EPN Repro2: A reference GNSS tropospheric dataset over Europe.

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Abstract. The present availability of 18+ years of GNSS data belonging to the EUREF Permanent Network (EPN, http://www.epncb.oma.be/) is a valuable database for the development of a climate data record of GNSS tropospheric products over Europe. This data record can be used as a reference 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. In the framework of the EPN-Repro2, the second reprocessing campaign of the EPN, five Analysis Centres homogenously reprocessed the EPN network for the period 1996-2014. A huge effort has been made 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. This paper is focused on the EPN Repro2 tropospheric product. The combined product is described along with its evaluation against radiosonde data and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim) data.

1. Introduction

The EUREF Permanent Network (Bruyninx et al., 2012; Ihde et al., 2013) is the key geodetic infrastructure over Europe currently made by over 280 continuously operating GNSS reference stations maintained on a voluntary basis by EUREF (International Association of Geodesy Reference Frame Sub-Commission for Europe, http://www.euref.eu) members. Since 1996, GNSS data collected at the EUREF Permanent Network have been routinely analysed by several (currently 16) EPN Analysis Centres (Bruyninx C. et al., 2015). For each EPN station, observation data along with metadata information as well as precise coordinates and Zenith Total Delay (ZTD) parameters are publicly available. Since June 2001, the EPN Analysis Centres (AC) routinely estimate tropospheric Zenith Tropospheric Delays (ZTD) in addition to station coordinates. The ZTD, available in daily SINEX TRO files, are used by the coordinator of the EPN tropospheric product to generate each week the final EPN solution containing the combined troposphere estimates with an hourly sampling rate.

The coordinates, as a necessary part of this file, are taken from the EPN weekly combined SINEX (http://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/Sinex Format/sinex.html) file. Hence, stations without estimated coordinates in the weekly SINEX file are not included in the combined troposphere solution. The generation of the weekly combined products is done for the routine analysis. Plots of the ZTD time series and ZTD monthly mean as well as comparisons with respect to radiosonde data are available in a dedicated section at the EPN Central Bureau web site (http://www.epncb.oma.be/_productsservices/sitezenithpathdelays/). Radiosonde profiles are provided by EUMETNET as an independent dataset to validate GPS (NAVSTAR Global Positioning System) ZTD data, and are exchanged between EUREF and EUMETNET for scientific purposes based on a Memorandum of Understanding between the two mentioned organisations, (http://www.euref.eu/documentation/MoU/EUREF-EUMETNET-MoU.pdf).

However, such time series are affected by inconsistencies due to updates of the reference frame and applied models, implementation of different mapping functions, use of different elevation cut-off angles and any other updates in the processing strategies, which causes inhomogeneities over time. To reduce processing-related inconsistencies, a homogenous reprocessing of the whole GNSS data set is mandatory and, for doing it properly, well-documented, long-term metadata set is required.

This paper is focused on the tropospheric products obtained in the framework of the second EPN Reprocessing campaign (hereafter EPN-Repro2), where, using the latest available models and analysis strategy, GNSS data of the whole EPN network have been homogeneously reprocessed for the period 1996-2014. The EPN homogeneous long-term GNSS time series can be used as a reference dataset for a variety of scientific applications in meteorological and climate research. Ground-based GNSS meteorology, Bevis et al. (1992), is very well established in Europe and dates back to the 90s. It started with the EC 4th Framework Program (FP) projects WAVEFRONT (GPS Water Vapour Experiment For Regional Operational Network Trials) and MAGIC (Meteorological Applications of GPS Integrated Column Water Vapour Measurements in the western Mediterranean) Project (Haase et al., 2001). Early this century the ability to estimates ZTDs in Near Real Time was demonstrated (COST-716, 2005), and the EC 5th FP scientific project TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) funded. Since 2005, the operational production of tropospheric delays has been coordinated and monitored by the EUMETNET EIG GNSS Water Vapour Programme (E-GVAP, 2005-2017, Phase I, II and III, http://egvap.dmi.dk). Guerova et al. (2016) report on the state-of-the-art and future prospects of the ground-based GNSS meteorology in Europe. On the other hand, the use of ground-based GNSS long-term data for climate research is still an emerging field.

To promote the use of reprocessed long-term GNSS-based tropospheric delay data sets for climate research is one of the objectives of the Working Group 3 'GNSS for climate monitoring' of the EU COST Action ES 1206 'Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)', launched for the period of 2013–2017. The Working Group 3 enforces the cooperation between geodesists and climatologists in order to generate recommendations on optimal GNSS reprocessing algorithms for climate applications and standardise the method of conversion between propagation delay and atmospheric water vapour, Saastamoinen, (1973), Bevis et al., (1992), Bock et al. (2015), with respect to climate standards. For climate application, maintaining long-term stability is a key issue. Steigenberger et al. (2007) found that the lack of consistencies over time due to changes in GNSS processing could cause inconsistencies of several millimetres in GNSS-derived Integrated Water Vapour (IWV) making climate trend analysis very challenging. Jin et al. (2007) studied the seasonal variability of GPS Zenith Tropospheric Delay (1994-2006) over 150 international GPS stations and showed the relative trend in northern hemisphere and southern hemisphere as well as in coastal and inland areas. Wang and Zhang (2009) derived GPS Precipitable Water Vapour (PWV) using the International GNSS Service (IGS), Dow et al. (2009), tropospheric products at about 400 global sites for the period 1997-2006 and analysed PWV diurnal variations. Nilsson and Elgered (2008) showed PWV changes from -0.2 mm to +1.0 mm in 10 years by using the data from 33 GPS stations located in Finland and Sweden. Sohn and Cho (2010) analysed GPS Precipitable Water Vapour trend in South Korea for the period 2000-2009 and examined the relationship between GPS PWV and temperature, which is the one of the climatic elements. Better information about atmospheric humidity, particularly in climate-sensitive regions, is essential to improve the diagnosis of global warming, and for the validation of climate predictions on which socio-economic response strategies are based with strong societal benefits. Suparta (2012) reported on the validation of PWV as an essential tool for solar-climate studies over tropical region. Ning et al. (2013) used 14 years of GPS-derived IWV at 99 European sites to evaluate the regional Rossby Centre Atmospheric (RCA) climate model. GPS monthly mean data were compared against RCA simulation and the ERA Interim data. Averaged over the domain and the 14 years covered by the GPS data, they found IWV differences of about 0.47 kg/m^2 and 0.39 kg/m^2 for RCA-GPS and ECMWF-GPS, with a standard deviation of 0.98 kg/m^2 whereas it is 0.35 kg/m^2 respectively. Using GNSS atmospheric water vapour time series, Alshawaf et al. (2016) found a positive trend at more than 60 GNSS sites in Europe with an increase of 0.3-0.6 mm/decade with a temporal increment correlated with the temporal increase in the temperature levels.

In this scenario, EPN Repro2 tropospheric product is a unique dataset for the development of a climate data record of GNSS tropospheric products over Europe, suitable for analysing climate trends and variability, and calibrating/validating independent datasets at global and regional scales. However, although homogenously reprocessed, this time series suffer from site-related inhomogeneity due, for example, to instrumental changes (receivers, cables, antennas, and radomes), changes in the station environment, which can affect the analysis of the long-term variability (Vey et al. 2009). Therefore, to get realistic and reliable climate signals such change points in the time series needs to be detected (Ning et al, 2016a).

This paper describes the EPN-Repro2 reprocessing campaign in Section 2. Section 3 is devoted to the combined solutions, i.e. the official EPN-Repro2 products, while in Section 4 the combined solutions is evaluated w.r.t. Radiosonde and ERA-Interim data. Summary and recommendations for future reprocessing campaign are drown in Section 5.

