (2003–2006) Targeting Optimal Use of GPS Humidity Measurements in Meteorology;

- E-GVAP (2005–present), towards operational use and establishing a GPS delay observing system.

In the E-GVAP framework, ASI/CGS is participating as Analysis Centre and Combination Centre delivering four tropospheric solutions:

1. Near Real Time ZTD (Operational): every hour, 15′ ZTD estimates with a 1h45′ latency for a European network of more than 200 sites;
2. Near Real Time Combined ZTD (Operational): every hour, the 15′ ZTD estimates from the contributing E-GVAP Analysis Centres are combined and made available to the project, using a combination scheme outlined in Pacione et al. (2011);
3. Near Real Time ZTD (Test): the aim of this solution is to evaluate IGS RT products in hourly PPP for NWP application;
4. Sub-hourly ZTD (Test): the aim of this solution is to test RT GNSS observation and products in sub-hourly PPP for now-casting application.

During the present COST Action, we increased the number of GNSS stations in Italy including several regional networks in the operational solution delivered to E-GVAP. Since 1996 ASI/CGS has been an EPN Analysis Centre, producing on a routine basis the requested solutions for the European Reference Frame definition and maintenance and tropospheric applications.

In 2014, at the EUREF Symposium in Vilnius, ASI/CGS was appointed as EPN Tropospheric coordinator with the task of monitor the EPN Analysis Centres troposphere solutions, generate the combined EPN station zenith path delay solutions and processes inter-technique tropospheric solutions.

On the long-term, a reprocessing was carried out in 2014. The whole EPN Network was analysed in a homogeneous way using the latest available models for the period 1996–2014 (Pacione et al. 2014). GNSS data have been analysed with GIPSY-OASIS II 6.2 in PPP mode applying the state-of-the-art models and the JPL reprocessed products. As a result, homogeneous time series of site coordinates as well as of ZTD and horizontal gradient parameters were generated.

The reprocessing efforts is part of the second EPN reprocessing campaign ‘EPN-Repro2’ organized in the framework of the special EUREF project ‘EPN reprocessing’ where the individual contributions of five EPN Analysis Centres are combined in order to provide the official EPN reprocessed products (Pacione et al. 2017a, b). For each EPN station, plots on ZTD time series, ZTD monthly mean, comparison versus Radiosonde data (if collocated), are available at the EPN Central Bureau (http://www.epncb.oma.be/_productsservices/sitezenithpathdelays/). EPN-Repro2 data can be used as a reference dataset over Europe for a variety of scientific applications and has a high potential for monitoring trend and variability in atmospheric water vapour, improving the knowledge of climatic trends of atmospheric water vapour and being useful for regional Numerical Weather Prediction (NWP) reanalyses as well as climate model simulations.

ASI/CGS has been also involved in the standardization and development of a unique format to exchange tropospheric and meteorological parameters. This format should be adopted within all the IAG services and by all the techniques dealing with

tropospheric parameters. The SINEX-TRO v2.00 format has been officially presented at the IGS Workshop (July 3–7, 2017, 2017), at the Unified Analysis Workshop (July 10–12, 2017, Paris), at the EPN Analysis Centre Workshop (October, 25–26, 2017 Brussels).

GNSS-Met activities at International Centre for Theoretical Physics: Within the STSMs of Riccardo Biondi and Rita Nogherotto, we have collected several severe weather cases in Europe and Indian Ocean (all the tropical cyclones passing over Ile de La Reunion), and archived the data and info into the Met Office server as planned during the meeting in Wroclaw 2015. The study first focused on severe events in Belgium and United Kingdom by using ground based GNSS measurements for the ZTD and IWV estimation, and GNSS Radio Occualtions (RO) for atmospheric vertical profiles, and it was then expanded to Italy. The combination of ground based measurements and RO has been used for developing the tomography of the single events (Brenot et al., in preparation). The focus work on Italy (Bonafoni and Biondi 2015), has analysed several precipitation events occurred exploiting the potential of the two GNSS techniques (i.e. ground-based and space-based GNSS receivers) showing a typical decrease of IWV with the rain and an increase of the cloud top altitude with the rain rate. From ground-based receivers, time series of IWV were produced at specific locations with the purpose of analysing the water vapour behaviour during precipitation events. From LEO receivers, the profiling potential was exploited to retrieve the cloud top altitude of convective events, taking into account that although GNSS RO could capture the dynamics of the atmosphere with high vertical resolution, the temporal resolution is not enough to continuously monitor such an event in a local area. A detailed analysis of all the tropical cyclone Bejisa (2013–2014) has been done with three ground based stations - REUN (Ile de La Reunion), ABPO (Madagascar) and VACS (Mauritius Island) – and collocated ROs. A statistical analysis has been done by using all the tropical cyclones´ tracks in the period of data availability (2007–2016) highlighting a specific trend of IWV before the cyclone overpass and a typical cyclone thermal structure.

For these analyses new collaborations were established within the COST member countries:

- H. Brenot (BIRA, Belgium) and J. Le Clair de Bellevue (Meteo France) for the study of tropical cyclones;
- H. Brenot (BIRA, Belgium), M. Kačmařík (Univ. Ostrava, Czech Republic) and W. Rohm (Wroclaw University, Poland) for the tomography models by using ground based GNSS and ROs.

Brenot, H., et al. (2018). Cross-validation of GNSS tomography models and methodological improvements using CORS network, AMT, in preparation for AMT.

Pacione, R., et al. (2011). Adv. Space Res., 47, 323–335, doi: https://doi.org/10.1016/j.asr.2010.07.021.

Pacione, R., et al. (2014). EGU GA 2014 http://meetingorganizer.copernicus.org/EGU2014/EGU2014-2945.pdf

6.1.16 Lithuania

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Vilnius University (Lithuania) as participating partner of COST Action ES1206 became at the end of 2013. In December 2014 we signed an agreement with Lithuanian Positioning System (LitPOS - the network of permanent reference GNSS stations) administration, for open data accessibility from their 25 GNSS stations for the needs of the COST activity. LitPOS is a state company and a part of EUPOS® for territory of Lithuania. EUPOS® provides high-quality differential GNSS information for high-precision positioning and navigation usable in a large field of applications.

RINEX format hourly data started to be processed in September 2015 by Jan Kaplon from the Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland (WUEL). The processed data since autumn 2015 are also available on the E-GVAP network. These data also are stored in ftp server of the Department of Hydrology & Climatology, Institute of Geosciences, Vilnius University: ftp://158.129.144.65/incoming/.

Vilnius University signed agreement concerning data availability also with other large GNSS reference station network in Lithuania – Leica SmartNet LT. This is the private company operational since 2006 and manages the reference network consisting of 16 stationary GPS stations located at identical distances. Unlike the LitPOS the Leica SmartNet LT gave access to RINEX files only via http and these data still remain unprocessed.

The national MC member Dr Gintautas Stankunavicius participated in all Action ES1206 organised meetings since February 2014: February 2014, Munich, Germany; May 2015, Thessaloniki, Greece; September 2015, Wroclaw, Poland; March 2016, Reykjavik, Iceland; September 2016, Potsdam, Germany and February 2017, ESTEC, Noordwijk, Netherlands (in some meetings together with other national representatives).

The processed Lithuanian GNSS data already started to be used in educational process in Vilnius University – mainly for students' coursework but still wasn't used for extreme weather and regional climate research. Despite these shortages the processed GNSS data were used in common research with other GNSS4SWEC partners: WUEL and Royal Meteorological Institute of Belgium (RMI). Research results were presented in two international conferences: EGU 2016, Vienna and EMS Annual Meeting 2017, Dublin. Presentations are described below:

Kapłon J., Stankunavicius G. (2016) Effect of densifying the GNSS GBAS network on monitoring the troposphere zenith total delay and precipitable water vapour content during severe weather events. European Geosciences Union General Assembly 2016, Vienna, Austria, 18–22.04.2016 (poster), pp. Posters G5.2/

AS4.17/CL2.22 http://meetingorganizer.copernicus.org/EGU2016/EGU2016-12883.pdf
Van Malderen R., Pottiaux E., Stankunavicius G., Beirle S., Legrand J., Brenot H., Wagner T., De Backer H., Bruyninx C. (2017). A world-wide analysis of the time variability of Integrated Water Vapour, based on ground-based GNSS and GOMESCIA satellite retrievals, and with reanalyses as auxiliary tools.
European Meteorological Society Annual Meeting 2017, 04–08/09/2017, Dublin, Ireland.
https://meetingorganizer.copernicus.org/EMS2017/presentations/

6.1.17 Luxembourgh

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Through various projects the University of Luxembourg (ULX) was able to contribute to the objectives of the COST Action. The main activities at ULX revolved about the establishment of two near real-time GPS ZTD processing systems, the establishment of several real-time GPS and multi-GNSS ZTD processing systems and the use of a long-term GPS ZTD processing system as provided by the IGS TIGA Working Group Analysis Centre at ULX for benchmarking. ULX also hosted three STSMs and one ULX researcher visited MétéoFrance under the same scheme. In 2017 ULX established in collaboration with MétéoLux, the national meteorological service of Luxembourg, a new continuous GNSS station at the meteorological site Findel (WMO ID 06590). Besides the inputs from Norman Teferle the contributions came from one PhD candidate (Furqan Ahmed) and two post-doctoral researchers (Wenwu Ding, Addisu Hunegnaw) at ULX and the three STSM visitors (Tzvetan Simeonov, Anna Klos and Tomas Hadaś). Besides numerous presentations at COST Action workshops and international conferences the small team also published six peer-reviewed papers on the related subjects and Furqan Ahmed completed his PhD thesis.

6.1.17.1 Near Real-Time GPS Processing Systems

Two near real-time (NRT) GPS processing systems for ZTD estimation have been developed at ULX. The first one provides hourly NRT solutions with 15-min ZTD estimates and has contributed to the EUMETNET EGVAP program (http://egvap.dmi.dk/) as solution UL01. The second one provided 15-min NRT solutions with 15-min ZTD estimates. This solution was abandoned due to the newly developed real-time processing systems. The NRT system UL01 is based on BSW50 and uses double differencing to process a Europe-wide network (Fig. 6.15). With the support for BSW50 by the University of Berne ceasing in 2017, the system could no longer

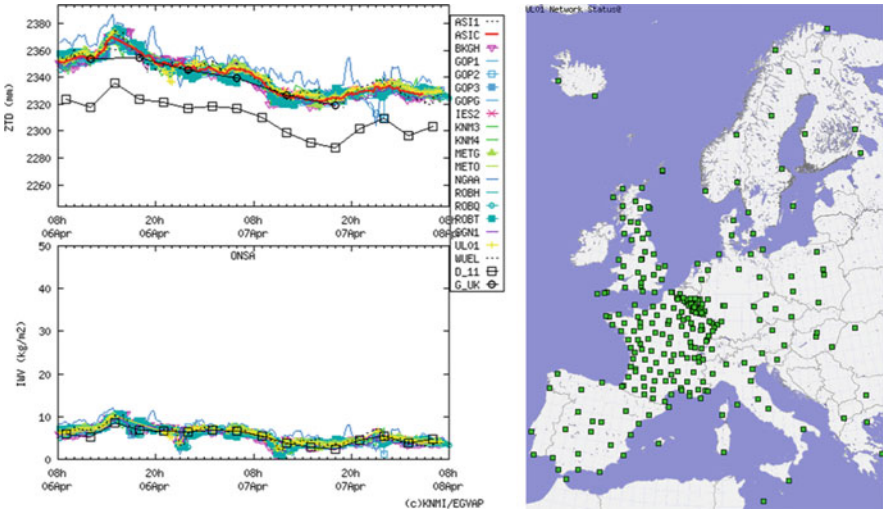

Fig. 6.15 Network of the GNSS stations processed by UL01 (right panel) and evaluation of the UL01 solution (yellow line) by EGVAP (left panel). (Reproduced from egvap.dmi.dk)

be supported. The update of the system to BSW52 is underway and will also allow the inclusion of GLONASS beside that of GPS.

6.1.17.2 Real-Time GPS/Multi-GNSS Processing Systems

The work on the real-time (RT) processing systems involved a comparison of various RT PPP software capable of producing ZTD estimates from GNSS data streams. From this evaluation the software PPP-Wizard was selected to go forward for modifications to develop a multi-GNSS PPP processing system for ULX. Using products from the Centre National d'Études Spatiales (CNES) the system is capable of producing PPP ambiguity resolved solutions with ZTD estimates every few second. ULX contributed to the RT Demonstration Campaign with two solutions based on these systems. In future the RT system can be employed for severe weather monitoring over Luxembourg.

