JWG 4.3.8: GNSS tropospheric products for Climate

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1. Introduction

The Joint Working Group was established in 2015 with the approval of the terms of reference and objectives. The main objectives targeted by the working group are: to assess existing reprocessed GNSS tropospheric products, foster the development of forthcoming reprocessing activities, test different homogenization methodologies to setup a common long-term homogenized dataset to be reused for climate trends and variability studies, review and update GNSS-based product requirements and exchange formats for climate, and promote their use for climate research, including a possible data assimilation of GNSS troposphere products in climate reanalysis.

The main targeted results and deliverables are datasets, reports and scientific papers, which have been elaborated in collaboration among the participants.

The activities of this working group continued within the main lines sketched by the WG3 during the COST Action ES1206 “Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate” (GNSS4SWEC: http://gnss4swec.knmi.nl/).
2. **2015-2019 Activities**

The activities have followed the timeline reported in Figure 1.

A dedicated website was set-up ([http://iag-gnssclimate.oma.be/index.php](http://iag-gnssclimate.oma.be/index.php) Figure 2) in order to disseminate the main outcomes for each of the five scientific objectives, and a dedicated mailing list ([http://mailman-as.oma.be/mailman/listinfo/iag.gnssclimate](http://mailman-as.oma.be/mailman/listinfo/iag.gnssclimate)) was established for the communication among the members. After an inquiry sent out to the members about their individual contribution(s), a work plan has been prepared and distributed. The work plan is also publicly available on the website at [http://iag-gnssclimate.oma.be/Outreach/Documents.php](http://iag-gnssclimate.oma.be/Outreach/Documents.php).
Below are listed the main activities carried out during the 4-year period for each of the five scientific objectives.

**Objective 1 REPRO**: Assess existing reprocessed troposphere solutions and provide recommendations for the forthcoming reprocessing activities.

**International Reprocessing Activities:**

- **EUREF Tropospheric 2nd Reprocessing Campaign (Pacione, 2016, Pacione et al. 2017)**
  
  A reference tropospheric dataset over Europe has been generated in the framework of the second EPN (EUREF Permanent Network) Reprocessing campaign, hereafter EPN-Repro2. A huge effort has been made by five EPN AC to homogenously reprocess the EPN network for the period 1996-2014 (from GPS week 0834 to 1824) for providing solutions that are the basis for deriving new coordinates, velocities, and troposphere parameters for the entire EPN. The individual contributions are then combined in order to provide the official EPN reprocessed products. The EPN-Repro2 tropospheric dataset is open to the user community. Solutions (eu0wwww7.tro.Z, where wwww is the GPS week) in SINEX-TRO format along with a summary file (eu0wwww7.tsu.Z) with some statistics about it, can be downloaded at the EPN-Repro2 product directory at the BKG data center. For each EPN stations time series files are available here. The dataset has been evaluated against radiosonde data and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) data.

- **TIGA Reprocessing Campaign**
  
  The consortium of the British Isles continuous GNSS Facility (BIGF) and the University Of Luxembourg TIGA Analysis Centre (BLT), as one of the ACs contributing to the IGS Tide Gauge Benchmark Monitoring (TIGA) Working Group, completed a new solution using up to 750 GPS stations with global distribution and observation time spans of 6 to 21 years. The selected station network included all IGb08 core stations and more or less the complete archive of TIGA, which encompasses a large number of GPS stations at or near the global network of tide gauges. The GPS data was re-processed using the Centre for Orbit Determination in Europe (CODE) final precise orbits and Earth orientation parameters. The IGS08 satellites and receiver antenna phase center models were employed and an elevation cut-off angle of 3° was adopted. In the reprocessing, the Vienna Mapping Function 1 (VMF1) was used. It allows the mapping function to describe the atmosphere with the finest detail, leading to the highest precision in the derived tropospheric parameters. We also modelled the azimuthal asymmetry in the troposphere using gradient (tilt) corrections in North-South direction (GN) and in East-West direction (GE), following Chen and Herring [1997]. In BSW52 the ZHD is parameterized as a piece-wise function variation of the delay using a piecewise linear interpolation between temporal nodes. Observations of atmospheric pressure at the GPS station offer high precision for the ZHD estimates and minimize station height errors. However, many of the TIGA and IGS stations do not possess integrated meteorological sensors. Thus, ZHD in units of meters was a priori obtained reliably from surface pressure data from the gridded output of the ECMWF NWP model, and is provided by VMF1 using the modified Saastamoinen model, which assumes that the atmosphere is in hydrostatic equilibrium. The ZTD parameters were estimated in an interval of 1 hour with a loose constraint of 5 meters. In addition, horizontal gradients in the North-South and East-West directions are estimated in a 24 hour interval with the same 5 meters loose relative constraint.
• GRUAN Reprocessing Campaign


The Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) of the World Meteorological Organization (WMO) is an international observing network, designed to meet climate requirements. Upper air observations within the GRUAN network will provide long-term high-quality climate records. The data will be used to constrain and validate data from space based remote sensors, and for scientific studies of atmospheric processes.

National Reprocessing Activities

• CORDEX.be Reprocessing Campaign (Belgium)

http://cordex.meteo.be/

The CORDEX.be project brought together the Belgian climate and impact modelling research groups into one network as the first step towards the realization of climate services. It is based on the international CORDEX ("COordinated Regional Climate Downscaling Experiment") project but the '.be' indicates that it goes beyond for Belgium. Within CORDEX.be, a specific task is dedicated to the validation of the high-resolution (3 to 5 km spatial resolution) climate simulations using GNSS-derived products. Therefore, a careful reprocessing of the historical observations at about 320 world-wide GNSS stations has been carried out for the period 2000-2010 (period of assessment for the models). First results show that the 4 climate models participating in this project correlate well with the GNSS-derived products.

• Historical Reprocessing of the German Network (SAPOS).

• Reprocessing of the Japanese nationwide GNSS network (established mid-90’s) to derive GNSS-based PWV (Precipitable Water vapour) using IGS’s 2nd reprocessed ephemerides (IG2).

• IPGP-IGN (former IGN/LAREG) prepared a new enhanced global IWV dataset (436 stations over the 1994-2018 period) built up from CODE REPRO_2015 solution for the period 1994-2014 and CODE operational solution for the period 2015-2018 (Bock, 2019). Consistency between the two data streams has been checked on the common year 2014. The ZTD data are based on long-arc (3-days) solutions produced by AIUB (University of Berne) with a time sampling of 2 hours. The ZTD data have been screened based on a range-check and outlier check, and converted to IWV using ERA-Interim pressure level data (one every 6 hours) with bi-linear horizontal interpolation from four surrounding grid points. Daily and monthly IWV values are available from AERIS data portal (https://en.aeris-data.fr/).

Objective 2 HOMO: Set-up a common GNSS climate dataset on which different homogenisation methodologies can be tested. The homogenised common long-term dataset can then be re-used for climate trends and variability studies within the community.

In the last years, several groups studied the homogeneity of the re-processed GNSS ZTD time series. They clearly showed evidence that these time series, even if carefully reprocessed, still suffer from inhomogeneity which e.g. may impact the calculation of the long-term water vapour trend (and its associated error), hence preventing a correct and precise interpretation in terms of climate change and time variabilities. Consequently during the COST Action ES1206 (GNSS4SWEC), a sub-WG was formed with the aim to inter-compare different statistical methods that detects change points in time series, identify their capability, advantages and drawbacks in identifying these change points, with the final goal to come up with a homogenised dataset for further climate trends and variability studies within the community. These activities have been a follow-up of the GNSS4SWEC sub-WG3 on data homogenisation. In that context a specific attention will be given to the available meta-data necessary for the homogenization, process and their exchange format (see also objective 4 on product
requirements and exchange formats). The ultimate objective if this activity is to use the homogenized long-term datasets for further studies, e.g. determination of the long-term trends of the water vapour, and/or investigation the temporal and spatial variability of the water vapour.