2. EPN second reprocessing campaign

EPN-Repro2 is the second EPN reprocessing campaign organized in the framework of the special EUREF project "EPN reprocessing". The first reprocessing campaign, which covered the period 1996-2006, Voelksen (2011), involved the participation of all sixteen EPN Analysis Centres (ACs) reprocessing their own EPN sub-network. This guarantees that each site is processed by three ACs at least which is an indispensable condition for proving a combined product. The second reprocessing campaign covered all the EPN stations, which were operated from January 1996 through December 2013. Then, participated ACs decided to extend this period until the end of 2014 for troposphere products. Data from about 280 stations in the EPN historical database have been considered. As of December 2014, 23% of EPN stations are between 18-15 years old, 26% are between 14-10 years old, 30% between 10-5 years old, and 21% less than 5 years old. Only five, over sixteen, EPN ACs (see Table 1) took part in EPN-Repro2 each providing one reprocessed solution at least. One of the goal of the second reprocessing campaign was to test the diversity of the processing methods in order to ensure verification of the solutions. For this reason, the three main GNSS software packages Bernese (Dach et al., 2014), GAMIT (King et al., 2010) and GIPSY-OASIS II (Webb et al., 1997) have been used to reprocess the whole EPN network and several variants have been provided in addition. In total, eight individual contributing solutions, obtained using different software and settings, and covering different EPN networks, are available. Among them, three are obtained with different software and cover the full EPN network while three are obtained using the same software (namely Bernese) and covering different EPN networks. In Table 2 the processing characteristics of each contributing solution are reported. Despite the software used and the analysed networks, there are a few diversities among the provided solutions, whose impact needs to be evaluated before performing the combination. As far as the GNSS products used in the reprocessing campaign all the ACs used

CODE Repro2 product (Lutz et al., 2014) with one exception (see Table 2) where JPL Repro2 products (Desai et al., 2014) are used. For tropospheric modelling two mapping functions are used: GMF (Boehm et al., 2006a) and VMF1 (Boehm et al., 2006b), whose impact has been evaluated in Tesmer et al., 2007.

2.1 Impact of GLONASS data

GPS data are used by all ACs in this reprocessing campaign, while two of them (namely IGE and LPT) reprocessed GPS and GLONASS (Global'naja Navigacionnaja Sputnikovaja Sistema) observations. The impact of GLONASS observations has been evaluated in terms of raw differences between ZTD estimates as well as on the estimated linear trend derived from the ZTD time series. Two solutions were prepared and compared. Both were obtained using the same software and the same processing characteristics except the observation data: one with GPS and GLONASS, and one with GPS data only. GLONASS observations are available since 2003, but only from 2008 onwards the amount of GLONASS data (see Figure 1) is significant. The difference in terms of the ZTD trends (Figure 2) between a GPS-only and a GPS+GLONASS solution shows no significant rates for more than 100 stations (rates usually derived from more than 100000 ZTD differences. This indicates that the inclusion of additional GLONASS observations in the GNSS processing has a neutral impact on the ZTD trend analysis. Satellite constellations are continuously changing in time due to satellites being replaced are newly added for all systems. This result is a positive sign that climate trends can be determined independently of the satellite systems used in the processing. In near future the inclusion of additional Galileo (Satellite System in Europe) and BeiDou (Satellite system in China) data will become operational in the GNSS data processing. These data will certainly improve the quality of the tropospheric products but, hopefully, will not introduce systematic changes in terms of ZTD trends as a possible climate indicator.

2.2 Impact of IGS type mean and EPN individual antenna calibration models

According to the processing options listed in the EPN guidelines for the Analysis Centre (http://www.epncb.oma.be/_documentation/guidelines/guidelines_analysis_centres.pdf), when available EPN individual antenna calibration models have to be used instead of IGS type mean calibration models. Currently, individual antenna calibration models are available at about 70 EPN stations. As reported in Table 2 there are individual solutions carried out with IGS type mean antenna calibration models (Schmid et al., 2015) only and others with IGS type mean plus EPN individual antenna calibration models. It may happen that for the same station there are contributing solutions obtained applying different antenna models. To evaluate the impact of using these different antenna calibration models on the ZTD, two solutions were prepared and compared. Both were obtained using the same software and the same processing characteristics except the calibration models. First one used the IGS type mean models only, while second one used the individual calibrations whenever it was possible and IGS type mean for the rest of the antennas. An example of the time series of the ZTD difference obtained applying 'Individual' and 'Type Mean' antenna calibration models for the EPN station KLOP (Kloppenheim, Frankfurt, Germany) is shown in Figure 3. KLOP station is included in the EPN network since June, 2nd 2002, a TRM29659.00 antenna with no radome was installed. Two instrumentation changes occurred at the station: the first in June 27th 2007, when the previous antenna was replaced with a TRM55971.00 and a TZGD radome, the second in June 28th 2013 with the installation of a TRM57971.00 and a TZGD radome. For all of them the individual calibrations are available through the data sets compiled by the EPN Central Bureau (ftp://epncb.oma.be/pub/station/general/epnc_08.atx). Switching between phase centre corrections from type mean to individual (or vice versa) causes a disagreement in the estimated height of the stations, as it mentioned by Araszkiewicz and Voelksen (2016), as well as in their ZTD time series. Depending on the antenna model, the offset at station KLOP in the up component is -5.2 ± 0.5 mm, 8.7 ± 0.6 mm and 5.6 ± 0.8 mm with a corresponding offset in the ZTD of 0.2 ± 0.5 mm, -1.5 ± 0.5 mm, -1.4 ± 0.8 mm, respectively. Similar situation appears also for all stations/antennas for which individual calibration models are available. The corresponding offset in the ZTD has opposite sign for the antennas with offset in the up component larger than 5 mm (16 antennas) and, generally, not exceeding 2 mm for ZTD. Such inconsistence in the ZTD time series are not large enough to be captured during the combination process (see Section 3) where 10 mm threshold in the ZTD bias (about 1.5 kg/m^2 IWV) is set in order to flag problematic ACs or stations.

2.3 Impact of non-tidal atmospheric loading

As reported in the IERS Convention (2010), the diurnal heating of the atmosphere causes surface pressure oscillations at diurnal S1, semidiurnal S2, and higher harmonics. These atmospheric tides induce periodic motions of the Earth's surface (Petrov and Boy, 2004). The conventional recommendation is to calculate the station displacement using the Ray and Ponte (2003) S2 and S1 tidal model. However, crustal motion related to non-tidal atmospheric loading has been detected in station position time series from space geodetic techniques (van Dam et al., 1994; Magiarotti et al., 2001, Tregoning and Van Dam, 2005). Several models of station displacements related to this effect are currently available. Non-tidal atmospheric loading models are not yet considered as Class-1 models by the International Earth Rotation and Reference Systems Service (IERS 2010) indicating that there are currently no standard recommendations for data reduction. To evaluate their impact, two solutions, one without and one with non-tidal atmospheric loading, have been compared for the year 2013. In the last one, the National Centers for Environmental Prediction (NCEP) model is used at the observation level during data reduction (Tregoning and Watson, 2009).

Dach et al. (2010) have already found that the repeatability of the station coordinates improves by 20% when applying the effect directly on the data analysis and by 10% when applying a post-processing correction to the resulting weekly coordinates compared with a solution without considering these corrections. However, the effect of applying non-tidal atmospheric loading on the ZTD seems to be negligible. Generally, it causes a difference below 0.5 mm with a scattering not larger than 0.3 mm. The difference is thus below the level of confidence. Figure 4 shows time series of the differences of the ZTD and up component between two time series obtained with and without non-tidal atmospheric loading for two EPN stations: KIR0 (Kiruna, Sweden) and RIGA (Riga, Latvia). There is also no correlation between values of estimated differences and vertical displacements caused by non-tidal atmospheric loading. Correlation coefficients for analysed EPN stations were below 0.2.

3. EPN Repro2 combined solutions

The EPN ZTD combined product is obtained applying a generalized least square approach following the scheme described in Pacione et al. (2011). The first step in the combination process is reading and checking the SINEX TRO files delivered by the ACs. At this stage, gross errors (i.e. ZTD estimates with formal sigma larger than 15 mm) are detected and removed. The combination starts if at least three different solutions are available for a single site. Then, a first combination is performed to compute proper weights for each contributing solution to be used in the final combination step. In this last step the combined ZTD estimates, their standard deviations and site/AC specific biases are determined. The combination fails if, after the first or second combination level, the number of ACs become less than three. Finally, ZTD site/AC specific biases exceeding 10 mm are investigated as potential outliers.