6.1.17.3 Outcomes

Besides the establishment of the various processing systems which can be used for further research and development, the most important outcome for Luxembourg is the fact that it was possible to show that the assimilation of NRT ZTD estimates from UL01 in the AROME numerical weather prediction model of MétéoFrance positively impacts the model output with the potential to improve weather forecasts for Luxembourg and the Greater Region (Fig. 6.16). Using objective forecast skill

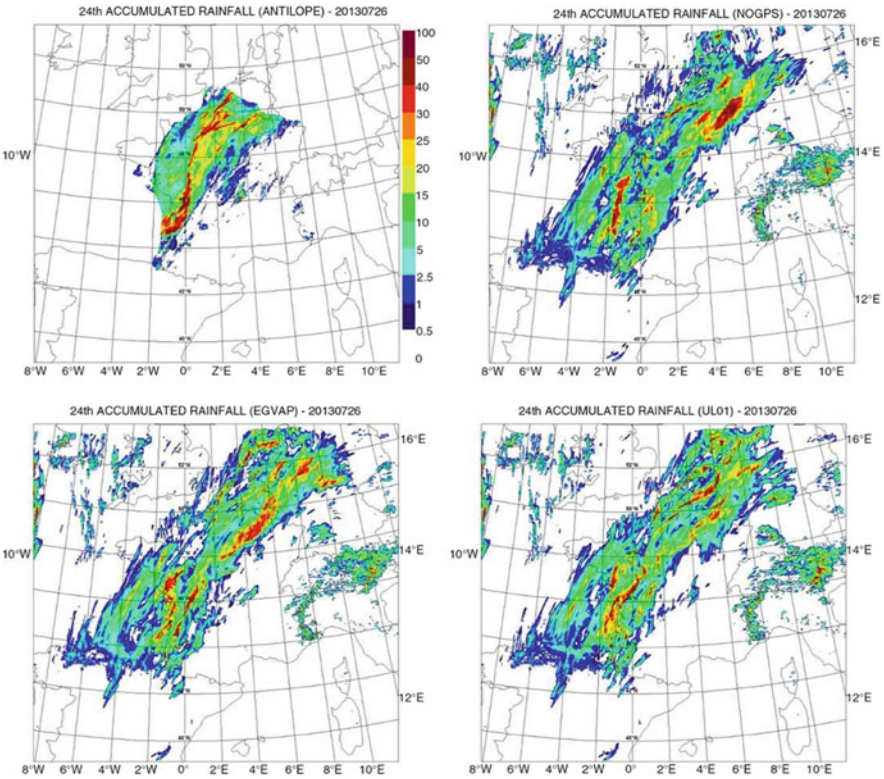

Fig. 6.16 Daily accumulated precipitation in mm as analysed by ANTILOPE and simulated by the AROME model starting from different atmospheric analyses on 26 July 2013: analysis (upper left), experiment NOGPS (upper right), experiment EGVAP (lower left), experiment UL01 (lower right). (Reproduced from Mahfouf et al. 2015)

scores, a small positive benefit has been noticed both on screen-level relative humidity and 24-h precipitation accumulations. The categorical scores are systematically improved when the UL01 data are assimilated on top of EGVAP ZTD observations. When examining case studies, it has been confirmed that GPS ZTD observations affect the predicted location and intensity of rainy systems that generally improves the quality of the numerical forecasts. For such specific situations the additional ZTD data processed by ULX significantly modify rainfall patterns with, most of the time, a better location and intensity of precipitating cells.

Gaining on importance in the future are the results from the long-term GPS processing system when changes in atmospheric water vapour from GNSS are analysed for climate trends. Through the STSM of Anna Klos the ZTD time series of the reprocessed solution from the IGS TIGA analysis centre at ULX were analysed in order to investigate the noise characteristics of these as there may be an impact on the uncertainties associated with the trend estimates. The study showed

that a combination of an autoregressive process with white noise needs to be taken into account when aiming at the estimation of secular trends from ZWD, ZTD or IWV time series. If a proper stochastic model is not employed, one will obtain results that should not be interpreted in terms of climate change as the trend uncertainties may be underestimated by a factor of 5–14 compared to the white noise only assumption. Moreover, a global comparison was performed between the ZTD derived from the ERA-Interim and that derived from ground-based GPS. It was found that the ability of ERA-Interim to predict the ZTD degrades with the increase in the amount of atmospheric water vapour, and vice versa. This comparison was based on a 5-years long dataset comprising of 406 globally distributed GPS stations. The ERA-Interim data was provided by Jan Douša of GOP.

Acknowledgments
Furqan Ahmed and Wenwu Ding were funded by the Fonds National de la Recherche, Luxembourg through projects PWVLUX (Reference No. 1090247) and POSILUX (Reference No. 6823109). Addisu Hunegnaw was funded through the competitive ULX research projects GSCG and SGSL. Besides the IGS and EUREF special acknowledgment is given to the GNSS data provides Walcors, SPSLux and BIGF, who provided real-time streams and hourly RINEX files for the various processing systems at ULX. The Administration des Services Techniques de l'Agriculture (ASTA) and MétéoLux of the Administration de la Navigation Aérienne (ANA) for the provision of meteorological data from Luxembourg and the latter for advise on meteorological aspects and its continued support of ULX GNSS meteorology activities. MétéoFrance is acknowledged for collaboration and the hosting of the STSM of Furqan Ahmed. Finally, Nottingham Geospatial Institute and the UK Met Office are thanked for their support with the near real-time GPS processing systems.

6.1.18 Poland

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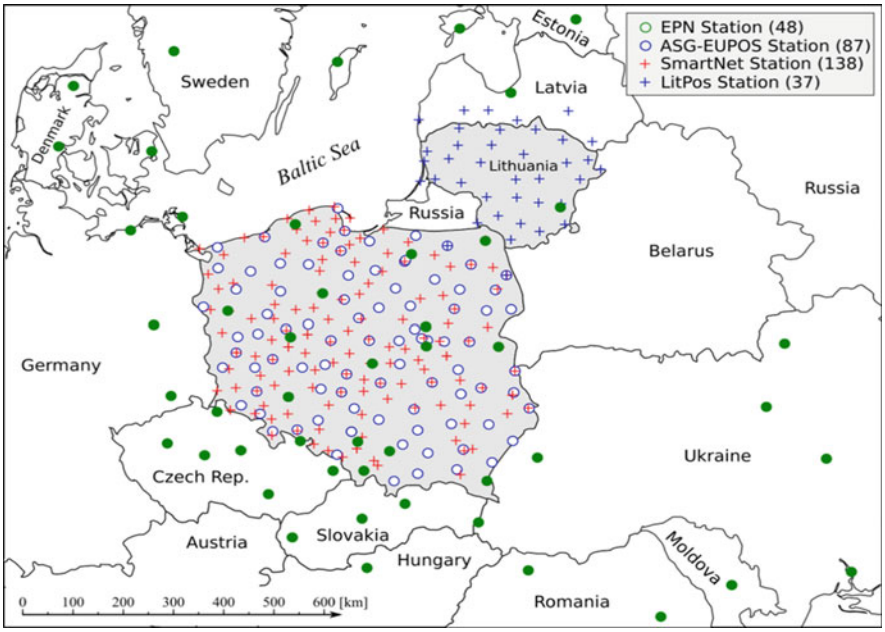

Fig. 6.17 WUEL and WLIT (E-GVAP) networks stations processed for troposphere state estimation at WUELS

ZTD/IWV estimation in Poland: Analysis centre held at Institute of Geodesy and Geoinformatics GNSS&Meteo Working Group of Wrocław University of Environmental and Life Sciences (WUELS) is participating in ZTD/IWV estimation from GNSS data in Poland, Lithuania (in cooperation with Vilnius University) as well as in Victoria state in Australia (in cooperation with RMIT University in Melbourne). ZTD estimates including horizontal gradients from Polish and Lithuanian stations are submitted hourly to the E-GVAP database in COST-716 format. Except of near real-time GNSS data processing, WUELS is also developing ultra-fast ZTD estimation services, estimating troposphere products each 15 min. The pilot implementation of processing engine at Wroclaw Centre of Networking and Supercomputing (WCSS) was developed in 2017. The ultra-fast processing is now optimized to process GNSS data from 50 stations (15 EPN + 35 selected from Leica SmartNet, Fig. 6.17).

The details of WUELS GNSS data processing activities for troposphere study are as follows:

- WUEL network (submitted to E-GVAP): since 2012, 225 stations (EPN + ASG-EUPOS+SmartNet),
- WLIT network (submitted to EGVAP): since 2016, 50 stations (EPN + LitPOS),
- VICNET network (Australia): since 2015, 149 stations (IGS + APREF+GPSNet).

- Ultra-fast processing (each 15 min) for EPN and SmartNet stations in Poland (50 stations).

WG1 tasks: Except of ZTD/IWV estimation the GNSS&METEO research group at WUELS is working on real-time ZTD multi-GNSS (GPS/GLO/GAL/BDS) PPP service, tropospheric refractivity and slant path delays estimation from NWP models and GNSS data as well as real-time precise point positioning augmented with high-resolution NWP models. Research group at Advanced Methods for Satellite Positioning Laboratory University of Warmia and Mazury in Olsztyn (UWM) is working on exploitation of NWP-derived tropospheric products in RTK positioning and GNSS-derived IWV vs. microwave radiometer data analysis.

WG2 tasks: Two Polish research groups were working on WG2 tasks including GNSS RO processing and raytracing in NWP WRF model domain (WUELS), GNSS tomography TOMO2 software development (WUELS), assimilation of GNSS data from local dense GNSS networks in NWP WRF model (WUELS) and Centre of Applied Geomatics of the Military University of Technology in Warsaw (MUT).

WG3 tasks: The research on noise characteristics in ZTD from homogeneously reprocessed GPS time series was performed at MUT as well as the investigation of the influence of adopted GNSS processing strategy on ZTD parameter, including e.g. various mapping functions, elevation mask, troposphere alignment or software. The same group was working on the influence of incorrectly modelled vertical position on tropospheric delay parameters and uncertainties of ZTD linear trend estimation process.

MUT contributed significantly with synthetic benchmark datasets for homogenization of IWV time series retrieved by GPS delivered to the GNSS4SWEC community. WUELS group investigated on refractivity coefficients obtained from ERA-Interim data.

Research group at UWM analysed the influence of troposphere modelling on the realization of the ETRS89 by the reference stations of the Polish national Ground Based Augmentation System (GBAS) network – ASG-EUPOS, and also on the tropospheric parameters. In addition, the influence of the network design strategy on the estimated coordinates of permanent stations, ZTD and gradients time series was investigated, especially in the context of GNSS meteorology and climate studies (Stepniak et al. 2018). Other goal of UWM study was to test and compare of relative and precise point positioning (PPP) techniques to determine which processing is most suited for achieving high accuracy, stability, and homogeneity in the estimated tropospheric parameters.

6.1.19 Portugal

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6.1.19.1 Areas of Research

(a) GPS data processing for tropospheric products using GIPSY-OASIS; Improvement on the solutions testing different parameterization.
(b) Development of new software using parallelized Algebraic Reconstruction Techniques (ART) for the water vapour tomography.
(c) Analysis of the influence of a-priori values on the derived ZTD solutions. The daily boundary problem.
(d) Correlation between (ocean and atmospheric) loading and PWV.
NUVEM – New methods to Use GNSS Vapour Estimates for Meteorology of Portugal.

NUVEM is using 146 GNSS stations (Fig. 6.18) from six GNSS receiver networks over Portugal and Spain. NUVEM is operational (http://nuvem.di.ubi.pt) and the implemented processing in shown in Fig. 6.19. The water vapour tropospheric tomography has been one of the areas with strong research. A tomographic software (SWART – SEGAL GNSS Water Vapour Reconstruction Image Software) to estimate the 3D field of tropospheric water vapour in a region, in order to evaluate its high spatial-temporal variability in a 4D reference (spatial 3D plus time) was developed from scratch at SEGAL (UBI/IDL) and applied to a set of case studies. In respect of the COST action, SWART was used in an intercomparison study for cross-validation concerning the potential of GNSS tomography for meteorological applications and for tomographic methodological improvements.

The periodic Ocean Tide Loading (OTL) effects in tropospheric delays have been also studied. OTL corrections are not perfect, especially at coastal sites where OTL is several cm and mismatches between predicted and actual OTL can reach the cm level. Using the latest ocean tide models and an improved elastic model of the Earth, better OTL and therefore better ZTD estimates will be produced for selected coastal sites (Fig. 6.20).

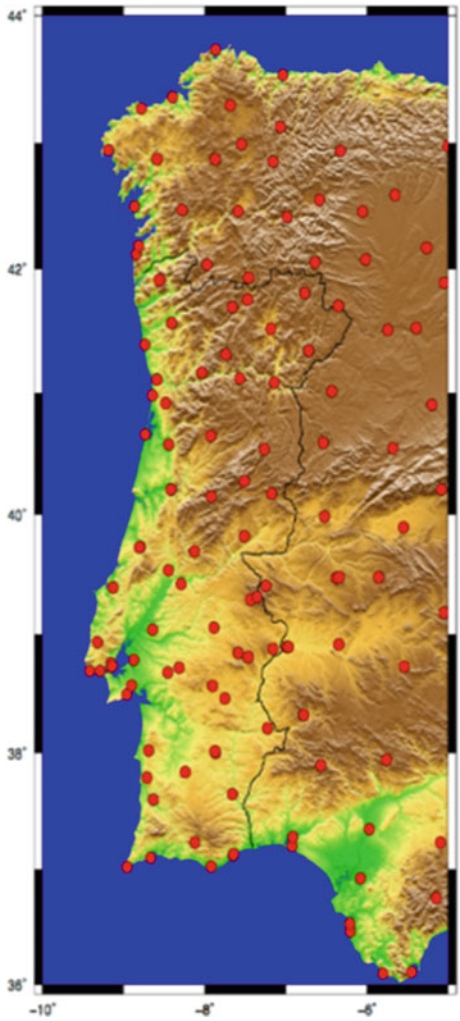

Fig. 6.18 NUVEM GNSS stations

6.1.20 Slovakia

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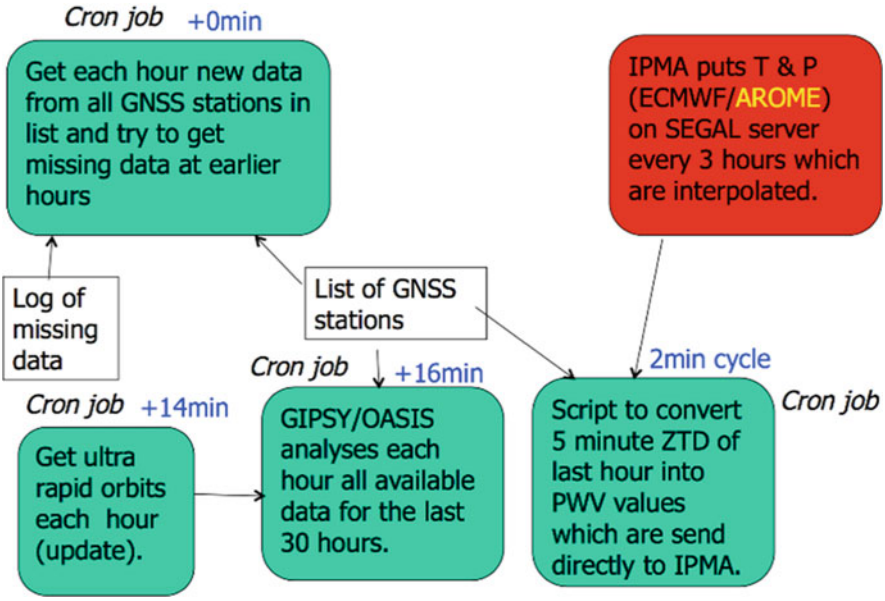