To assess the performance of the different statistical methods synthetic datasets with increasing complexity level and mimicking the characteristic of the actual dataset (i.e. the dataset that we wanted to homogenise) have been created. It was then asked to run each statistical method on each synthetic dataset and on daily and monthly aggregated time series, when possible. The performance was then assessed in terms of statistical and probabilistic scores and skills, but also in terms of CRMSEs and trend bias. In total 13 break detection methods (from 8 operators) have been evaluated. The statistical methods includes 1) t-test with cutting algorithms, 2) t-test with cutting algorithms, 3) t-test with cutting algorithm, and 4) t-test with cutting algorithms. Recently, a new R-package dedicated to the homogenization of daily differenced GNSS IWV series (candidate minus reference series) was developed at IPGP-IGN (former IGN/LAREG). The segmentation algorithm is based on the classical model of a Gaussian random process with the unknown means and multiple breakpoints, modified to account for specific characteristics of the GNSS – ERAI differences: a monthly varying variance (Bock et al., 2018) and a seasonal bias represented by a Fourier series of order 4 (Quarello et al., in preparation). A penalized maximum likelihood approach is used with several different penalty criteria implemented. The R-package provides diagnostics such as the sum of squares, estimated parameters, their formal errors, etc., to select the best solution. A fully automatic mode is also implemented. The R-package “GNSSseg” is available on the Comprehensive R Archive Network (https://cran.r-project.org/).

A review of the homogenization activity has been presented at EGU General Assembly 2019 (Pottiaux et al., 2019). The assessment of the performance of the different contributing homogenization algorithms on the break identification for three different sets of benchmark time series (with different complexity on the used noise model, the presence of gaps and trends) will be submitted to JGR – Atmospheres in 2019.

**Objective 3 ASSIM:** Advocate the data assimilation of GNSS troposphere products in Climate Re-Analysis.

Activities carried out during the period 2015-2019:

- At University at Albany: use GNSS PW (Precipitable Water) data to develop PW diurnal matrices and validate weather and climate models, and plan to deploy a GNSS receiver in a fix or mobile mode for New York State Mesonet validation and calibration.

- At the Met Office: As part of the European FP7 UERRA (Uncertainties in Ensembles of Regional Re-analysis, http://www.uerra.eu/) project, EPN-Repro2 reprocessed Zenith Total Delay observations were assimilated into a European regional climate model, which produced a climate reanalysis for 1979 to 2014. Zenith Total Delay observations were bias corrected using an online bias correction to account for any evolution of systematic bias. The regional reanalysis data is available through the UERRA website.

- At Hong Kong Polytechnic University: collaboration with the China Meteorological Administration (CMA) scientists to evaluate PW accuracy of CMA’s weather satellites’ various PW products, using GNSS-derived and other PW data (such as WVR) as a reference.

- At GFZ: In recent publications (Alshawaf et al. 2016 and Alshawaf et al. 2018) the temporal trends estimated from GNSS time series are compared with those estimated from European Center for Medium-Range Weather Forecasts Reanalysis (ERA-Interim) data and meteorological measurements to evaluate climate evolution in Germany by monitoring different atmospheric variables such as temperature and PWV (Precipitable Water vapour). PWV time series were obtained by three methods: 1) estimated from ground-based GNSS observations using the method of Precise Point Positioning (PPP), 2) inferred from ERA-
Interim reanalysis data, and 3) determined based on daily in situ measurements of temperature and relative humidity. The other relevant atmospheric parameters are available from surface measurements of meteorological stations or derived from ERA-Interim. The trends are estimated using two methods; the first applies least squares to seasonally adjusted time series and the second using the Theil-Sen estimator. The trends estimated at 113 GNSS sites, with 10 and 19-year temporal coverage varies between −1.5 and 2 mm/decade with standard deviations below 0.25 mm/decade. These values depend on the length and the variations of the time series. Therefore, we estimated the PWV trends using ERA-Interim and surface measurements spanning from 1991 to 2016 (26 years) at synoptic 227 stations over Germany. The former shows positive PWV trends below 0.5 mm/decade while the latter shows positive trends below 0.9 mm/decade with standard deviations below 0.03 mm/decade. The estimated PWV trends correlate with the temperature trends.