The EPN-Repro2 combination activities were carried out in two steps. First, a preliminary combined solution for the period 1996-2014 was performed taken as input all the available eight homogeneously reprocessed solutions (see Table 2). The aim of this preliminary combined solution is to assess each contributing solution and to investigate site/AC specific biases prior to the final combination, flag the outliers and send a feedback to the ACs. The agreement of each contributing solution w.r.t. the preliminary combination is given in terms of bias and standard deviation (not showed) As far as the standard deviation is concerned, it is generally below 2.5 mm with a clear seasonal behaviour, while the bias is generally in the range of +/- 2 mm. However, there are several GPS weeks for which the bias and standard deviation values exceeded the before mentioned limits. To investigate these outliers, the time series of site/AC specific bias has been studied, since it can be a useful tool to detect bad periods of data and provide information useful for cleaning the EPN historical archive. An example is given in Figure 5 for the station VENE (Venice, Italy) for three contributing solutions AS0, GO4 and MU2 (G00 and GO1 are not shown but are very close to GO4). In the first years of acquisition, tracking issues were experienced at VENE, which are clearly mirrored in the bias time series.

All the site/AC specific biases are divided into three groups: the red group contains site/AC specific biases whose values are larger than 25 mm, the orange group contains site/AC specific biases in the range of [15 mm, 25 mm] and the yellow group contains site/AC specific biases in the range of [10 mm, 15 mm]. In Table 3 summarizes percentages of red, orange and yellow biases for each contributing solution. The majority of biases belong to the yellow group; the percentage of biases in the orange group ranges from 12% for LP0 and LP1 solutions to 27% for AS0 solution, while percentage of biases in the red group ranges from 3% for MU4 solution to 22% for IG0 solution.

The final EPN Repro2 tropospheric combination is based on the following input solutions: AS0, GO4, IG0, LP1 and MU2. MUT AC provided the MU2 solution after the preliminary combination, its only difference with respect to MU4 is the use of type mean antenna and individual calibration models, whose effect is shown in section 2.2. The agreement in terms of bias and standard deviation of each contributing solution w.r.t. the final combination is shown in Figure 6. As regard as the standard deviation, there is a clear improvement with respect to the preliminary combination due to the removal of the outliers detected during the preliminary combination. The standard deviation is below 3 mm from GPS week 835-1055 and 2 mm after. This is somehow related to the worse quality of data and products during the first years of the EPN/IGS activities.

The final EPN Repro2 tropospheric combination is consistent to the final coordinate combination performed by the EPN Analysis Centre Coordinator. During the coordinate combination all stations were analyzed by comparing their coordinates for specific ACs and the preliminary combined values. In case where the differences were larger than 16 mm in the up component, the station was eliminated and the whole combination was repeated, up to three times, if necessary. This ensures the consistency of final coordinates at the level of 16 mm in the up component (Figure 7). As a rule of thumb, 9 mm in the height component (i.e. 3 mm in ZTD as explained in Santerre, 1991) are needed to fulfill the requirement of retrieving IWV at an accuracy level of 0.5 kg/m2 (Bevis et al., 1994), Ning et al (2016b). As shown in Figure 7, only one site, MOPI (Modra Piesok, Slovakia), exceed this threshold on a long term. As reported at the EPN Central Bureau, MOPI has been excluded several times from the routine combined solutions. MOPI has very bad periods of observations in past due to radome manipulation that caused jumps in the height component. However, several stations exceeded it temporary during bad periods, as shown in Figure 8 for VENE (Venezia, Italy).

4. Evaluation of the ZTD Combined Products with respect to independent data set

The evaluation with respect to other sources or products, such as Radiosonde data from the E-GVAP and numerical weather re-analysis from the European Centre for Medium-Range Weather Forecasts, ECMWF (ERA-Interim), provides a measure of the accuracy of the ZTD combined products.

4.1 Evaluation versus radiosonde

For the GPS and Radiosonde comparisons at the EPN collocated sites, we used profiles from the World Meteorological Organization provided by EUMETNET in the framework of the Memorandum of Understanding between EUREF and EUMETNET. Radiosonde profiles are processed using the software (Haase et al., 2003) that checks the quality of the profiles, converts the dew point temperatures to specific humidity, transforms the radiosonde profile to correct for the altitude offset between the GPS and the radiosonde sites and determines ZTD, ZWD and IWV compensating for the change of gravitational acceleration, g, with height.

Figure 9 shows an example for the EPN site CAGL (Cagliari, Sardinia Island, Italy). For all the 183 EPN collocated sites, and using all the data available in the considered period, we computed an overall bias and standard deviation (Figure 10). The sites are sorted according to the increasing distances from the nearest Radiosonde launch site. MALL (Palma de Mallorca, Spain) is the closest (0.5 km to Radiosonde code 8301) while GRAZ (Graz, Austria) is the most distant (133 km to Radiosonde code 14015). The amount of data available for the comparisons varies between sites depending on the availability of the GPS and Radiosonde ZTD estimates in the considered epoch and it ranges from 121 for VIS6 (Visby, Sweden, integrated in the EPN since 22-06-2014) up to 21226 for GOPE (Ondrejov, Czech Republic, integrated in the EPN since 31-12-1995).

The bias ranges from -0,87%, which corresponds to -21,2 mm, (at EVPA, Ukraine, and distance from the Radiosonde launch site 96.5 km, Radiosonde code 33946) to 0,68%, which corresponds to 15,4 mm, (at OBER, Germany, and distance from the Radiosonde launch site 90.8 km, Radiosonde code 11120). The mean bias for all sites is -0,6 mm with standard deviation of 4.9 mm. For the more than 75% (178 pairs), the agreement is below 5 mm and only 5.5% (13 pairs) have bias higher than 10 mm. The higher biases concern mostly the pairs over 50 km away from each other, like GPS stations OBER, OBE2 and OBET located in Oberpfaffenhofen (Germany) and collocated with Radiosonde (VRS90L code 11120) launched from Innsbruck Airport in Austria on the opposite side of North Chain in the Karwendel Alps. Our results are at odds with Wang et al. (2007), where authors compared PW from GPS and global Radiosonde. In contrast to them, we received small negative bias

-1.19 mm for Vaisala Radiosondes, which is the most common type used in Europe (81% of all used in this study). For MRZ, GRAW and M2K2 Radiosonde type, which represent 4.6%, 3.4% and 3.0% of compared Radiosondes respectively, we received systematic positive bias. However, Wang et al. (2007) used global Radiosonde data from 2003 and 2004, while we used all available data over Europe from 1994 to 2015. This can partly explain the disagreement even though more analysis deserves to be done. Further investigation is also needed for several near or moved GPS stations. For example in Brussels (Belgium) BRUS station, included in the EPN network since 1996, was replaced by BRUX in 2012. Their bias w.r.t. the same Radiosonde (VRS80L code 6447) has opposite sign (-1.2 mm and 3.4 mm respectively). A possible explanation is the different time span over which the bias has been computed (1996-2012 for BRUS, 2012-2015 for BRUX).

In agreement with Ning et al. 2012, the standard deviation generally increases with the distance from the Radiosonde launch site. It is in the range of [0,16; 0,76] % ,which corresponds to [3; 18] mm, till 15 km (first band in Figure 10); [0,29;0,78] % ,which corresponds to [7; 19] mm, till 70 km (second band in Figure 10) and [10; 33] mm till 133 km (third band in Figure 10). The evaluation of the standard deviation is comparable with previous studies. Haase et al. (2001) showed very good agreement with biases less than 5 mm and the standard deviation of 12 mm for most of analysed sites in Mediterranean. Similar results (6.0 mm ± 11.7 m) were obtained also by Vedel et al. (2001). Both of them based on non-collocated pairs distant less than 50 km. Pacione et al (2011), considering 1-year of GPS ZTD and Radiosonde data over the E-GVAP super sites network, obtained a standard deviation of 5-14 mm. Dousa et al. 2012 evaluated ZTD and Radiosonde on a global scale over 10-month period and reported a standard deviation of 5–16 mm.

The assessment of the EPN Repro1 ZTD product with respect to Radiosonde using the same period, i.e. 1996-2014 when completed with the EUREF operational product after GPS week 1407 (December 30, 2006), and EPN Repro2 with respect to the Radiosonde data has an improvement of approximately 3-4% in the overall standard deviation.

4.2 Evaluation versus ERA-Interim data

ERA-Interim (Dee et al., 2011) from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used as Numerical Weather Prediction (NWP) model data. The ERA-Interim is a re-analysis product available every 6 hours (00, 06, 12, 18 UTC) with a horizontal resolution of 1×1 degree and 60 vertical model levels.