Fig. 6.19 NUVEM implemented structure

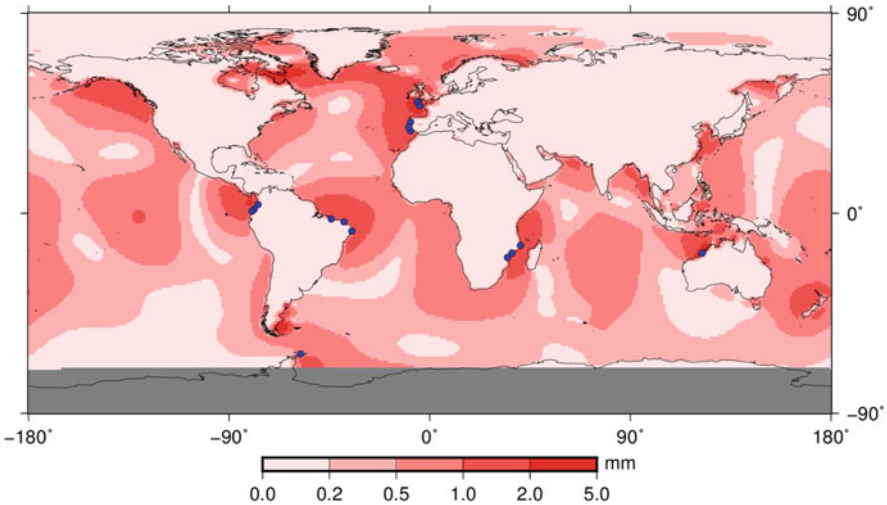

Fig. 6.20 Difference in vertical ocean tide loading (computed using tide model FES2004, harmonic M2) using the standard PREM and modified PREM elastic Earth model. The blue dots represent GNSS stations

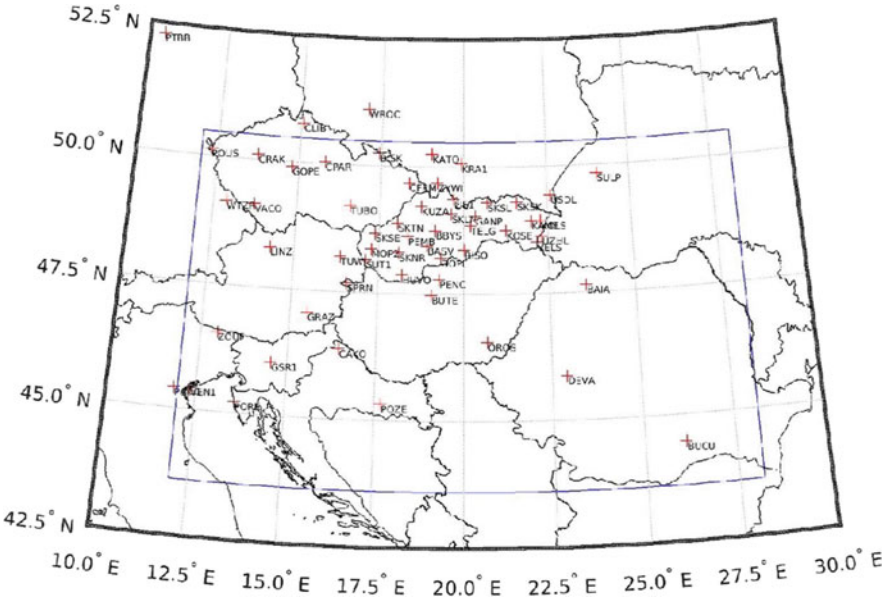

Fig. 6.21 GNSS station network

In last 4 years we have achieved at Slovak University of Technology (SUT) in Bratislava significant progress in Global Navigation Satellite Systems (GNSS) meteorology. There was developed a routine hourly processing system based on BSW52, which is computing ZTDs from network of selected national permanent GNSS stations extended by stations from neighbouring countries. Our processed network recently consists in full constellation from 59 permanent stations (Fig. 6.21). Twenty-two of them are from Slovak National Network of GNSS stations, maintained by Slovak University of Technology, Department of Theoretical Geodesy, and by Geodetic and Cartographic Institute in Bratislava. We have established beneficial cooperation with Slovak Hydro-Meteorological Institute (SHMU) in Bratislava. SHMU is providing us pressure, temperature and relative humidity at all Slovak GNSS permanent stations from numerical weather prediction model ALADIN. With these meteorological data we are able to transform ZTD at permanent stations to PWV and visualize ZTD and PWV maps over Slovakia. Selected results are available online at http://space.vm.stuba.sk/pwvgraph/. Files of ZTD for direct assimilation to numerical weather prediction model are generated every 6 h.

We assimilate our estimated ZTD to non-hydrostatic spectral mesoscale AROME model with three-dimensional data assimilation system. At this state we are able to apply ZTD from 53 stations. Static bias correction of ZTD, estimated from statistics of first guess departures between AROME and ZTD at station, is used to correct ZTD before assimilation. In last year we have performed several impact studies of

ZTD assimilation to accumulated rainfall, relative and specific humidity and others atmospheric parameters. This impact studies were made on interesting meteorological situations like heavy rainfall or strong wind. More data assimilation studies and technical work will be necessary until we will be fully prepared to assimilate ZTD into operational numerical weather prediction model. For more information, please contact responsible researcher from SUT Martin Imrisek via e-mail martin.imrisek@stuba.sk.

6.1.21 Spain

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Spain's participation in this action is based on the work of three organisations: National Geographic Institute (IGN), Spanish Meteorological Agency (AEMET), Polytechnic University of Valencia (UPV) and Public University of Navarra (UPN).

Firstly, National Geographic Institute manages a network of about 85 GNSS permanent stations, 26 of them integrated in international networks such as EUREF and IGS (Fig. 6.22).

Fig. 6.22 IGN GNSS permanent stations network (ERGNSS)

IGN GNSS permanent stations network (ERGNSS): IGN is a EUREF Local Analysis Centre (LAC) since 2001, processing a subnetwork of 75 EPN stations and therefore submitting troposphere files for the project "Troposphere Parameter Estimation" where ZPD series and other products are being elaborated since 2001. On the other hand, this institution is an E-GVAP Analysis Centre since 2008, providing ZTD from about 340 stations for Spain and Portugal in near real time. For this purpose, 1 h GNSS data files are downloaded every hour from 22 regional networks servers and immediately after the download, the processing starts, submitting to EUMETNET partner agencies files containing ZTD every 15 min in cost2.2 format. The processing is run with BSW52 and it takes 5 min. About 300 of the processed stations are located in the Iberian Peninsula, about 70 IGS or EPN stations and 10 E-GVAP "supersites" in order to check the ZTD quality estimation. The standard deviation for the ZTD estimation use to be about 7–8 mm.

IGN, as EUREF LAC, has participated in the second reprocessing of the EPN, carried out in 2015 (Fig. 6.23). Thanks to this project, a new set of homogeneous ZPD have been obtained from the combination of individual LAC solutions in the whole EPN network. IGN processed a subnet of 125 EPN stations from 1996 to 2014.

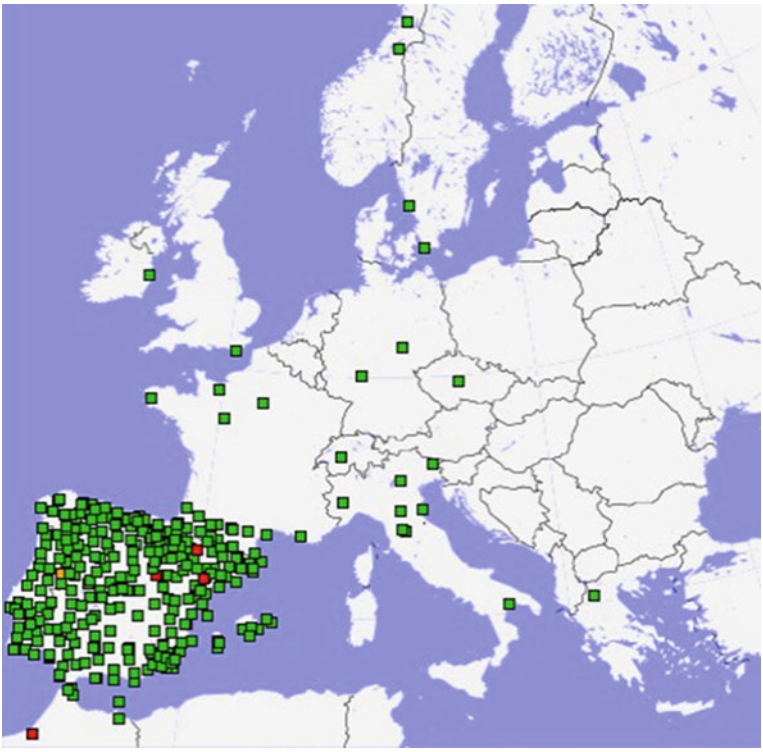

Fig. 6.23 GNSS network processed by IGN in EGVAP project (from http://egvap.dmi.dk)

Secondly, the Spanish Meteorological Agency (AEMET) started in 2001 with the assimilation of GNSS ZTD observations in HIRLAM and HARMONIE-AROME high resolution models in the framework of other European projects like COST717 and TOUGH. During this Action ES126, AEMET has also participated in the HyMeX project, assimilating GNSS ZTD observations together with data targeting of radiosondes on a series of experiments over the Mediterranean area. At the beginning of the Action, AEMET prepared the HARMONIE-AROME km scale data for assimilation of GNSS ZTD observations. A three-dimensional variational data assimilation was applied and the importance of using an extensive observation handling was pointed out, and in particular the benefit of using an adaptive so called variational bias correction for these observations. Currently, AEMET is assimilating operationally more than 200 GNSS sites over Iberian Peninsula and Canary Islands domains together with conventional and ATOVS observations due to the good impact found on the assimilation of this humidity source. A daily monitoring of the availability and quality of the data is therefore performed over the two domains.

And thirdly, the Polytechnic University of Valencia and the Public University of Navarra have been several research on the analysis of local rainfalls with ZTD GNSS. In 2013, the first experiments were focused in the relationship between rain occurrence and atmospheric pressure and atmospheric water vapour content (PW-GNSS estimated). The available 9 years' time series in Pamplona of each variable were analysed. It allowed to state the existence of three rain patterns and monthly differences in the pressure and precipitable water combinations.

Later, it was analysed all the cases of heavy rain over 15 years in Valencia city (Fig. 6.24). In all of these cases, it exists an apparent link between pressure drops at times of high levels of IWV with severe precipitation events. In 2017, additional case studies are being developed to quantify this apparent link and it might be the basis for a future severe weather warning system.