We have determined linear trends of IWV from synchronized time series of VLBI and GNSS atmospheric parameters as well as from ECMWF ERA-Interim at co-located sites. The three solutions were all determined at GFZ. The GNSS solution was part of the second TIGA reprocessing solution that included 840 stations in total (Deng et al., 2016) and the numerical weather model was exploited applying the Direct Numerical Simulation (DNS) software (Zus et al. 2012; 2014; 2015). The VLBI solution was determined by the VLBI group at GFZ with the software VieVS@GFZ (Nilsson et al. 2015). The linear IWV trends show a range of values below 1 kg/m^2 / yr magnitude with positive and negative signs. The linear trends significantly vary depending on the start and end date of the time series what is probably caused by the large seasonal signals that show inter-annual variations. Some linear trends are quite small or even insignificant. The agreement between the techniques is rather low and sometimes the trends show different signs. As an explanation for the disagreement, we suppose several data analysis aspects that affect the determination of atmospheric parameters.

VLBI for Climate: As part of the assessment we investigated the sensitivity of linear trends determined by VLBI w.r.t. various analysis options. One possibility for the trend differences might be the usage of different delay and gradient mapping functions. We tested three mapping functions: GPT2w (Böhm et al. 2015), Potsdam Mapping Function (PMF), and VMF1 (Böhm et al. 2006), but did not find significant different IWV trends. The largest effect on the trends was found to be the usage of atmospheric pressure in the analysis of space geodetic techniques. The atmospheric pressure enters the a priori hydrostatic zenith delay models in VLBI and GNSS analyses. A trend in the a priori hydrostatic zenith delays in the sequel propagates into the trend of the non-hydrostatic zenith delays that is directly proportional to the IWV trend. In contrast to other space geodetic techniques, VLBI data have been recorded together with atmospheric pressure records from nearby meteorological sensors. As any longer time series of meteorological data, these recordings need to be homogenized. This has been done in the past and was recently repeated (Balidakis et al. 2016). The usage of different atmospheric pressure data for the analysis of space geodetic techniques results in significantly different IWV trends (Balidakis et al. 2017).

IPGP-IGN and LATMOS analysed IWV from GPS observations and two modern atmospheric reanalyses (ERA-Interim and MERRA-2) for the period 1995–2010. Means, variability and trend signs were in general good agreement. Regions and GPS stations with poor agreement were investigated further. Representativeness issues, uncertainties in reanalyses, and inhomogeneities in GPS were evidenced. Reanalyses were compared for an extended period, and a focus on North Africa and Australia highlighted the impact of dynamics on water vapour trends (Parracho et al., 2018). Consistency and representativeness differences between GPS IWV data and ERA-Interim reanalysis were further investigated. It was shown that both average and extreme representativeness differences exhibit a strong location dependence (due to station specific geographic, topographic, and climatic features). A methodology for
reducing the representativeness errors and detecting the extreme, outlying, cases was proposed (Bock and Parracho, 2019).

- Berckmans et al. (2018) used the EPN-Repro2 IWV dataset to evaluate the regional climate model ALARO running at 20 km horizontal resolution and coupled to the land surface model SURFEX, driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) data.

- SMHI (Swedish Meteorological and Hydrological Institute) is contracted to provide the Regional Reanalysis for Europe by the EU Copernicus Climate Change Service (C3S_322 Lot 1). A high-resolution (5 km grid) reanalysis from the early 1980's up to today will be delivered. It uses state-of-the-art data assimilation and a wide range of observations including many remote sensing instruments. GNSS Zenith Total Delay observations are planned to be used in the HARMONIE-ALADIN modelling system. There is several years operational experience of using near real-time data at SMHI and its partner institutes. There is a variational bias correction used and a white list of stations to be considered reliable. The EPN-Repro2 data (Pacione et al. 2017) from 1997-2014 have been retrieved, resorted and reformatted for assimilation. A 4-week test assimilation has shown that it works and the data give a reasonable and small positive impact. In addition, the operational EPN product will be accessed after 2014.