For the period 1996-2014 and for each EPN station, ZTD and tropospheric linear horizontal gradients were computed using the GFZ (German Research Centre for Geosciences) ray-tracing software (Zus et al., 2014). Combined EUREF Repro1 and Repro2 products as well as individual ACs tropospheric parameters were assessed with the corresponding parameters estimated from the NWM re-analysis. The evaluation of GNSS and NWM was performed using the GOP-TropDB (Gyori and Dousa, 2016) via calculating parameter differences for pairs of stations using values at every 6 hours (00:00, 6:00, 12:00 and 18:00) as available from the NWM product. A linear interpolation from values -/+ 30 min was thus necessarily applied for all GNSS products providing HH:30 timestamps as required for the combination process. As all compared GNSS products has the same time resolution (1 hour), the interpolation is assumed to affect all products in the same way. Therefore, we assume all inter-comparisons to a common reference (NWM) principally reflects the quality of the products. No vertical corrections were applied since NWM parameters were estimated for the long-term antenna reference position of each station.

Table 4 summarizes the mean total statistics of individual (ACs) and combined (EUREF) tropospheric parameters, ZTDs and horizontal gradients, over all available stations. The EUREF combined solution does not provide tropospheric gradients and these could be evaluated for individual solutions only. In Table 4, we can observe a common ZTD bias of about -1.8 mm for all GNSS solutions compared to the ERA-Interim, however still highly varying for individual stations as obvious from estimated uncertainties. ZTD standard deviations are generally at the level of 8 mm between GNSS and NWM products, but for IG0 solution performing about 25% worse than others as already detected during the combination. Two solutions, AS0 and LP1 are slightly better than GO4 and MU2 – reaching the standard deviation of 7.7 mm their accuracy is at the level of the EUREF combined solution. The better performance of the AS0 solution can be considered due to its theoretical better capability of the modelling true dynamics in the troposphere as the solution applied a stochastic troposphere modelling using undifference observations sensitive to the absolute tropospheric delays. On the other hand, LP1 included roughly one third from of EPN stations which were properly selected according to the station quality thus making a difficulty to interpret the difference with respect to those processing full EPN.

The comparison of tropospheric linear horizontal gradients (East and North) from GNSS and NWM revealed a problem with the MU2 solution showing a high inconsistency of results over different stations, which is not visible in the total statistics, but mainly in the uncertainties by an order higher compared to all others. Geographical plot (not showed) confirmed this site-specific systematic, but in both positive and negative senses. The impact was however not observed in MU2 ZTD results. Additionally, the GO4 solution performed slightly worse than the others. It was identified as a consequence of estimating 6-hour gradients using the piece-wise linear function and without any absolute or relative constraints. In such case, higher correlations with other parameters occurred raising uncertainties of the estimates. For this purpose, the GO6 solution (not showed) was derived fully compliant with the GO4, but stacking tropospheric gradients into 24 hours piece-wise linear modelling. By comparing the GO6 (Dousa and Vaclavovic, 2016), the standard deviations dropped from 0.38 mm to 0.28 mm and from 0.40 mm to 0.29 mm for East and North gradients, respectively which corresponds to the LP1 solution applying the same settings. Additionally, Dousa and Vaclavovic, 2016 found a strong impact of a low-elevation receiver tracking problem on estimation of horizontal gradients which was particularly visible when compared to the ERA-Interim. Systematic behaviour in monthly mean difference in gradient seems to be a useful indicator for instrumentation-related issues and should be applied as one of the tools for cleaning the EPN historical archive.

For completeness, we evaluated also EPN Repro1 ZTD product with respect to the ERA-Interim using the same period, i.e. 1996-2014 when completed with the EUREF operational product after GPS week 1407 (December 30, 2006). Comparing EPN Repro1 and EPN Repro2 with the numerical weather re-analysis showed the 8-9% improvement of the latter in both overall standard deviation and systematic error. Figure 11 shows distributions of station means and standard deviations of EPN Repro1 and EPN Repro2 ZTDs compared to NWM ZTDs using the whole period 1996-2014. Common reductions of both statistical characteristics are clearly visible for the majority of all stations. From data of Figure 11, we also expressed site-by-site improvements in terms of ZTD bias, standard deviation and RMS (Figure 12). Calculated medians reached 21.1 %, 6.8 % and 8.0 %, respectively, which corresponds to the abovementioned improvement of 8-9 %. The degradation of standard deviation was found at three stations: SKE8 (Skellefteaa, Sweden, integrated in the EPN since 28-09-2014), GARI (Porto Garibaldi, Italy, integrated in the EPN since 08-11-2009) and SNEC (Snezka, Czech Republic, former EPN station since 14-06-2009) all of them providing much less data compared to others, 1%, 30% and 3%, respectively. All other stations (290) showed improvements. We also found 72 stations with increased absolute bias in EUREF Repro1 compared to Repro2 while all others, 221 stations (75%), resulted in reduced systematic error.

Time series of monthly mean biases and standard deviations for ZTD differences of EPN Repro2 and the ERA-Interim is showed in Figure 13. The small negative bias slowly decreases towards 2014, but a high uncertainty of the mean indicates site-specific behaviour depending mainly on latitude and altitude of the EPN station and the quality of both NWM and GNSS products. There is almost no seasonal signal observed in time series of ZTD mean biases or the uncertainty, but clearly in ZTD standard deviation and the uncertainty. Slightly increasing standard deviation towards 2014 can be attributed to the increase of number of stations in EPN starting from about 30 in 1996 and with more than 250 in 2014. More stations reduces a variability in monthly mean biases, however, site-specific errors then contribute more to higher values of standard deviation.

Figure 14 displays the geographical distribution of total ZTD biases and standard deviations for all sites. Prevailing negative biases seem to become lower or even positive in the mountain areas. There is no latitudinal dependence observed for ZTD biases in Europe, but a strong one for standard deviations. This corresponds mainly to the increase of water vapour content and its variability towards the equator.

5. Conclusion

In this paper, we described the activities carried out in the framework of the EPN second reprocessing campaign. We focused on the tropospheric products homogenously reprocessed by five EPN Analysis Centres for the period 1996-2014 and we described the ZTD combined products.

Both individual and combined tropospheric products along with reference coordinates and other metadata, are stored in SINEX TRO format, Gendt, G. (1997), and are available to the users at the EPN Regional Data Centres (RDC), located at BKG (Federal Agency for Cartography and Geodesy, Germany). For each EPN station, plots on ZTD time series, ZTD monthly mean, comparison versus Radiosonde data (if collocated), and comparison versus the ERA-Interim data will be available at the EPN Central Bureau (Royal Observatory of Belgium, Brussels, Belgium).

Assessment of the EPN Repro1 and Repro2 with respect to the Radiosonde data has an improvement of approximately 3-4% in the overall standard deviation.

Assessment of the EPN Repro1 and Repro2 with respect to the ERA-Interim re-analysis showed the 8-9% improvement of the latter over the former in both overall standard deviation and systematic error which was obvious for majority of the stations. Comparisons of the GNSS solutions with the NWM, i.e. independent source, showed the overall agreement at the level of 8-9 mm, however, rather site-specific ranging from 5 mm to 15 mm for standard deviations and from -7 mm to 3 mm for biases considering 99% of results roughly.

The use of ground-based GNSS long-term data for climate research is an emerging field. For the assessment of Euro-CORDEX (Coordinated Regional Climate Downscaling Experiment) climate model simulation IGS Repro1, Byun and Bar-Sever, (2009), has been used as reference reprocessed GPS products (Bastin et al. 2016). However, this data set is quite sparse over Europe (only 85 stations over the 280 EPN stations) and covers the period 1996-2010. According to Wang et al. (2007) IGS ZTD products are valuable source of water vapor data for climate and weather studies. The GPS PW is useful also for monitoring the quality of the radiosonde data. However, a better spatial coverage of the GNSS PW data is needed to investigate and reduce systematic biases in comparison with the global radiosonde humidity data (Wang and Zhang, 2009). On the other hand extending the observation period and complement of temporal coverage is necessary to calculate more reliable mean values and trends. As it was pointed by Baldysz et al. (2015, 2016) additional two years of ZTD data can change estimated trends up to 10%. Therefore, data after 2010 and with a better coverage over Europe are required for improving the knowledge of climatic trends of atmospheric water vapour in Europe. In this scenario, EPN-Repro2 can be used as a reference data set with a high potential for monitoring trend and variability in atmospheric water vapour.