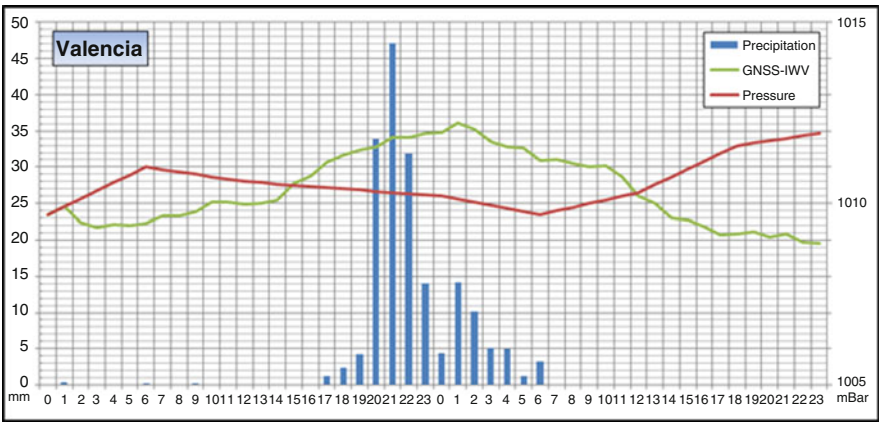

Fig. 6.24 Time evolution of IWV and atmospheric pressure along with the amount of rainfall registered

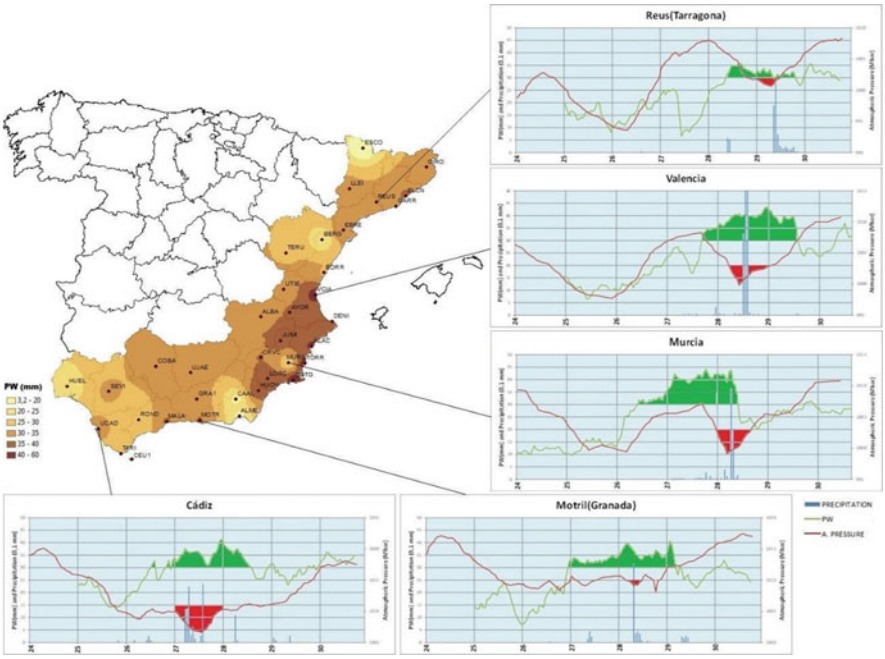

Fig. 6.25 Spatial distribution of IWV along the Spanish Mediterranean coast

Apart from that, several monitoring ZTD GNSS during some heavy rainfall event have been conducted (Fig. 6.25). Those analyses are being done in the Spanish Mediterranean area, where Precipitable Water values are higher, due to the contribution of moisture from the Mediterranean Sea. All GNSS stations show a quick and clear increase in IWV a few hours before the onset of precipitation.

The results of all of this research have been published in four papers of different journals (Appendix 4).

6.1.22 Sweden

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Since June 2016 Lantmäteriet (Swedish Mapping, Cadastre and Land Registration Authority) became one of the analysis centres in E-GVAP and is in charge of the data processing for the GNSS stations in Sweden, Finland, Norway, Denmark, and some IGS stations, in total approximately 700 (Fig. 6.26). Two near real-time (NRT) ZTD products (NGA1 and NGA2) are currently provided. The NGA1 product is obtained from the BSW52 network solution, while the NGA2 is from the GIPSY/OASIS II v.6.2 data processing using the Precise Point Positioning (PPP) strategy.

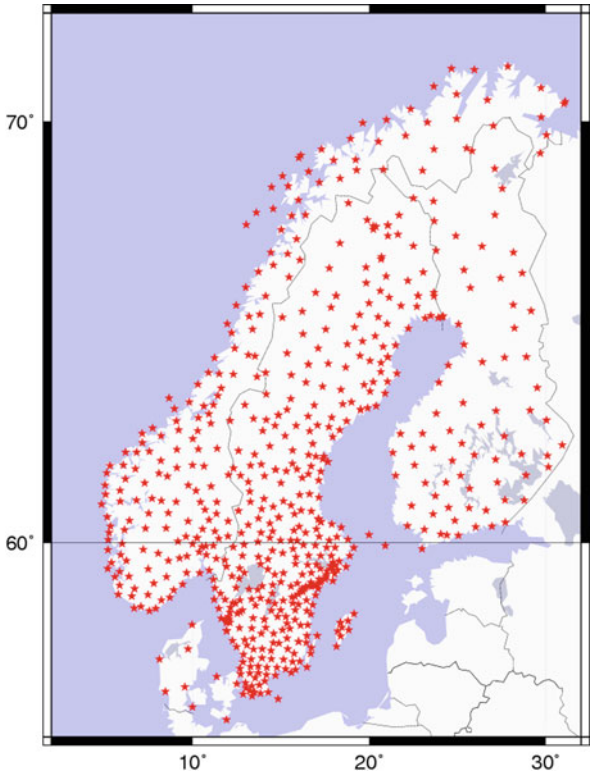

Fig. 6.26 GNSS stations processed by Swedish mapping, cadastre and land registration authority

The NGA1 product is obtained from a BSW hourly data processing. We use the ultra-rapid GPS orbit products provided by CODE (ftp.unibe.ch). The ocean tide loading correction (FES2004) and the antenna PCV absolute calibration are implemented. The tropospheric estimates are updated every 15 min and a 10° elevation cut-off angle is used with a GMF. The NGA1 product is currently under the operational status with a time delay of 45 min.

The NGA2 product from the GIPSY NRT data processing where the GPS data were analysed by GIPSY-OASIS v6.2 using the PPP strategy. Currently we use the ultra-rapid GPS orbit and clock products provided by JPL. The same set-ups are used for the GIPSY data processing, i.e., FES2004 model, antenna PCV absolute calibration, a 10° elevation cut-off angle, and a GMF. The tropospheric estimates are updated every 5 min. In addition, the single receiver phase ambiguity resolution is also implemented. The NGA2 product is now under a test mode due to a longer time delay of about 1.5 h for fetching the JPL ultra-rapid orbit and clock products.

The benefit of using GNSS ZTD in the state-of the art HARMONIE-AROME km-scale data assimilation and forecasting system has been demonstrated in cooperation with colleagues from Spain, Norway and Iceland (Sánchez Arriola et al. 2016). A three-dimensional variational data assimilation was applied and the importance of using an extensive observation handling was pointed out, and in particular the benefit of using an adaptive so called variational bias correction. Based on the research GNSS ZTD is now used operationally in the Nordic MetCoOp HARMONIE-AROME numerical weather prediction system (Muller et al. 2017). The system has been further optimized through sensitivity experiments and the benefit of utilizing GNSS ZTD processed by the newly re-vitalised NGAA processing centre has been demonstrated (Lindskog et al. 2017). GNSS ZTD data from the NGAA processing centre is recently assimilated operationally in the Nordic MetCoOp HARMONIE-AROME numerical weather prediction system, in addition to GNSS ZTD processed by the Met Office processing centre in the UK (METO) and by the Royal Observatory of Belgium (ROBH).

The uncertainty of the IWV estimated from GNSS observations needs to be thoroughly assessed as required by climate applications. All relevant error sources in GNSS-derived IWV are therefore essential to be investigated. A theoretical analysis was carried out where the uncertainties associated with the input variables in the estimations of the IWV were combined in order to obtain the total uncertainty of the IWV. We calculated the IWV uncertainties for several sites, used by the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN), with different weather conditions. The results show a similar relative importance of all uncertainty contributions where the uncertainties in the ZTD dominate the error budget of the IWV, contributing over 75% of the total IWV uncertainty. The impact of the uncertainty associated with the conversion factor between the IWV and the ZWD is proportional to the amount of water vapour and increases slightly for moist weather conditions (Ning et al. 2016a).

Estimated horizontal gradients were used as a tool for assessment of GNSS data quality**.** We have searched for any systematic changes in the horizontal gradients using 17 years (1997–2013) of estimated gradients from GPS data for 21 sites in

Sweden. We conclude that estimated gradients from GPS data are not only of an atmospheric origin. Statistics of long term time series can be a valuable tool to search for problems in the GPS data, such as sudden changes in the electromagnetic environment of the GPS antenna. Long-term trends estimated in the IWV are important for climate monitoring as an independent data source. However, potentially unwanted temporal shifts in the IWV time series from the different techniques can change the trends significantly. In order to obtain reliable climate signals a homogenization of the IWV time series is necessary. The time series of the differences between the GPS-derived IWV and the one obtained from the ERA-Interim model was used for the data homogenization. A statistical test, the penalized maximal t test, modified to account for first-order autoregressive noise (PMTred), is used to identify possible sudden mean shifts in the time series. Different tunings are also carried out in the PMTred test in order to find the optimal set up for the data homogenization (Ning et al. 2016b).

A 17-year long time series (1997–2013) of IWV obtained from homogenously reprocessed ground-based GNSS data was produced. The GNSS data were acquired at 123 European sites located between the latitudes 39°N and 79°N, and between the longitudes −69°E and + 31°E. The IWV data set was used for evaluation of the atmospheric water vapour content in a regional climate model, both in terms of a comparison of monthly means and for diurnal components (amplitude and phase) (Ning et al. 2013).

Climate models overestimate the positive feedback from the greenhouse effect of water vapour for ENSO (Chen et al. 2013). Therefore, it is important to evaluate observations of water vapour and the relation to global phenomena as El Niño/Southern Oscillation (ENSO) and other climate processes. We used monthly means of water vapour data, from GPS and ERA-Interim reanalysis, to investigate global inter-annual water vapour climate variability by calculating the correlations with climate indices representing ENSO and the North Atlantic Oscillation (NAO). The GPS IWV data came from reprocessed ZTD solutions from the IGS network, we used 120 stations worldwide for the time-period 1995–2010. The ERA-Interim IWV was extracted for the four closest grid-points to the GPS station and vertically adjusted to the station height using ERA-Interim temperature and humidity fields on pressure levels and thereafter horizontally interpolated to the station. The climate indices ENSO Nino3.4 and NAO were obtained from NOAA. We find that GPS and ERA-Interim IWV correlates with the ENSO and NAO indices on global and regional scales, the pattern resembles corresponding patterns for surface temperature and precipitation for both ENSO and NAO as expected. The GPS and ERA-Interim IWV correlations with the indices are fairly similar except for ENSO over Antarctic. The study will be continued after the COST project including other climate processes and indices on seasonal and monthly scales, for evaluation of the Swedish global climate model EC-Earth and other CMIP5 and CMIP6 models. A main benefit of the GPS IWV data, compared to reanalysis data is the high temporal resolution, as shown by Bock et al. (2007). Investigating water vapour variability on shorter time scales than 2 days could show the benefit of using GPS data for climate process evaluations.

6.1.23 Switzerland

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GNSS-Meteo activities at Swisstopo: Swisstopo is active in the GNSS-Meteo field since 2000 and contributed to the COST-716 project as well as to the EUMETNET E-GVAP projects until today. There are important synergies between geodetic applications and meteorological applications. In the near real-time field, hourly solutions are computed to validate the stability of the reference points. As an added-value results of ZTD parameters are determined and submitted to MeteoSwiss and to UK Met Office for numerical weather prediction applications. Figure 6.27 shows the monitoring status of the network consisting of about 200 stations. On the long-term, a reprocessing was carried out in 2014. Data of about 200 stations, covering a time span starting 1996, were analysed with various options in a homogeneous way using the BSW52. Since 2004, also GLONASS observations were used. As a result, homogeneous series of coordinates as well as for ZTD parameters

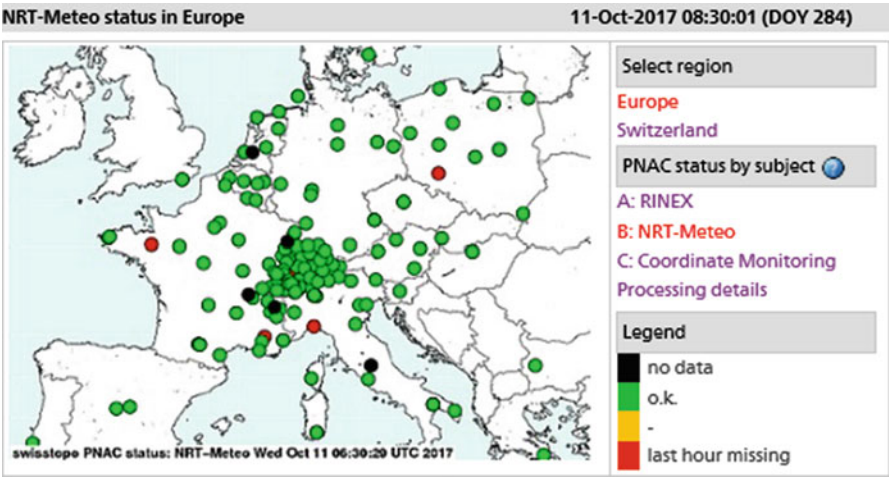

Fig. 6.27 Near real-time status of the hourly Swisstopo processing for the delivery of ZTD parameters (October 11, 2017). Hourly updates at http://pnac.swisstopo.admin.ch/

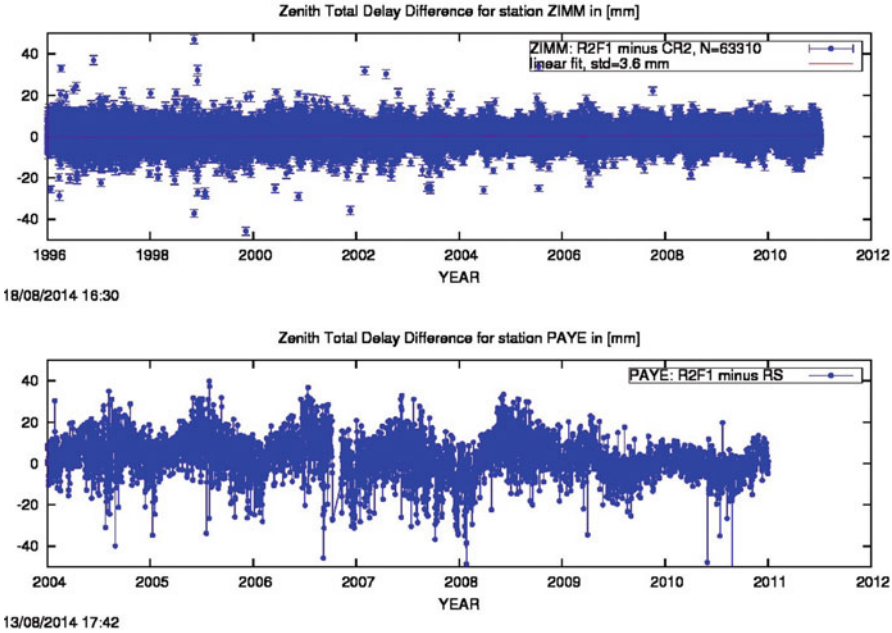

Fig. 6.28 Swisstopo Repro2 compared with CODE Repro2 for station ZIMM (upper diagram) and with radiosonde derived ZTD estimates for station PAYE (lower diagram)

were generated. Overlapping 3-day solutions were generated to optimize the ZTD estimates at midnight. The long-term ZTD parameters were compared to other post-processing results as well compared to radiosonde data (Fig. 6.28). The impact of additional GLONASS observations on the long-term was especially analysed in this project. Fortunately, the impact of the additional GLONASS observations is negligible when analysing ZTD trends.