- Van Malderen et al. (2018) compare and investigate different aspects of the Integrated Water Vapour (IWV) variability for the period 1995/96-2010 at 118 globally distributed Global Positioning System (GPS) sites, using additionally UV/VIS satellite retrievals by GOME, SCIAMACHY and GOME-2 (denoted as GOMESCIA below), and ERA-Interim reanalysis output at these site locations: the geographical distribution of the frequency distributions of the IWV time series, the seasonal cycle and linear trend differences among the three different datasets. Finally, we reconstruct the monthly mean IWV time series by means of a stepwise multiple linear regression from the mean annual cycle, the linear trend, and a selection of regionally dependent candidate explanatory variables.

Objective 4 FORMAT: Review and update GNSS-based product requirements and exchange format for climate.

An effort on SINEX-TRO standardization was carried out in collaboration with the GNSS4SWEC WG3, E-GVAP, IGS, EUREF, and GRUAN. The collection, exchange format, and usage of metadata information (particularly important for the processing and for the homogenisation) has been revisited in this context. A new SINEX-TRO v 2.0 (Pacione and Dousa, 2018) has been established. At the IGS Workshop in Wuhan 2018, the IGS Troposphere WG recommended the use of this format for exchanging tropospheric parameters. From GPS week 2034 on, the EPN combined tropospheric product is delivered in SINEX-TRO v 2.0 format in addition to the legacy one.

Objective 5 COOP: Strengthen the cooperation between geodesists and climatologists.

See section 3, 4 and 5.

3. Interaction with other research programmes

Collaboration/cooperation has been done with researchers from national, European and international organisations through participation of experts to the working group activities:


5. European FP7 project UERRA (Uncertainties in Ensembles of Regional Re-analysis, http://www.uerra.eu/).
7. IAG JWG 1.3: Tropospheric ties.

An IAG workshop on ‘Satellite Geodesy for Climate’ was organized in September 19-21, 2017, in Bonn, Germany. This was a joint workshop between the IAG SC 2.6: ‘Gravity and Mass Transport in the Earth System’, the IAG JWG 2.6.1: ‘Geodetic Observations for Climate Model Evaluation’, and the IAG JWG 4.3.8: ‘GNSS Tropospheric Products for Climate’.

The before mentioned IAG Working Groups "GNSS tropospheric products for climate" and ‘Geodetic Observations for Climate Model Evaluation’ have been the pillars for the foundation of an IAG Inter-Commission Committee on “Geodesy for Climate Research”. This ICC will be proposed, and most likely accepted, during the next IUGG conference in Montreal in June 2019, and will continue the roadmap initiated at the successful workshop “Satellite Geodesy for Climate Studies”, which, for the first time, brought together geodesists representing all different observation techniques and climate scientists in a dedicated framework.

4. Outreach Presentations

The activities of the working group have been presented at the following conferences:

1. IAG JWG 4.3.8: GNSS tropospheric products for Climate, R. Pacione, E. Pottiaux and JWG members, COST ES1206 Workshop, 8-10 March 2016, Reykjavik, Island.
2. IAG JWG 4.3.8: GNSS tropospheric products for Climate, E. Pottiaux, R. Pacione and JWG members, IAG Commission 4 Symposium Wroclaw, Poland, 4-7 September 2016 http://www.igig.up.wroc.pl/IAG2016/.


4. Berckmans, J., Van Malderen, R., Pottiaux, E., Pacione, R., and Hamdi, R.: Validating the water vapour content from a reanalysis product and a regional climate model over Europe based on


44. Zus, F., G. Dick, J. Dousa and J. Wickert (2015) Systematic errors of mapping functions which are based on the VMF1 concept, GPS Solutions, 19, 2, 277-286, doi:10.1007/s10291-014-0386-4


1. Alshawaf, F. and Hinz, S. Determination of atmospheric water vapor using GNSS and InSAR measurements with comparison to numerical atmospheric models, COST Action ES1206 "GNSS4SWEC" 3rd Workshop, 08-10/03/2016, Reykjavik, Iceland.