Considering five EPN stations, among those with the longest time span, GOPE (Ondrejov, Czech Republic, integrated in the EPN since 31-12-1995), METS (Kirkkonummi, Finland, integrated in the EPN since 31-12-1995), ONSA (Onsala, Sweden, integrated in the EPN since 31-12-1995), PENC (Penc, Hungary, integrated in the EPN since 03-03-2096) and WTZR (Bad Koetzting, Germany, integrated in the EPN since 31-12-1995), we have computed ZTD trends using EPN Repro2, EPN Repro1 completed with the EUREF operational products, radiosonde and ERA-Interim data. All of them are also in the IGS Network, for which IGS Repro1 completed with the IGS operational products are available and extracted from the GOP-TropDB. First we have removed annual signal from the original time series and marked all outliers according to 3-sigma criteria. Then for all GPS ZTD data sets we have estimated all well-known and recognized shifts related to the antenna replacement. No other unexplained breaks has been removed to be sure that we not introduce any artificial errors. Based on the cleaned and filtered data we have used linear regression model before and after the considered epoch independently. The difference between those two models in specific epoch is considered as a shift. Then, we have removed all the estimated shifts from the original time series. Generally, the size of the shifts is much lower than noise level and depends on the applied method of its estimation. Therefore, the final results are affected by used methodology and cannot be considered as an absolute values. No homogenization has been done for radiosonde since radiosonde metadata are not available. Finally, a LSE method have been applied to estimate linear trends and seasonal component. ZTD trends (Figure 15) for all three GPS ZTD data sets are consistent, as soon as the same homogenisation procedure is applied. Then overall RMS is 0.02 mm/year. Among all five ZTD sourced, we find the best agreement for ONSA (RMS=0.04mm/year) and WTZR (RMS=0.02mm/year). For PENC we have good agreement with respect to ERA-Interim (0.05 mm/year), but a large discrepancy versus radiosonde (-0.31 mm/year). This large discrepancy is probably due to the distance to the radiosonde launch site (40.7 km, radiosonde code 12843) and to the lack of the homogenisation stage. Over the five considered stations the agreement with respect to ERA-Interim (RMS = 0.11 mm/year) is better than that with respect to radiosonde (RMS = 0.16

mm/year). Even though for the five considered stations EPN Repro2 do not change significantly the detection of ZTD trends, it has a better agreement with respect to radiosonde and ERA-Interim data than EPN Repro1.It has also the best spatial resolution than IGS Repro1 and radiosonde data, which are used today for long-term analysis over Europe. Taking into account the good consistency among trends, EPN Repro2 can be used for trend detection in areas where other data are not available.

Comparisons with regional climate model simulations is one of the application of EPN-Repro2. Ongoing at Sofia University is comparison between GNSS IWV, computed from EPN-Repro2 ZTD data for SOFI (Sofia, Bulgaria), and ALADIN-Climate IWV simulations conducted by the Hungarian Meteorological Service, for the period 2003-2008. The preliminary results show a tendency of the model to underestimate IWV. Clearly, larger number of model grid points need to be investigated in different regions in Europe and the EPN-Repro2 data is well suited for this. Climate research is not only limited to comparison with climate model and derivation of trends. At the Met Office, the UK's national weather service, within the framework of the European FP7 project UERRA (Uncertainties in Ensembles of Regional Re-analysis, http://www.uerra.eu/), assimilation trials of reprocessed ZTD into a 12 km European climate reanalysis beginning in 1979 are ongoing. To account for any systematic bias or bias change, the reprocessed ZTDs will have a bias correction applied before assimilation.

The reprocessing activity of the five EPN ACs was a huge effort generating homogeneous products not only for station coordinates and velocities, but also for tropospheric products. The knowledge gained will certainly help for a next reprocessing activity. A next reprocessing will most likely include Galileo and BeiDou data and therefore it will be started in some years from now after having successfully integrated these new data in the current operational near real-time and daily products of EUREF. The consistent use of identical models in various software packages is another challenge for the future to be able to improve the consistency of the combined solution. Prior any next reprocessing, it was agreed in EUREF to focus on cleaning and documenting data in the EPN historical archive as it should highly facilitate any future work. For this purpose, all existing information need to be collected from all the levels of data processing, combination and evaluation which includes initial GNSS data quality checking, generation of individual daily solutions, combination of individual coordinates and ZTDs, long-term combination for velocity estimates and assessments of ZTDs and gradients with independent data sources.

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4.2. All authors contributed to section 5. All authors approved the final manuscript before its submission.

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Table

Table Captions

Table 1: EPN Analysis Centres providing EPN Repro2 solutions**.**

Table 2: EPN Repro2 processing options for each contributing solutions. AS0 solutions provided by ASI/CGS (Matera, Italy), GO0, GO1 and GO4 solutions provided by GOP (Pecny, Czech Republic), IG0 solution provided by IGE (Madrid, Spain), LP0 and LP1 solutions provided by LPT (Waben, Switzerland), MU2 and MU4 solutions provided by MUT (Warsaw, Poland*).*

Table 3. Percentage of red, orange and yellow bias for each contributing solution**.**

Table 4. Mean statistics and uncertainties, calculated from results of individual stations, provided for AC individuals and EUREF combined (Repro1 and Repro2) tropospheric parameters compared to the ERA-Interim re-analysis.

AC	Full name	City	Country	SW	EPN Network
ASI	Agenzia Spaziale Italiana	Matera	Italy	GIPSY-OASIS II	Full EPN
GOP	Geodetic Observatory	Pecny	Czech Republic	Bernese	Full EPN
IGE	National Geographic Institute	Madrid	Spain	Bernese	EPN-Subnetwork
LPT	Federal Office of Topography	Wabern	Switzerland	Bernese	EPN-Subnetwork
MUT	Military University of Technology	Warsaw	Poland	GAMIT	Full EPN

Table 1: EPN Analysis Centres providing EPN Repro2 solutions.

	AS0	GO0	GO1	GO4	IG0	LP0	LP1	MU2	MU4
SW	GIPSY 6.2	Bernese 5.2			Bernese 5.2	Bernese 5.2		GAMIT 10.5	
GNSS	G	G			G + R	G + R		G	
SOLUTION TYPE	PPP	Network			Network	Network		Network	
STATIONS	Full EPN	Full EPN			EPN Subnetwork	EPN Subnetwork		Full EPN	
ORBITS	JPL R2	CODE R2			CODE R2	CODE R2		CODE R2	
ANTENNAS	IGS08	IGS08 + Individual.			IGS08+ Individual.	IGS08	IGS08 + Individual.	IGS08 + Individual	IGS08
IERS	2010	2010			2010	2010		2010	
GRAVITY	EGM08	EGM08			EGM08	EGM08		EGM08	
TROPOSPHERE Estimated Parameters	ZTD (5min) GRAD (5min)	ZTD (1h) GRAD (6h)			ZTD (1h) GRAD (6h)	ZTD (1h) GRAD (24h)		ZTD (1h) GRAD (24h)	
MAPPING FUNCTION	VMF1	GMF	VMF1	VMF1	GMF	GMF	VMF1	VMF1	
ZTD/GRAD time stamp	hh:30 24 estimates/day	hh:30 (and hh:00) 24(+24) estimates/day			hh:30 24 estimates/day	hh:30 (and hh:00) 24(+24) estimates/day		hh:30 24 estimates/day	
IONOSPHERE	HOI included	CODE, HOI included			CODE (HOI included)	CODE (HOI included)		CODE IONEX + IGRF11 (HOI included)	
REFERENCE. FRAME	IGb08	IGb08			IGb08	IGb08		IGb08	
OCEAN TIDES	FES2004	FES2004			FES2004	FES2004		FES2004	
TIDAL-ATMOSPHERIC LOADING	NO	NO			YES	YES	YES	YES	
NON-TIDAL-ATMOSPHERIC LOADING	NO	NO	NO	YES	NO	NO	YES	NO	
ELEVEVATION CUTOFF	3	3			3	3		5	
Delivered SNX_TRO Files [from week to week]	0834-1824	0836-1824			0835-1816	0835-1802		0835-1824	

Table 2: EPN Repro2 processing options for each contributing solutions. AS0 solutions provided by ASI/CGS (Matera, Italy), GO0, GO1 and GO4 solutions provided by GOP (Pecny, Czech Republic), IG0 solution provided by IGE (Madrid, Spain), LP0 and LP1 solutions provided by LPT (Waben, Switzerland), MU2 and MU4 solutions provided by MUT (Warsaw, Poland).