In 2015, the complete Swiss GNSS network AGNES was enhanced with GPS + GLO + GAL+BDS capable receivers. In 2016, most operational computations are based on Multi-GNSS already. The complete data flow was switched from RINEX-2 to RINEX-3 and the analysis is performed on a Multi-GNSS development version BSW5.3 (Fig. 6.29).

Many tools, developed to analyse the reprocessing results within the COST GNSS4SWEC project, are applied in the operational processing scheme. Routinely, various validations of the complete time series, consisting of reprocessing results till end 2014 and operational solutions till today, are calculated and made available on the Swisstopo web. These type of plots are available:

- ZTD differences at 30 double stations (nine in Switzerland),
- ZTD differences to radiosondes (61 stations),
- ZTD estimation details (including estimated formal RMS values, spectral analyses and estimation of an approximated mean ZTD model; Fig. 6.30).

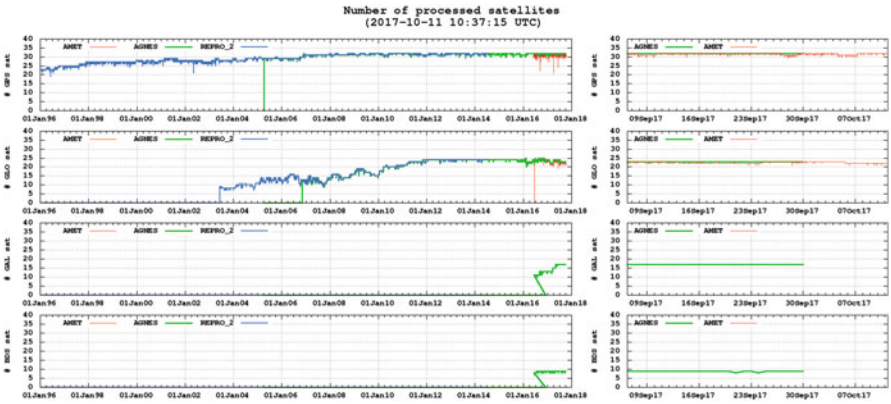

Fig. 6.29 Number of satellites used in the various processing chains (GAL+BDS processing since June 2016)

GNSS-Meteo activities at ETHZ: The Mathematical and Physical Geodesy chair, former Geodesy and Geodynamics Lab at ETH Zurich has developed a software package COMEDIE (Collocation of Meteorological Data for Interpretation and Estimation of Tropospheric Path delays) to interpolate and extrapolate meteorological and tropospheric parameters, especially zenith path delays, from the real measurements to the arbitrary locations. The method used in the software is the least-squares collocation technique, where each observation is divided into a deterministic part, a regular stochastic part (signal) and an irregular stochastic part (noise). The selected parameters from different data sources are estimated simultaneously in the least-squares sense taking into account the two kinds of errors. Using the obtained model coefficients, it is possible to reconstruct the value of considered parameter at any time and place. Originally, the software was used to interpolate the meteorological parameters: air pressure, temperature and humidity, but currently also the models of refractivity and tropospheric delays are implemented. The input data source in the software can be ZTD from Swisstopo or meteorological parameters from ground-based stations, radiosondes or numerical weather model (NWM). The tropospheric models calculated with COMEDIE can be used in any measuring technique where a microwave signal is delayed in the atmosphere, especially for GNSS Precise Point Positioning (PPP). Currently at ETHZ, the COSMO-1 model from MeteoSwiss along with ZTDs from Swisstopo processing are used as a base of building the tropospheric correction's model for space-borne Synthetic Aperture Radar Interferometry (InSAR), In a regional scale, it is possible to also use the relative ZTDs from a network of permanent GPS stations operated in the Matter Valley (Swiss Alps) since winter 2010/2011 in the framework of the interdisciplinary project X-Sense. Currently there are 32 stations equipped with low-cost L1 GPS receivers. The major goal of the X-Sense project is the monitoring of alpine mass movements such as rock glaciers.

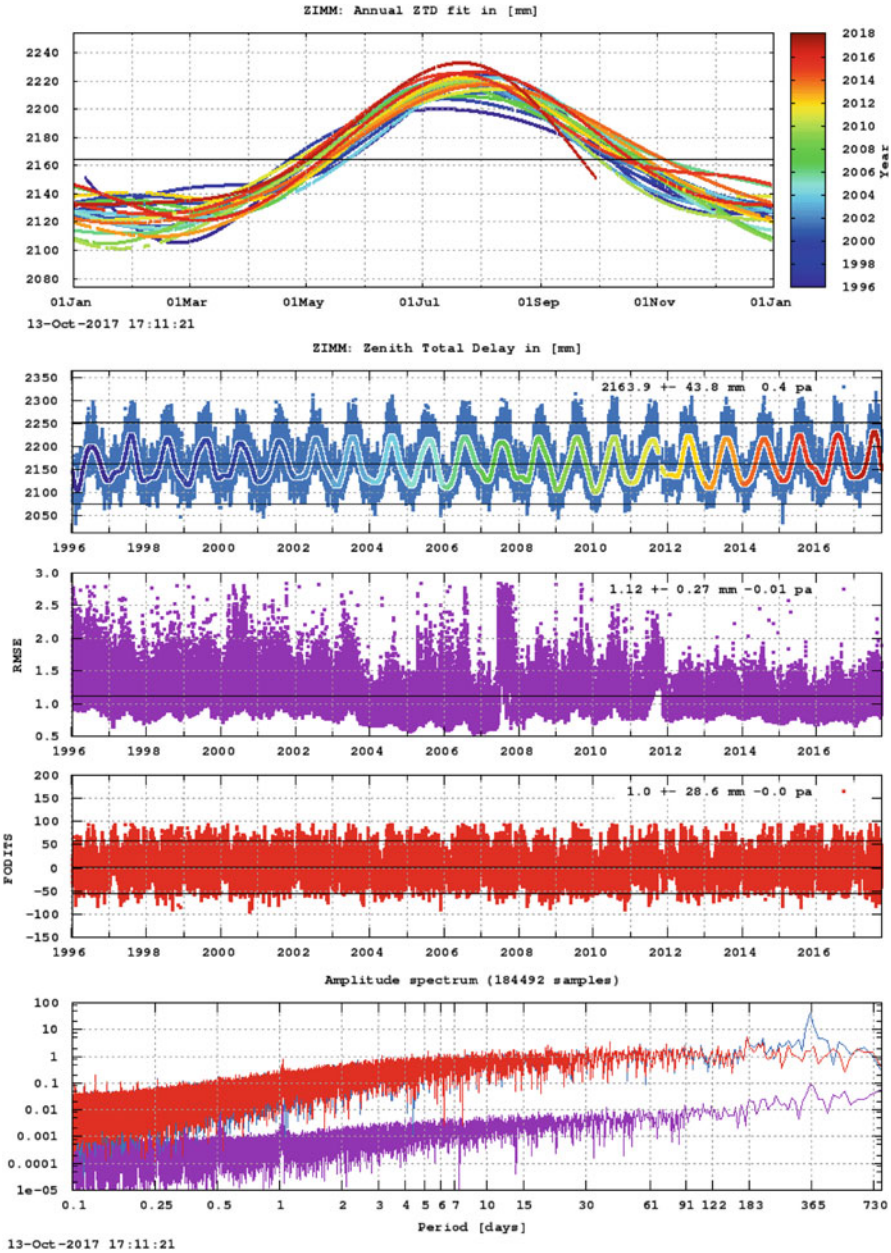

Fig. 6.30 Details of the ZTD estimates (Repro till end 2014, then continued with operational) for station ZIMM. Mean annual model (upper graph) and various other information (lower graph)

In the context of environmental and climate research, ETH develops the applications of GNSS in reflectometric methods for the determination of snow depth and snow water equivalents. The meteorological data which is used in the studies described above is mostly provided by MeteoSwiss (http://www.meteoswiss.admin.ch). The SwissMetNet network of ground-based meteorological stations consists of about 160 automatic monitoring stations. Standard stations record temperature, humidity, atmospheric pressure, solar radiation and the volume of precipitation as well as the wind direction and speed with 10 min resolution. The only aerological sounding station is located at the Payerne regional centre of MeteoSwiss. The measurements are taken twice a day at midnight and 12:00 UTC. The balloons are tracked up to an altitude of 30–35 km. The radiosondes measures wind speed and direction, air pressure, temperature and humidity. MeteoSwiss uses two radiometer types to measure temperature (TEMPRO, HATPRO) and humidity profiles (HATPRO) which provide vertical profiles from ground up to approximately 6 km every 10 min. The average vertical resolution is around 500 m. The temperature profiles allow to detect certain patterns in the atmosphere like temperature inversions in the troposphere. The temperature and humidity radiometers are also used in the meteorological surveillance tool of nuclear power plants (CN-MET).

MeteoSwiss uses the COSMO (Consortium for Small-scale Modelling) NWM. There are currently three configurations of COSMO models:

- COSMO-1: High-resolution model for short-range weather forecast for current and next day; grid size: 1.1 km, area: the entire Alpine region
- COSMO-E: This ensemble model calculates a probabilistic forecast based on 21 individual model runs.; grid size 2.2 km, area: the entire Alpine region
- COSMO-7: Lower-resolution model with forecasts for 3 days ahead; grid size: 6.6 km; area: central and western Europe.

6.1.24 Turkey

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Recent studies on GNSS Meteorology in Turkey: The Project titled “The Estimation of Atmospheric Water Vapour Using GPS “is supported by The Scientific and Technological Research Council of Turkey (TUBITAK) (May 2013–October 2015). Aims of this project are to determine the total zenith delays and the precipitable water vapour accurately and reliably from TUSAGA-Active (CORS-TR), and to produce the numerical models based on time and position In this context, the weighted mean temperature model ($T_m = 48.55 + 0.80T_s$) and the conversion factor model (QBEU = 5.7053–0.0067 (Ts [K]-287.7620) + 0.0130 θ [°] + 0.0833 H [km] + 0.0709sin (2πtD365) +0.1195 cos(2πtD365)) are developed by analysing 8 radiosonde stations in Turkey (4103 radiosonde profiles for the year of 2011).

PWV are estimated from a year of observations at the Ankara and Istanbul RS-GNSS stations (PWV_{GNSS}) and later they are compared with PWV derived from radiosonde observations (PWV_{rad}). Standard deviations of the differences of PWV_{GNSS} from PWV_{rad} are consistent with Haase et al. (2003) (7 ± 12 mm), (−2.8 ± 4.1 mm).

Since May 2013, the ZTDs and PWVs have been being estimated using regional or global networks at Bulent Ecevit University, Geomatics Engineering Department. As a result of studies conducted until 2015, Turkey finally started to take steps to join near real-time activities exploiting the meteorological aspects of the dense CORS-TR (Continuously Operating Reference Station called TUSAGA-active) network of 146 reference stations operated by General Command of Mapping and Organization of the General Directorate of Land Registry and Cadastre in Turkey for positioning applications. However, at the moment several permanent GNSS stations belong to Bulent Ecevit University (BEU) and Bursa Water and Sewerage Administration (BUSAGA Network) are actively being used for computation of NRT-ZTDs. It has been initiated to include the CORS-TR stations in the NRT-ZTD estimation processes. The hourly observations of 18 Turkish permanent GNSS stations belong to BEU (Bulent Ecevit University), ISKI-UKBS and BUSAGA Network are processed. This network is extended beyond the country to cover about 40 stations covering Europe. The data analysis is being carried out using the BSW52 GPS data processing software with the help of powerful computer obtained through the grant of TUBITAK (The Scientific and Technological Research Council of Turkey) project no. 112Y350.

The tropospheric estimates have been obtained from the Analysis Centre (AC) at the Bulent Ecevit University which has been established with the help of Jan Douša from GOP (Geodetic Observatory Pecny) using Trop-NET software package, and routinely estimating ZTD's since July 2015. This analysis centre called BEU1, has been joined E-GVAP (GNSS Water Vapour Programme of the Network of European Meteorological Services, EUMETNET) and thus continuously sending results to E-GVAP system.

6.1.25 United Kingdom

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6.1.25.1 History of GNSS Meteorology at the UK Met Office

The Met Office has had an interest in GNSS as far back as 1998, when a small number of Ashtech Z-XII receivers and choke-ring antennae were purchased and installed at locations in the UK collocated with other meteorological remote sensing equipment, such as at operational radiosonde sites. At this time, the main purpose of

the GPS receivers was experimental (was there additional, useful information which could be obtained from GNSS?), primarily for validation of radiosonde humidity data. Between 1998 and 2003, the Met Office sent raw GNSS data to the Geodetic Observatory Pecny, Czech Republic (http://www.pecny.cz/gop/) for processing. Data would then be send on CD-ROM back to the Met Office for comparison against radiosonde humidity data. It was soon evident that not only was GNSS useful for radiosonde validation but was of sufficient quality to be assimilated operationally. A number of case studies were carried out using GNSS data to identify radiosonde dry humidity bias cause by solar heating of the radiosonde sensor, and following this assessment, it was deemed that GNSS was in fact more reliable than radiosonde for retrieving an integrated total column water vapour observation.