2. Elgered, G. and Ning, T. Can horizontal delay gradients estimated from GNSS data be used in climate research? COST Action ES1206 "GNSS4SWEC" Working Group Meeting, 01-02/09/2016, Potsdam, Germany.

3. Fernandez, L., Mendoza, L., Natali, M. P., Meza, A., and Bianchi, C: Comparison of GNSS integrated water vapor and NWM reanalysis data over Central and South America, EGU GA.
22. Fionda E., Caddeu M., Mattioli V., Pacione R., Analysis of integrated water vapour observed in sub-arctic Finland from GPS, ground-based microwave radiometers and RAOB data, Vol. 20, EGU2018-8277, 2018 EGU General Assembly 2018


40. Liu, Zhizhao (2016), Identifying the Optimal Atmospheric Correction Model for GPS Applications in High-altitude Region, China, Presentation at Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Lanzhou, Gansu, China 04 March 2016

41. Liu, Zhizhao (2017), Remote Sensing of Atmospheric Water Vapor: A Global Prospect. 3S Technological Development Summit and PolyU-Hohai University Joint Laboratory Seminar, Nanjing, China, 16–18 June 2017

42. Liu, Zhizhao (2018). GNSS for Atmospheric Remote Sensing, for the Wuhan University-Tongji University Summer Exchange Program at the Hong Kong Polytechnic University, Hong Kong, 2 August 2018

43. Liu, Zhizhao (2019), Improving GNSS PPP Accuracy through WVR PWV Augmentation, Presentation at Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan, China, 23 March 2019


46. Mota GV., Shuli S., Stępniak K., Assessment of integrated water vapor through ground-based GNSS dataset over central and northeastern Amazonia, AGU Fall Meeting, 10-14.12.2018, Washington, USA


48. Ning, T.: Homogenization of the synthetic water vapour time series using the penalized maximal t test modified to account for first-order autoregressive noise, 2nd Workshop of the COST Action 1206 sub-Working Group on Data Homogenisation, 23-25/01/2017, Warsaw, Poland.

49. Ning, T. and Elgered G.: Homogenization of the GPS-derived water vapour time series using the penalized maximal t test modified to account for first-order autoregressive noise, COST Action ES1206 "GNSS4SWEC" Final Workshop, 21-23/02/2017, Noordwijk, Netherlands


56. Pacione R., Long-Term Ground-Based GNSS Tropospheric Products for Climate, invited presentation at IAG Workshop Satellite Geodesy for Climate Studies, Bonn, Germany, September 19-21, 2017

57. Pacione R. and Dousa J., Geodesy and Atmospheric Science: a collaboration mutually beneficial, invited presentation at IX Hotine-Marussi Symposium, Rome, 18-22 June, 2018


65. Stepniak K., Bock O., Wielgosz P., Reduction of ZTD outliers through improved GNSS data processing and screening strategies, COST Action ES1206 GNSS4SWEC final workshop, 21-23.02.2017, ESTEC, Noordwijk, Netherlands


67. Stepniak K., Bock O., Improved GNSS processing and screening for ZTD monitoring in national network, AGU Fall Meeting, 12-16.12.2016, San Francisco, USA


70. Stepniak K., Bogusz J., Klos A., Wielgosz P., Assessment of tropospheric delay estimation methods on Precise Point Positioning time series, 26th IUGG General Assembly, 22.06-2.07.2015, Prague, Czech Republic

71. Stepniak K., Bock O., Wielgosz P., Assessment of ZTD screening methods and analysis of water vapour variability over Poland, COST ES1206 Workshop, 11-14 May 2015, Thessaloniki, Greece


81. Van Malderen R., and Pottiaux E.: Robust, non-parametric techniques for the identification of change-points in the mean, 2nd Workshop of the COST Action 1206 sub-Working Group on Data Homogenisation, 23-25/01/2017, Warsaw, Poland.


90. Van Malderen R., Berekmans J., Pottiaux E., and Pacione R., "Evaluation of the atmospheric water vapor content in the regional climate model ALARO-0 using GNSS observations from EPN Repro2", European Geosciences Union General Assembly 2018, Vienna, Austria, 8–13 April 2018