Solution	%Red bias	% Orange bias	% Yellow bias
AS0	17	27	56
G00	10	22	67
G01	12	23	65
G04	12	23	65
IG0	22	14	64
LP0	10	12	79
LP1	10	12	78
MU2	3	15	82

Table 3. Percentage of red, orange and yellow bias for each contributing solution.

Solution	ZTD bias [mm]	ZTD sdev [mm]	EGRD bias [mm]	EGRD sdev [mm]	NGRD bias [mm]	NGRD sdev [mm]
AS0 (full EPN)	-1.7±2.0	7.7±1.9	0.00±0.06	0.32±0.09	0.09±0.06	0.33±0.10
GO4 (full EPN)	-1.9±2.4	8.1±2.1	-0.04±0.09	0.38±0.10	0.00±0.09	0.40±0.12
MU2 (full EPN)	-1.8±2.0	8.3±2.1	-0.03±0.32	0.35±2.46	-0.01±0.84	0.34±2.37
IG0 (part EPN)	-1.6±2.3	10.7±2.2	-0.05±0.09	0.33±0.11	0.04±0.12	0.36±0.12
LP1 (part EPN)	-1.7±2.4	7.7±1.7	-0.02±0.06	0.28±0.05	0.03±0.09	0.27±0.06
EUR Repro2	-1.8±2.1	7.8±2.2	-	-	-	-
EUR Repro1	-2.2±2.3	8.5±2.1	-	-	-	-

Table 4. Mean statistics and uncertainties, calculated from results of individual stations, provided for AC individuals and EUREF combined (Repro1 and Repro2) tropospheric parameters compared to the ERA-Interim re-analysis.

Figure

Figure Captions

Figure 1. Time series of the number of GNSS observations for the period 1996-2014. GPS observations are shown in red, GPS+GLONASS in blue and their differences in green. The difference is significant starting 2008.

Figure 2. ZTD trend difference GPS – GPS/GLO, computed over 111 sites. The rate in violet (primary y-axis) and the number of used difference is in green (secondary y-axis).

Figure 3. EPN station KLOP (Kloppenheim, Frankfurt, Germany) ZTD time series difference between 'individual' and 'type mean' calibration model. Two instrumentation changes occurred at the station (marked by red lines): the first in June 27th 2007, when the previous antenna was replaced with a TRM55971.00 and a TZGD radome, the second in June 28th 2013 with the installation of a TRM57971.00 and a TZGD radome.

Figure 4. Left part: Time series of the ZTD and up component differences between two time series obtained with and without Non-Tidal Atmospheric Loading for two EPN stations: KIR0 (Kiruna, Sweden) and RIGA (Riga, Latvia*)*.

Figure 5 VENE (Venice Italy) time series of bias and standard deviation for the three contributing solutions AS0, GO4 and MU4 for the period July 21st, 1996 - July 28, 2007 (GPS week 0863-1437). GO0 and GO1 are not shown since they are very close to GO4.

Figure 6 Weekly mean bias (upper part) and standard deviation (lower part) of each contribution solutions w.r.t. the final EPN Repro2 combination.

Figure 7. The final consistency in up component for all stations. Stations are sorted by name.

Figure 8 VENE (Venice Italy) time series of total consistency in up component for the period July 21st, 1996 - July 28, 2007 (GPS week 0863-1437).

Figure 9 EPN station CAGL (Cagliari, Sardinia Island, Italy). Upper part: Radiosondes (in red) and GPS (in blue) ZTD time series. Lower part differences.

Figure 10 GPS versus Radiosonde Bias. The error bar is the standard deviation. Sites are sorted according to the increasing distances from the nearest Radiosonde launch site.

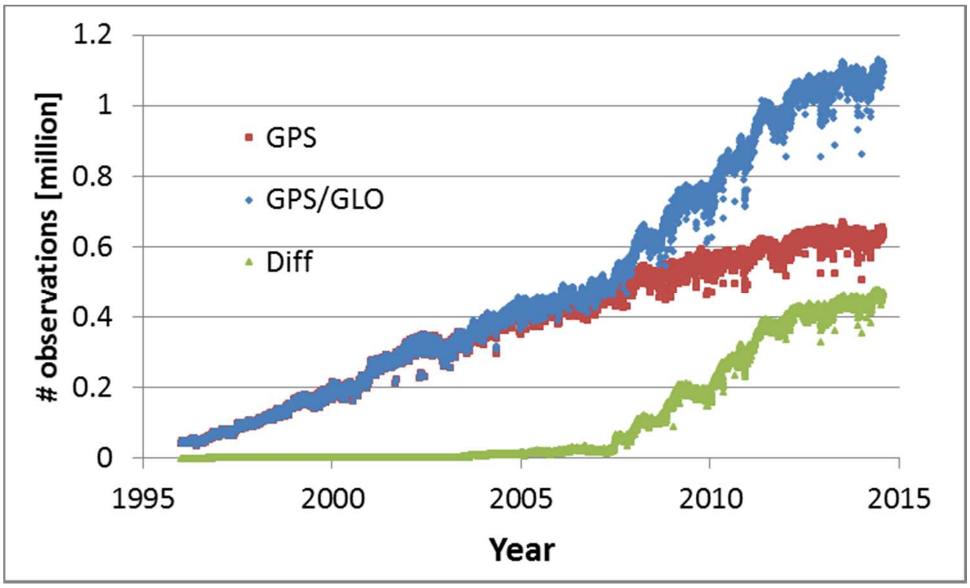
Figure 11: Distributions of station means (left) and standard deviations (right) of EPN Repro1 and Repro2 ZTDs compared to ERA-Interim ZTDs.

Figure 12: Site-by-site ZTD improvements of EPN Repro2 versus EPN Repro1 compared to ERA-Interim

Figure 13: Time series of monthly mean biases (lower part) and standard deviations (upper part) for ZTD differences of EPN Repro2 and NWM re-analysis. Uncertainties are calculated over all stations.

Figure 14: Geographical display of ZTD biases (left) and standard deviations (right) for EPN Repro2 products compared to the ERA-Interim.

Figure 15: ZTD trend comparisons at five EPN stations. The error bars are the formal error of the trend values.



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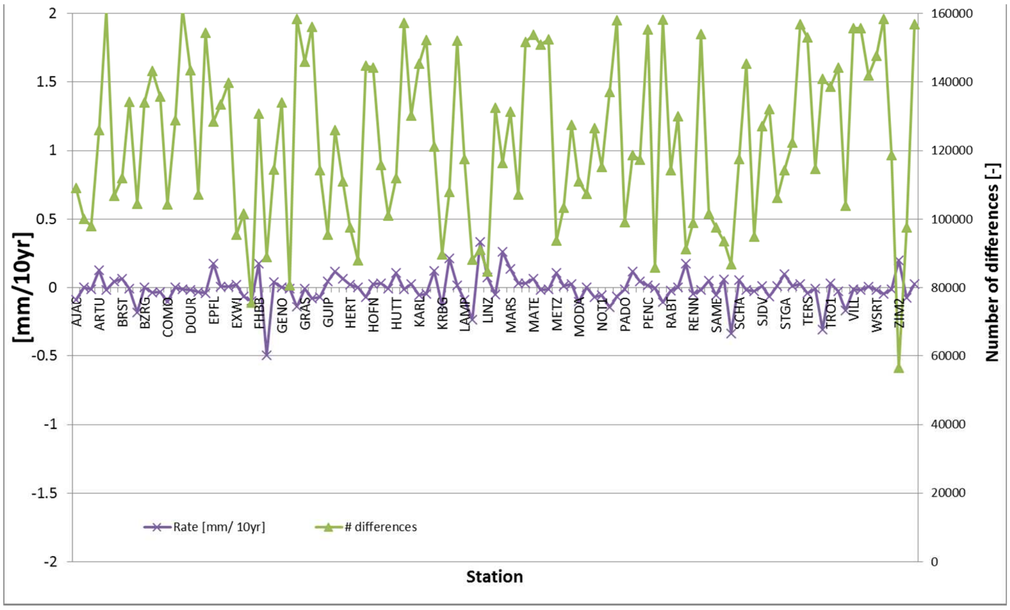