In 2003, the Met Office invested in GNSS-meteorology by determining that it needed its own operational processing capability and partnered with the Institute of Engineering, Surveying and Space Geodesy (IESSG), Nottingham University (now the Nottingham Geospatial Institute – https://www.nottingham.ac.uk/ngi/) to develop an robust 24/7 processing system, and awarded IESSG an R&D contracts to develop and deliver such a system to the Met Office.

In 2004, the Met Office took delivery of a prototype system based around Bernese v4.0 in double-difference mode, processing around 100 IGS and EUREF sites in near real-time. Over time, the system was upgraded to a Bernese v5 system processing over 200 sites from a European domain to feed the North-Atlantic and European (NAE) NWP model, which culminated in April 2007 with operational assimilation of GNSS ZTD data into the Met Office NAE model. At the time, the UK Met Office was the first national met service in the world to be processing and assimilating GNSS data (Fig. 6.31).

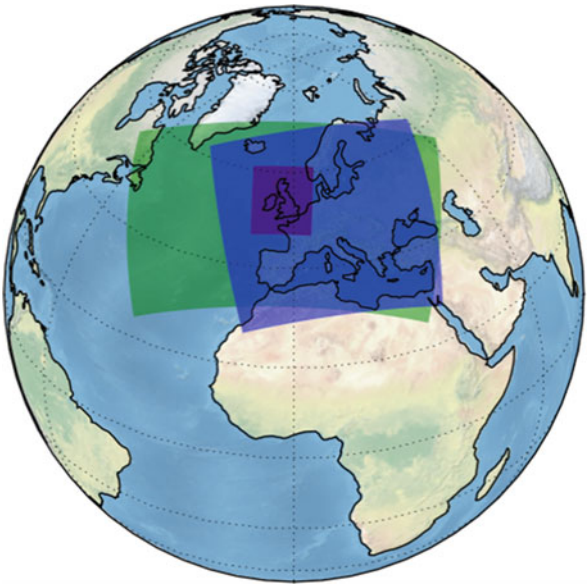

Fig. 6.31 2016 Met Office NWP model domains. No colour = global model (17 km resolution, 4D-Var DA). Blue = old NAE model (retired). Green = EURO4 model (4 km model, no DA). Purple = UKV model (1.5 km, 3D-Var)

6.1.25.2 Agreements with National Mapping Agencies

Whilst the Met Office has, since 1998, owned and operated its own network of GPS receivers, to provide the maximum benefit to both forecasting and NWP communities, additional raw data was required. In 2006 The Met Office signed a Memorandum of Understanding (MoU) with Ordnance Survey GB, stating that Ordnance Survey GB could install a number of GNSS equipment on Met Office sites around the UK, and in return Ordnance Survey would grant the Met Office access to data from their network of around 150 GNSS sensors in the UK, free of charge. Additionally, another MoU on the same basis was signed in 2006 between the Met Office and the Ordnance Survey of Northern Ireland.

In 2007, a 3-party MoU was signed between the Met Office (acting on behalf of the EIG EUMETNET E-GVAP Programme) and the Ordnance Survey of Ireland (OSi) and Met Eireann, whereby Osi would provide raw GNSS data to the Met Office, who, would process the data and provide processed data to Met Eireann for NWP assimilation of forecaster visualisation.

6.1.25.3 Tropospheric GNSS Processing at the UK Met Office

The original Met Office processing system (METO) was designed (in terms of data quality, timeliness and size and orientation of network processed) to best meet the needs of the NAE model. Positive benefit of GNSS ZTD assimilation was demonstrated (Bennitt and Jupp 2012) and other, internal assimilation impact experiments. From this work, it was decided that GNSS data would most likely be of benefit to the other Met Office NWP models such as the global model, and more recently the UKV 1.5 km UK-specific model. To meet the observational requirements of these models, additional GNSS processing systems were established, namely METG (global, hourly processing system) and METR (UK-specific, 15 min processing system). Both additional systems were again developed in partnership with the University of Nottingham under R&D contracts. In 2012, the Met Office started operational assimilation of GNSS data into the global model from a limited number of European ACs processing global networks of stations (METG and GOPG the global product from the Geodetic Observatory, Pecny, Czech Republic).

The Met Office process raw GNSS data on behalf of some countries who do not have the facility to process data themselves. In 2006 a 3-party Memorandum of Understanding was established between the Ordnance Survey of Ireland, Met Eireann and the UK Met Office, whereby the UK Met Office (acting on behalf of E-GVAP), would process raw GNSS data provided my OSi and make the products (ZTD and IWV) available to E-GVAP member Met Eireann for operational NWP assimilation or forecaster use. This service has been ongoing since and the Met Office is in the process of updating the system to provide Met Eireann with sub-hourly rather than hourly ZTD/IWV products. Similar, albeit less formal, arrangements (i.e. no MoU) are in place where the Met Office (again, acting on

behalf of E-GVAP) processes data on behalf of the Icelandic and soon to be, Canadian Met Services.

6.1.25.4 Data Use

NWP Data Assimilation

Operational GNSS data assimilation began in April 2007 in the NAE model, and, as mentioned in 2012 into the global model. When we look at the total Impact of observations in the global model for example for Sept. 2017 (Fig. 6.32), Ground GNSS is relatively low in terms of overall impact. When we consider the small number of observations in each assimilation cycle (as compared with traditional meteorological satellite observations for example), it is not surprising. However, when the impact per observation is assessed for the same time period (Fig. 6.33), ground-based GNSS observations of ZTD actually have the second highest impact per observation. Additionally, when the fraction of observations which have a beneficial effect on NWP is assessed (this time for July 2016) it can also be seen that GNSS is again one of the highest. This is shown in Fig. 6.34.

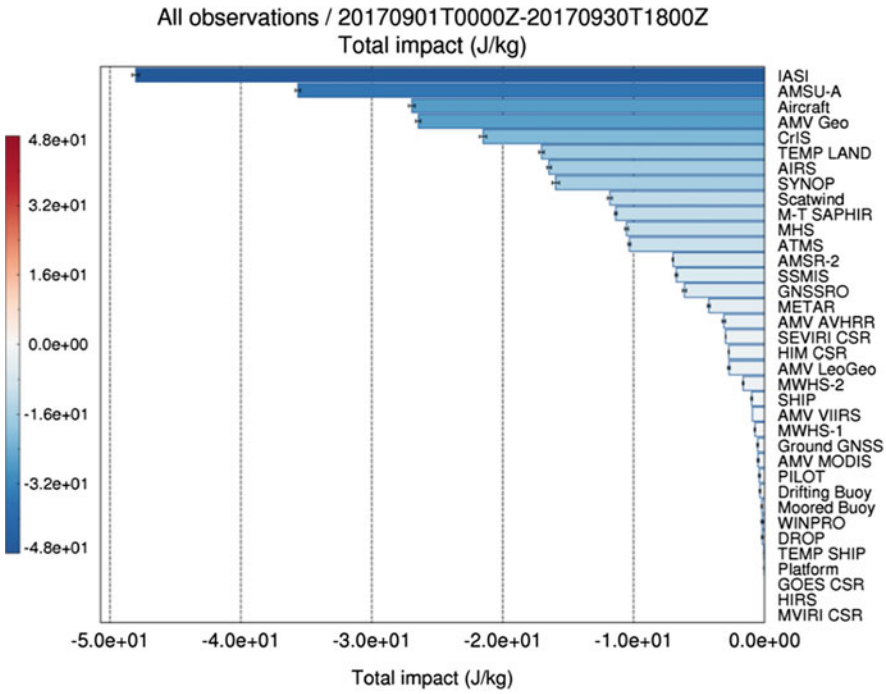

Fig. 6.32 Total impact per observation type in the Met Office Global NWP model, Sept. 2017

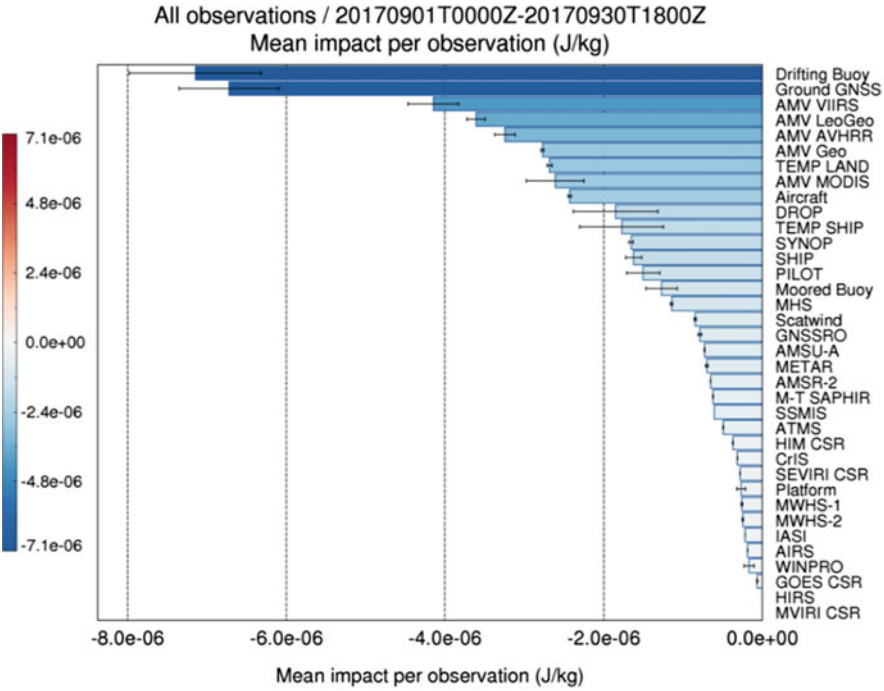

Fig. 6.33 NWP model impact per observation in the Met Office Global NWP model, Sept. 2017

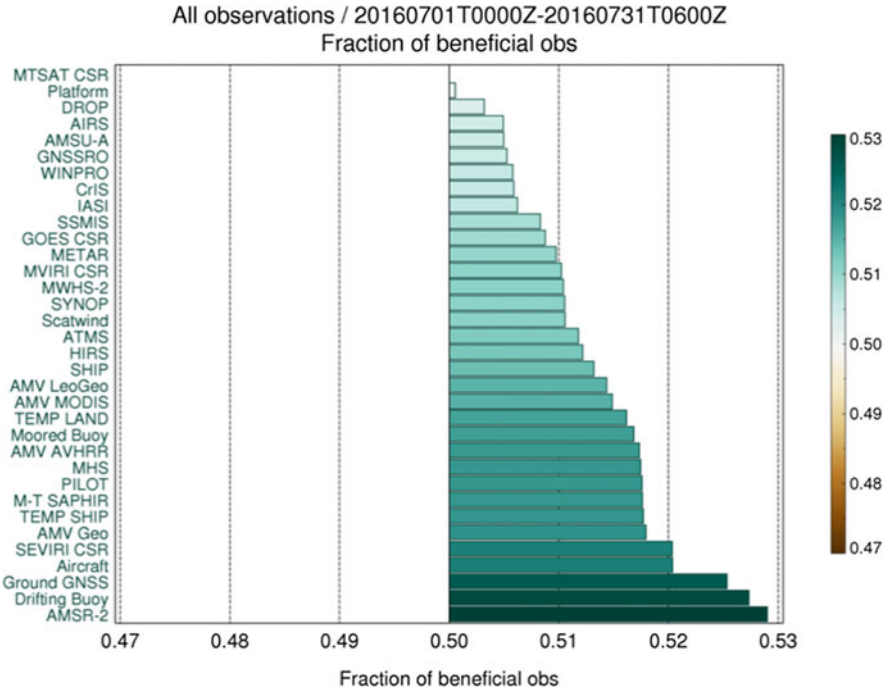

Fig. 6.34 Fractional benefit of all observations in the global NWP model, July 2016

From Figs. 6.32, 6.33 and 6.34, we can see that whilst the overall impact from GNSS in the global model is relatively low, this appears to be due to the very low number of observations actually assimilated in any one model run. Figures 6.33 and 6.34 clearly demonstrate high impact per observation, thus suggesting additional GNSS processing and assimilation (particularly of remote sites) will have a direct, measurable positive impact on NWP scores.

6.1.25.5 Forecaster Use

Whilst the primary use of GNSS data in the UK Met Office is for NWP data assimilation, ZTD is also converted to IWV using nearby synoptic pressure and temperature observations and 2D maps and animations of water vapour fields are produced for operational forecaster use. A number of case studies were developed to aid forecaster understanding of humidity field evolution.

Ongoing forecaster evaluation is underway to determine which conditions are best suited to the use of IWV imagery from ground-based GNSS and thus aid operational forecasting, particularly of severe weather.

6.1.25.6 Climate

The Met Office has been actively involved the assimilation of high-quality reprocessed ZTDs (i.e. EUREF Repro2 products) in the regional climate reanalysis system (UERRA, http://www.uerra.eu/). This work is ongoing.