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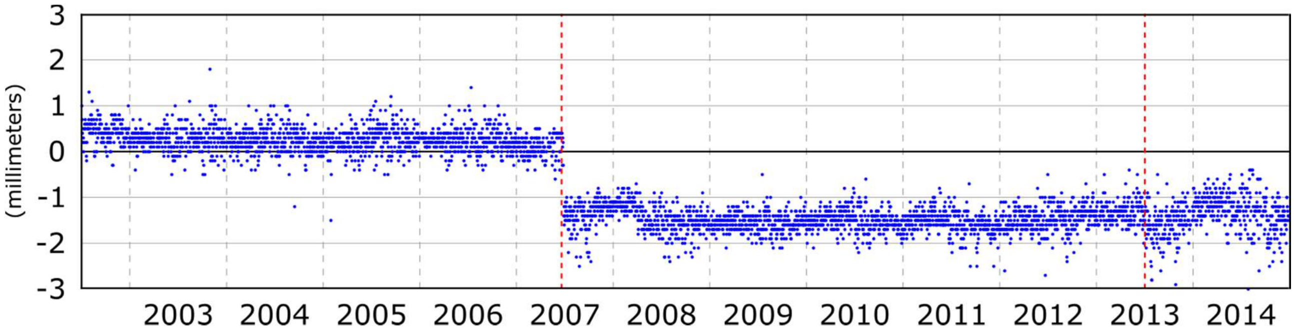

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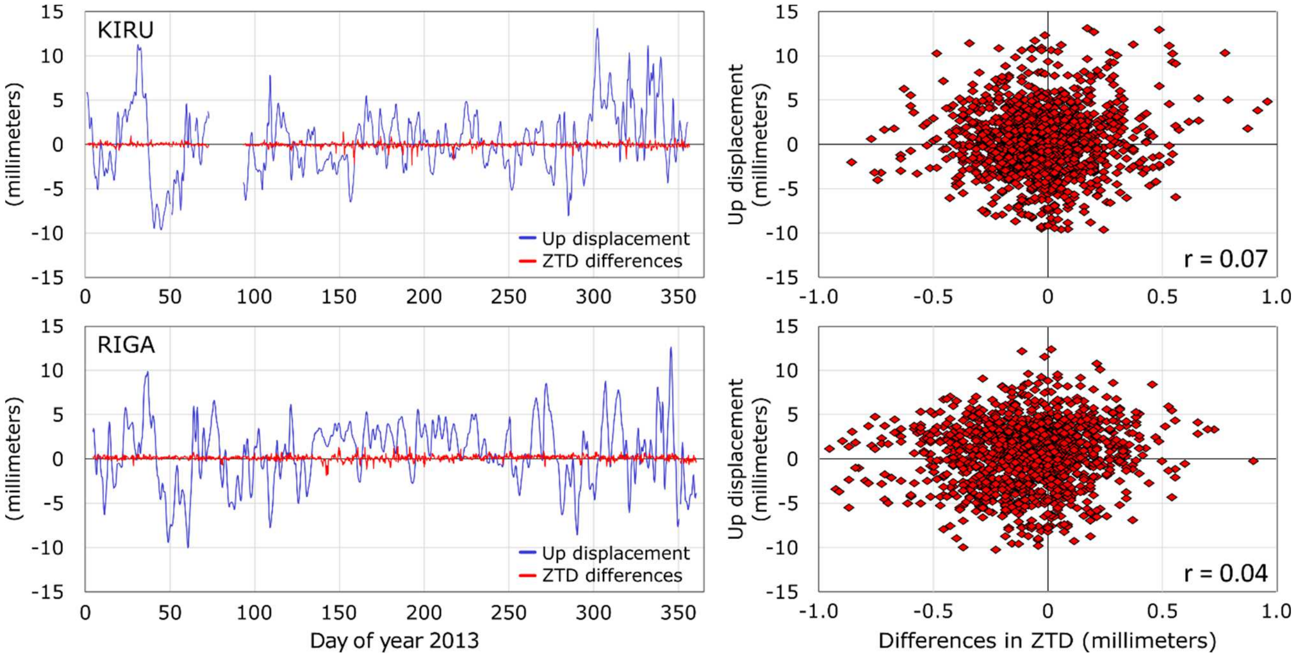

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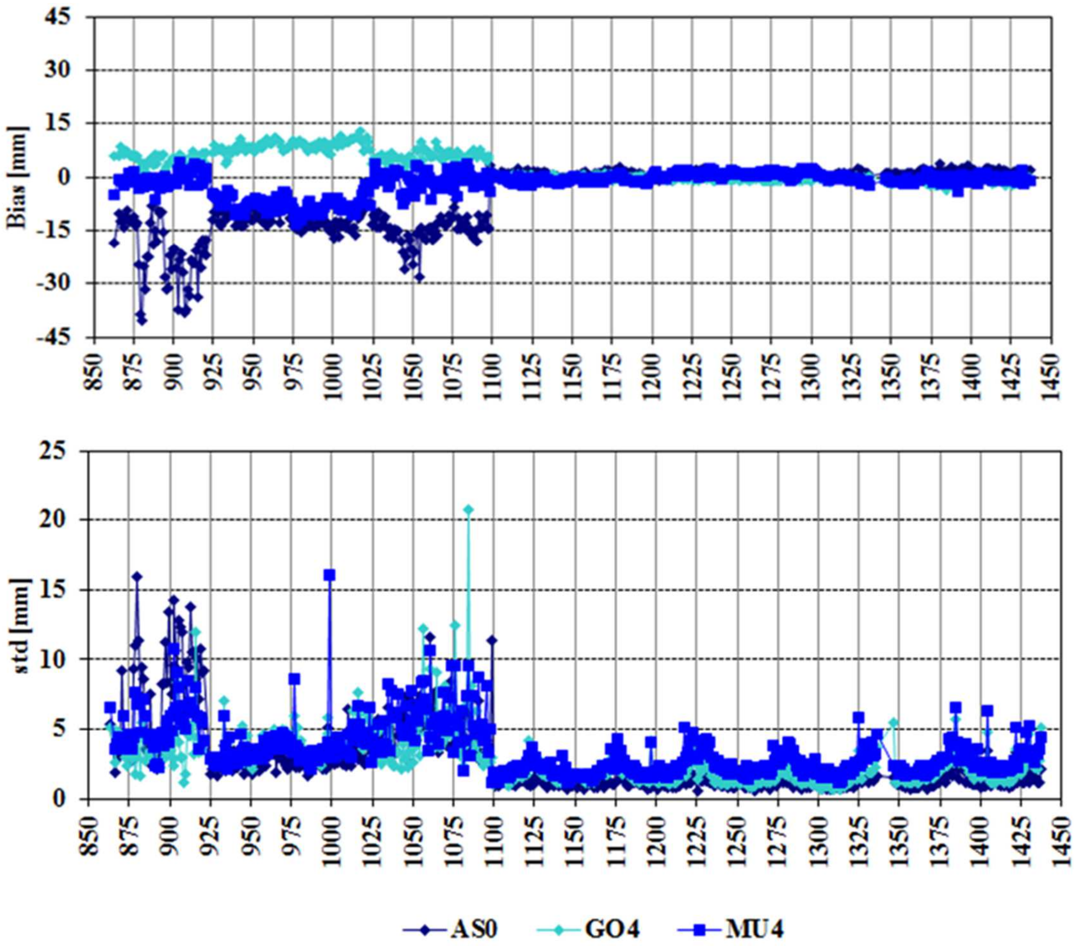