6.2 COST International Partner Countries

6.2.1 Hong Kong

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Abstract Apart from the well-known positioning, navigation and timing applications, GNSS (Global Navigation Satellite System) is now an established important atmospheric water vapour observing system. GNSS nowadays has been developed with capability to retrieve atmospheric water vapour with high spatial and temporal resolutions. In China, the application of GNSS in meteorology started at the last few

years of the twentieth century and today it is a well-established research field. This paper makes a review of the GNSS meteorology situation in China over the last 5 years from 2013 to 2017. Review includes the GNSS data processing for retrieving tropospheric products, advances in GNSS water vapour tomography, application of GNSS water vapour products for weather prediction and the GNSS raw data used in each study. In the last 5 years, GNSS meteorology in China has achieved abundant outcomes and attracted more attentions from other communities to this field.

Introduction Water vapour has always been a focus of research interest for many atmosphere-related studies, such as in climatology, meteorology, space geodesy, and satellite navigation. This is due to its important role in many atmospheric processes. Water vapour is the dominant natural greenhouse gas in the atmosphere and it provides the largest feedback on surface temperature among various climate feedbacks (Held and Soden 2000). Water vapour is also a precursor of precipitation and it provides the fuel for thunderstorms as a considerable amount of latent heat releases during the condensation process. Although the atmosphere contains only 0.001% of the total amount of water on the earth, water vapour takes an important part in the water cycle of the earth (Troller 2004). Due to the variations in water vapour concentration and in latent heat release, a small amount of water vapour may cause severe weather changes (Mohanakumar 2008). When the radio signal travels through the atmosphere, it will be refracted by the presence of water vapour and thus introducing an equivalent excess path length to the primary observable (Davis et al. 1985; Mendes 1998). Therefore, water vapour also acts as a major error source in range measurements of space geodetic applications. Over the years, many techniques have been developed to improve the atmospheric water vapour observation, including both ground-based observation systems and satellite-borne remote sensing sensors (Elgered et al. 1991; Niell et al. 2001). Among various platforms, Global Navigation Satellite System (GNSS) has been regarded as a potent approach to retrieve atmospheric water vapour with high spatial and temporal resolutions. In addition, GNSS also has the advantages of low operational cost and all-weather capability when compared to other traditional techniques. The strengths of GNSS in atmospheric sounding have significantly facilitated the development of GNSS meteorology, which has become a focus of multidisciplinary research in the fields of meteorology and space geodesy. This summary reviews the research work in GNSS meteorology in China over the last 5 years (2013–2017).

GNSS Meteorology in China: In mainland China, researchers from the Wuhan University have done many studies on GNSS meteorology over the last 5 years. Shi et al. (2015) investigated real-time GPS precise point positioning (PPP)-based PWV estimation and its potential for rainfall monitoring and forecasting. They compared the real-time PPP-derived PWV values with the post-processed counterparts at the IGS station WUHN, yielding a RMS error of 2.4 mm and a correlation coefficient of 0.99. By comparing the real-time PWVs with ground rainfall records during severe rainfall events, they demonstrated the feasibility of real-time GPS PPP-derived PWV for rainfall monitoring. The Chinese BeiDou Navigation Satellite System (BDS) is under progressive development and now can provide regional

Positioning, Navigation and Timing (PNT) services over the Asia–Pacific region since December 2012. Li et al. (2015) presented a study on PWV estimation using ground-based BDS observations using PPP technique. In their study, BDS and GPS data collected from ten stations located at the Asia–Pacific and West Indian Ocean regions during the year 2013 were processed using the PANDA (Position and Navigation Data Analyst) software package that was developed by the Wuhan University, China. BDS derived PWVs were compared to GPS PWVs at ten stations. The mean bias and StDev of their differences at ten stations are 0.78 mm and 1.77 mm, respectively. Their study indicates that the BDS is ready for the high precision meteorological applications in the Asia–Pacific and West Indian Ocean regions. Xu et al. (2013) from the Liaoning Technical University, China, estimated ZTD using BDS observations to assess its capacity for troposphere remote sensing. They used BDS data for the period 5–8 November 2012 collected from a local network with six stations in Hebei province. BDS data were processed in both network and PPP modes. Compared with the IGS ZTD products, results showed that the bias and the StDev of the ZTD differences are about 2 mm and 5 mm, respectively. More studies have been carried out for retrieving the water vapour fields with tomographic techniques. Xia et al. (2013) proposed a combined iterative and non-iterative method for reconstructing the water vapour field using tomographic technique. In this method, the non-iterative reconstruction algorithm is first applied to retrieve water vapour field using COSMIC RO data as a priori water vapour information. Then the estimates from non-iterative reconstruction are used as initial data in the iterative reconstruction method. They evaluated this combined method using 10-day GPS data in Hong Kong and COSMIC profiles. Evaluation results showed that water vapour density retrieved from the combined method has a good agreement with radiosonde data at altitudes above 2.5 km. The average RMS value of their differences above 2.5 km is 0.44 g m^{-3}. Jiang et al. (2014) developed a near real-time four-dimensional water vapour tomographic system. Sliding time window strategy and double-difference network solution are used to retrieve the GPS water vapour data. In order to improve the distribution of observations in the lowest layers of tomographic grid, they also assimilated the surface relative humidity data into the tomographic system. They tested this tomographic system by using the GPS data collected from the 12 stations of Hong Kong network in the year of 2010. Compared with the radiosonde profiles, this tomographic system achieved overall bias of 0.13 g m^{-3} and RMS error of 1.28 g m^{-3}. In the study reported by Ye et al. (2016), the water vapour tomography was optimized with the aid of radiosonde and COSMIC historical data. They first optimized the regional ZHD model by compensating the estimates from the Saastamoinen model. Second, the regional conversion factor of converting the ZWD to PWV is refined by improving the quality of the atmospheric weighted mean temperature. They developed a method for discretizing the tomography grid with an uneven voxel height and a varying water vapour top layer. They also proposed a Gaussian exponential vertical interpolation method for better reflecting the vertical variation characteristic of water vapour. The optimized tomography was assessed by using 1-month GPS data of February 2014 collected in Hong Kong. Compared with tomographic results

without optimization, the optimized method improved the tomographic water vapour results by 15% and 12% for layers below 3.75 km and above 3.75 km, respectively. Yao and Zhao (2016) presented a method to maximally use GNSS signals that penetrate the tomography area. They studied the possibility of selecting a reasonable tomography boundary and using signals entering the tomography area from side face. Based on 40-year radiosonde data, they determined the tomography boundary in Hong Kong. For the signals passing through the side face, they introduced a scale factor to determine the proportion of the signal that belongs within the tomography area. GNSS data from the 12 stations of Hong Kong over the period of 4–30 May 2013 were adopted to validate the proposed method. Comparisons showed that the utilization rate of signals is improved by 30.32% and the number of voxels crossed by rays is enhanced by 12.62% when considering the signals passing through the side. A comparison of radiosonde, ECMWF, and tomography showed that the RMS errors of the proposed method (1.23 and 2.12 g/m^3, respectively) are superior to those of the previous method (1.60 and 2.43 g/m^3, respectively). To fully use the GNSS signals passing through the tomographic region, Yao et al. (2016) also proposed an approach to use both signals that pass the side and top of a research area of the tomography. This method can enhance the utilization of GNSS data and increase the number of voxels crossed by satellite signals. They validated this approach by using GNSS data from 10 GNSS stations of the CORS network of Zhejiang Province, China from 1 to 31 May 2015. Compared with radiosonde profiles, they showed that the proposed approach is feasible and effective. In the study presented by Guo et al. (2016), an optimal weighting method was proposed to reasonably determine the weights of three types of tomography equations including the observation equation, the horizontal constraint equation, and the vertical constraint equation. Based on a GPS network consisting of seven stations in Wuhan, China, they demonstrated that the proposed method can adaptively adjust the weights for various equations and enable the posterior unit weight variances for the three types of equations that achieve statistically equal. Zhang et al. (2017) proposed an improved tomography method based on adaptive Laplacian smoothing (ALS) and ground meteorological observations. They tested this tomography approach in Hong Kong during a heavy rainy period and a rainless period. Results showed that the ALS method got better results than the constant Laplacian smoothing (CLS) method. They also found that the assimilation of ground meteorological data into tomography can solve the perennial problem of resolving the wet refractivity in the lower troposphere.

Wang et al. (2014) from the Nanjing University of Information Science and Technology, China, proposed two new statistical parameters to improve the deficiencies of existing accuracy evaluation parameters in algebraic reconstruction techniques (ART). The new statistical parameters, i.e. bias and RMS, are calculated from wet refractivity of the total voxels. Simulations showed that Gaussian constraints can be applied to update the value of voxels without ray-crossings and the new method can improve the overall accuracy, especially in a poor grid model with a lot of empty voxels.

Another group from the China University of Mining and Technology proposed a new GPS tomographic parameterization approach based on IDW (inverse distance weighted) interpolation (Ding et al. 2017). The proposed algorithm can avoid the use of horizontal constraints to smooth voxels without ray-crossings. They also applied a prime number decomposition (PND) access order scheme to minimize correlation between SWD observations. They carried out several tomographic experiments by using 14 days (dry days from 2 to 8 August 2015 and rainy days from 9 to 15 August 2015) of data from the Hong Kong GPS network. The new method was proved to have better performance under stable weather conditions than unstable weather (e.g., rainy days).

In Hong Kong, GNSS meteorology related work is mainly carried out at the Micro-Laboratory of Atmospheric Research and Geomatics Engineering (Micro-LARGE) at the Department of Land Surveying & Geo-Informatics, the Hong Kong Polytechnic University (PolyU). As the leader of Micro-LARGE, Dr Zhizhao Liu has conducted various studies on atmospheric water vapour retrieval using GNSS technology. Based on GNSS Precise Point Positioning (PPP) technique, Micro-LARGE developed the first PWV Real-Time Monitoring System (PWVRMS) for the Pearl-River-Delta region of China (Liu and Li 2013). The processed GNSS data are collected from three networks in Pearl-River-Delta region: Hong Kong SatRef GNSS network, Macao MoSRef GNSS network and Guangdong CORS network. In data processing, PWVRMS directly uses IGS predicted precise satellite orbit while the GPS satellite clock error is estimated in real-time. This PWVRMS system provides the PWV data with a temporal resolution of 10 min. Evaluation results by radiosonde showed that PWV data estimated by PWVRMS have an accuracy better than 2 mm. This PWVRMS system can provide real-time water vapour data to meteorological agency such as Hong Kong Observatory for weather forecasting service and research (Liu and Li 2013).

The Micro-LARGE has also done many studies in retrieving the three-dimensional atmospheric water vapour distribution with the use of tomographic technique. Micro-LARGE group developed a new method to optimize the discretization of the tomographic model (Chen and Liu 2014). Using this method, the tomographic voxel of Hong Kong region was optimized towards both high accuracy and high spatial resolution of the tomographic solutions. This tomographic voxel optimization method includes top boundary determination, vertical layer discretization, and horizontal boundary optimization. Unlike the traditional tomography, the horizontal boundary of the tomographic model is no longer fixed. For different tomographic period, predicted GPS satellite orbits are used to predefine the optimal horizontal boundary. The horizontal boundary optimization is achieved by moving the voxel location in latitude and longitude directions until the maximum number of voxels with ray crossings is reached. By using the observations collected from 12 Hong Kong GPS stations, extensive experiments were carried out to determine the optimal discretization of the tomographic model for Hong Kong region.

The Micro-LARGE developed and performed a multi-sensor tomographic method using water vapour data derived from GPS, radiosonde, WVR (water vapour

radiometer), NWP (numerical weather prediction), sun photometer, and synoptic observations in Hong Kong (Chen and Liu 2016). Based on extensive tomographic tests covering a 6-month period of May to October 2013, the multi-sensor tomography achieved obvious better performance than that using GPS data only. In the evaluation by radiosonde profiles, the multi-sensor tomography yielded an overall accuracy of 7.13 mm/km. For different vertical layers, RMS error generally decreased with altitude from 11.44 mm/km at the lowest layer (0–0.4 km) to 3.30 mm/km at the uppermost layer (7.5–8.5 km).

The Micro-LARGE applied the tomographic results to investigate the evolution of water vapour during three heavy precipitation events occurred in Hong Kong (Chen et al. 2017). They investigated the variability of the total ZWD and ZWDs at five different vertical layers (below 1 km, 1~2 km, 2~3 km, 3~5 km and above 5 km) during the three events. It was observed that the fluctuations (increase or decrease) in the total ZWD largely came from the water vapour variations in the layers above 3 km. The remarkable increase or decrease of water vapour in the vertical layers can be seen as precursors to detect heavy precipitations as they reflect the instability of the atmosphere. This study demonstrated that the tomographic water vapour fields can reveal water vapour accumulation, saturation, and condensation.

Conclusions In the future, it is expected that GNSS meteorology will gain more attentions and great development opportunities in China due to three reasons. First, an increasing number of cities and provinces are developing their own GNSS network for various applications including precise positioning, real-time positioning and navigation, urban plan, land surveying, cadastral management and environment monitoring, etc. The increasing number of GNSS stations will contribute to a better implementation of GNSS meteorology. Especially for water vapour tomography, denser ground GNSS stations could produce water vapour field with higher accuracy and spatial resolution. Second, with the rapid development of Chinese BeiDou system, the number of satellites visible to any location at any time will increase significantly. The increase of GNSS satellites implies more possible signals penetrating through the troposphere. The developing multi-GNSS constellations has the potential to provide more accurate high-resolution PWV and tropospheric gradient products. In addition, multi-GNSS will improve the geometry of observations in the tomographic modelling and thus have a positive impact on the accuracy of the tomographic solutions. Third, continued climate change will trigger more extreme weather events in China. This demands an improvement in the capability of short-term weather forecasting. GNSS meteorology products including PWV, tropospheric gradient and water vapour field, closely linked to strong humidity variations accompanying severe weather phenomena, are considered as new important data for meteorological applications, e.g., nowcasting of severe rainfall events.

6.2.2 Australia

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Since 2016 Geoscience Australia (GA) has produced two 'trial' Zenith Troposphere Delay (ZTD) products. They are currently being delivered to the Australian Bureau of Meteorology (BoM) and the E-GVAP in COST format. The first product is available in 'near-real-time' with a latency of approximately 40 min. The second, 'rapid' product, has a latency of approximately 18 h, and includes a much denser set of observations obtained from over 700 stations obtained mainly from the Asia Pacific Region.

Both products are derived using a Precise Point Positioning (PPP) based approach to estimate the ZTD. We found that there are a number of operational advantages to using a PPP based approach compared to a double-differenced approach. The PPP approach takes less compute resources to obtain a solution; in addition, the PPP solutions provides position and ZTD estimates that are consistent with the global reference frame. The software and models applied are detailed in Table 6.1.

Near-real time products: The near-real-time-product was put together with the aim of improving short range weather forecasting with latencies of 12 h and under. The processing system utilizes the GNSS network run and operated by GA. This consists of approximately 150 Continuously Operating Reference Stations (CORS), which span Australia, the South Pacific, and Antarctica. These stations stream real-time data directly back to GA's data centre. In addition to this network, a set of stations owned and operated by the Victorian State Government department to aid in the densification of the near-real-time ZTD estimates in Victoria, as well as data streams provided to the IGS by Land Information New Zealand (LINZ) are also utilised. The distribution of GNSS stations used for the near-real-time system is shown in Fig. 6.35.

Compute infrastructure: The data collection and processing system is based on infrastructure provided by Amazon Web Services (AWS). Moving to a cloud infrastructure has significantly improved the reliability of the compute infrastructure, and provided a straightforward pathway to increasing the scale of the processing system as required (Fig. 6.36).

Table 6.1 Processing details

Model/parameter	Type	Solution	Notes
Processing software	BSW52	NRT and rapid	
Processed observation	Ionosphere free	NRT and rapid	
Ambiguity resolution	No	NRT and rapid	Float solution only
GPS data	RTCM 3	NRT	Rolling 24 h window updated every hour
	RINEX 2.1	Rapid	24 h of observation based on UTC day
Elevation mask	10	10	
Clock products	'IGS02' – real time clocks	NRT	
	IGS rapid	Rapid	
Orbit products	IGS ultra rapid	NRT	observed and predicted
	IGS rapid	Rapid	
Earth-rotation parameters	IGS ultra-rapid	NRT	
	IGS rapid	Rapid	
Antenna model PCO and PCV	Latest IGS ANTEX igs14.atx	NRT and rapid	
DCB	CODE	NRT and rapid	
Atmosphere (Dry)	GMF	NRT and rapid	
Mapping function	GPT	NRT and rapid	
Atmosphere (wet)	Estimated	NRT and rapid	ZTD estimate provided for every hour of observed data processed

Rapid products: The 'rapid product' is primarily used as a quality control system for the GPS data aggregated by Geoscience Australia, with the aim of screening out poor or inconsistent meta data before the final geodetic processing is attempted. The rapid solution is also used to monitor the performance of the near-real-time ZTD estimates. Each day we compare the results obtained from the rapid product with the near-real-time product. Figure 6.37 below shows a yearly comparison of the ZTD estimates obtained from the IGS station MOBS, located at the Melbourne Observatory, Melbourne, Australia. Two ZTD comparison plots are viewable for each station processed (to view another station replace the four-char ID MOBS, with the four char ID of the station of interest):

1. Yearly comparison https://s3-ap-southeast-2.amazonaws.com/gnss-analysis/status/rapid/ztd/yearly_MOBS_ztd.png

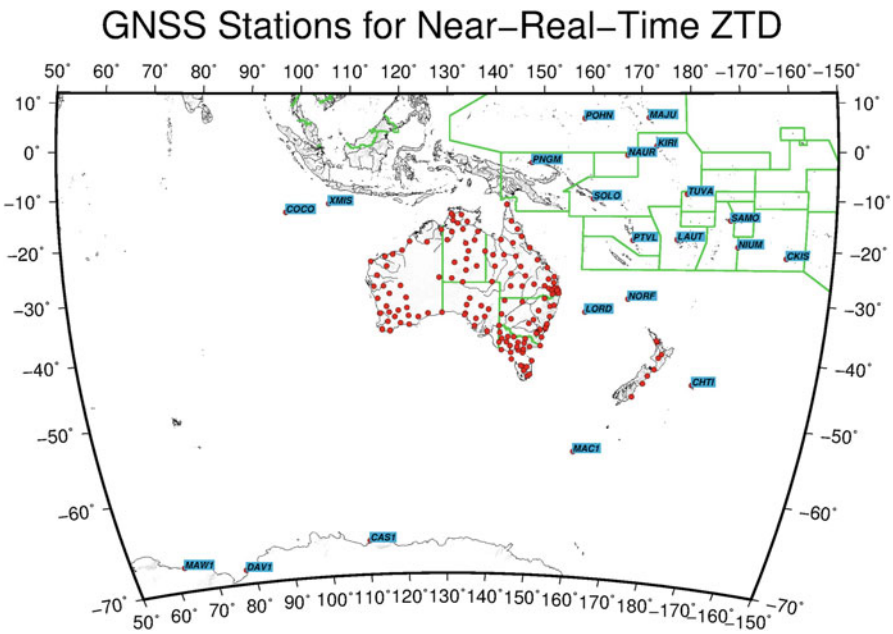

Fig. 6.35 The distribution of GNSS stations used for the near-real-time zenith delay estimates

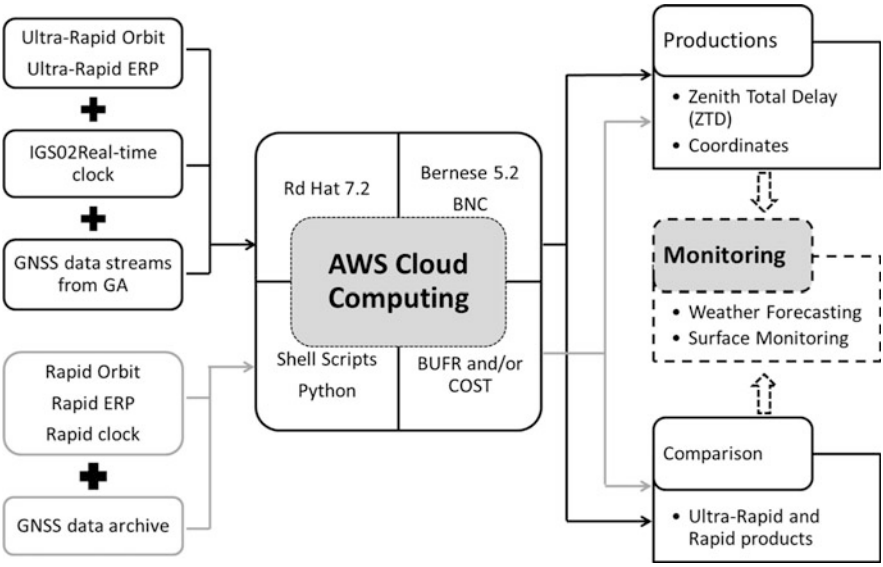

Fig. 6.36 The structure and flowchart of the Australian ZTD estimation system

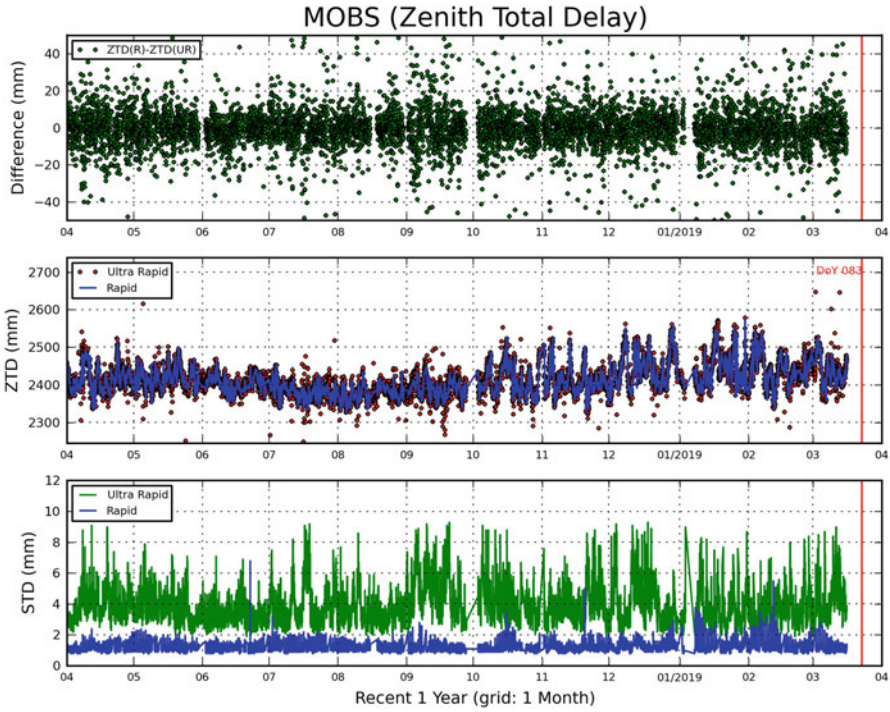

Fig. 6.37 An example plot of the comparison of the near-real-time and rapid processing result obtained from the IGS station located at Melbourne Observatory (MOBS). The top plot shows a time series of the difference between the near-real-time and rapid product, the middle plot shows the estimates obtained from both solutions, and the bottom plot is the standard deviation for each of the solutions

2. Weekly comparison https://s3-ap-southeast-2.amazonaws.com/gnss-analysis/status/rapid/ztd/weekly_MOBS_ztd.png

The distribution of GNSS stations used for the rapid system is shown in Fig. 6.38 below.

Current and future focus: Currently the Australian BoM is trialling the near-real-time product in their test assimilation models. Initial results look promising and it is likely to be included into operation forecasts in the near future. Once the product has been accepted into operational forecast then we will start increasing the number of stations used to create the near-real-time product. We will be also looking at ways we can decrease the latency of the NRT product through tuning of the compute infrastructure, processing procedures and observation window length used. GA is also currently developing its own in-house real-time GNSS processing software package, and we will also assess the applicability of using this to provide ZTD

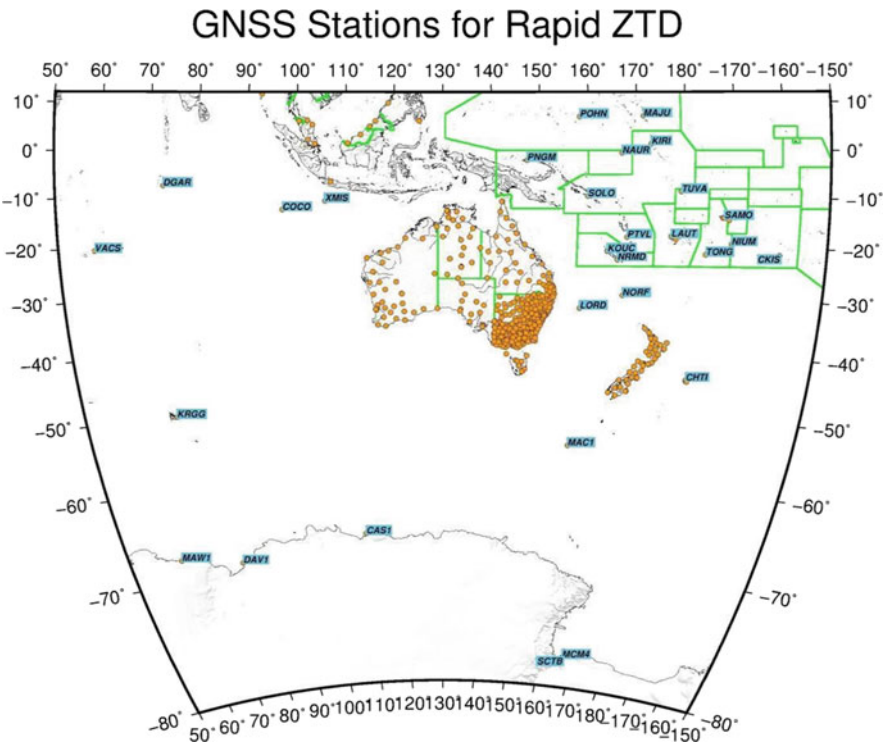

Fig. 6.38 GNSS stations used in the Asia Pacific Region for the rapid product (global stations not shown here)

estimates as the package matures. To help improve real-time positioning in Australia we are also looking at utilizing the ZTD estimates obtained from ray tracing of forecasted weather models. Currently we are trialling unassimilated ACCESS weather models to aid positioning for PPP-RTK applications.

6.2.3 Canada

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At Environment and Climate Change Canada (ECCC), we assimilate ZTD observations from the E-GVAP network that are available on the GTS. ZTD observations over North America from the NOAA GPS-IPW network were assimilated until December 2016 when free access to the data was cut off. The data are assimilated in our global and regional deterministic NWP systems. Recent research activities

related to ground-based GNSS include the diagnosis of ZTD observation errors and their temporal correlations. We plan to submit a paper on this research in the near future. GNSS IWV and ZTD observations are also used in one of our forecast verification systems. We are currently exploring ways to restore/replace the lost North American data and to obtain data from more GNSS sites in Canada. Options include obtaining data from UCAR, working with Natural Resources Canada geodetic division to provide ZTD for sites that they have access to, and producing ZTD data ourselves from raw GNSS receiver data.

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