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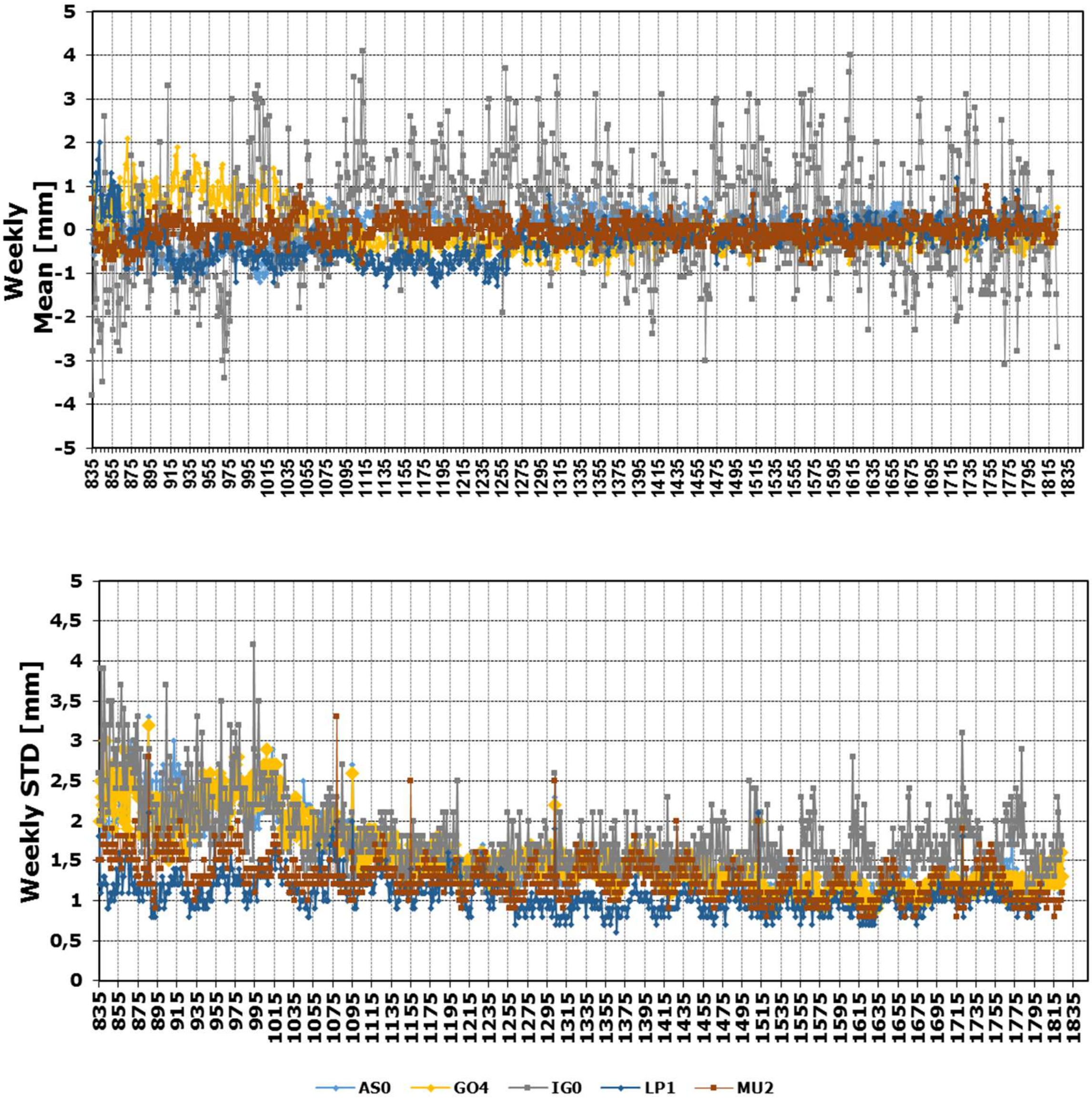

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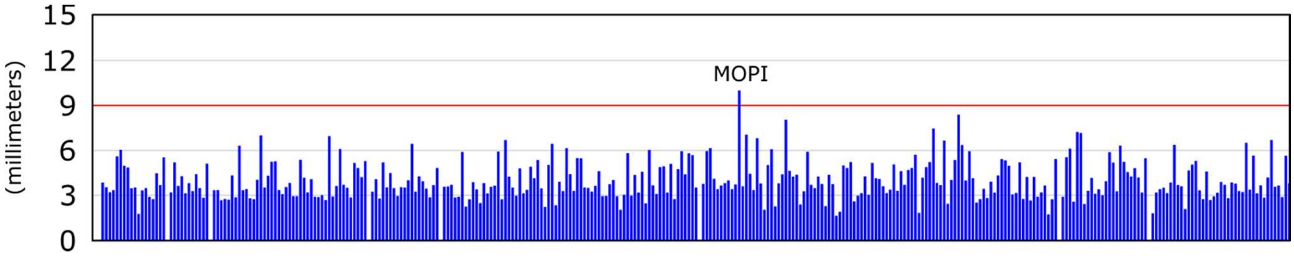

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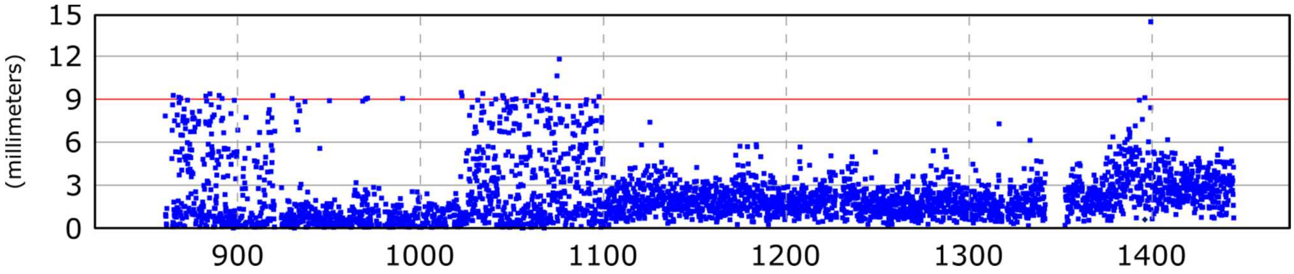

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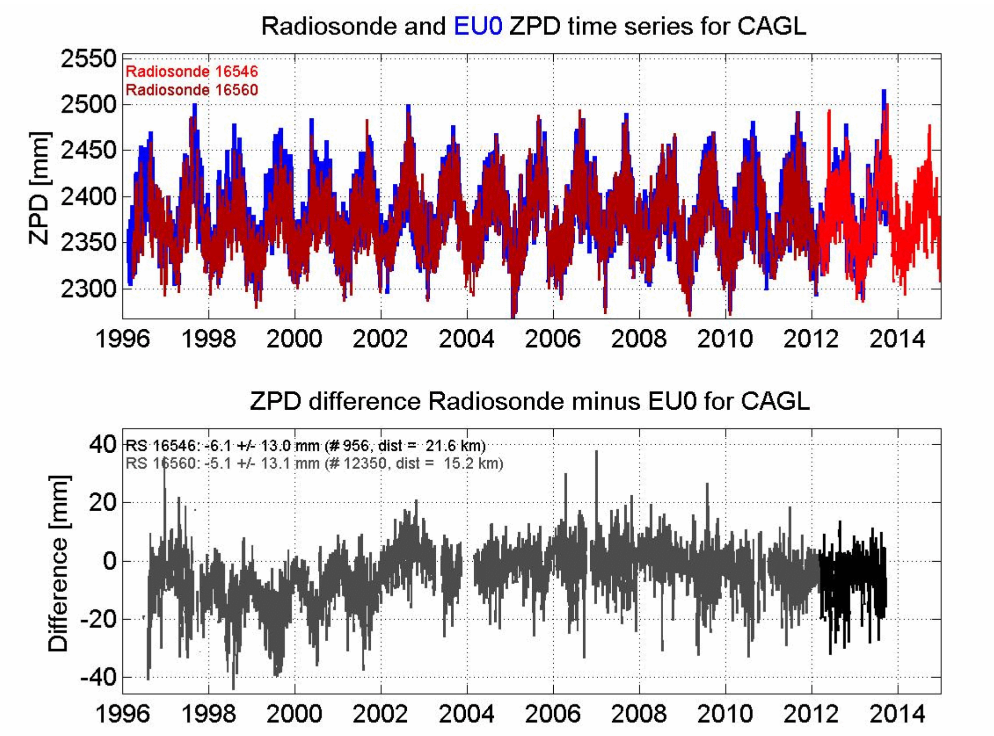

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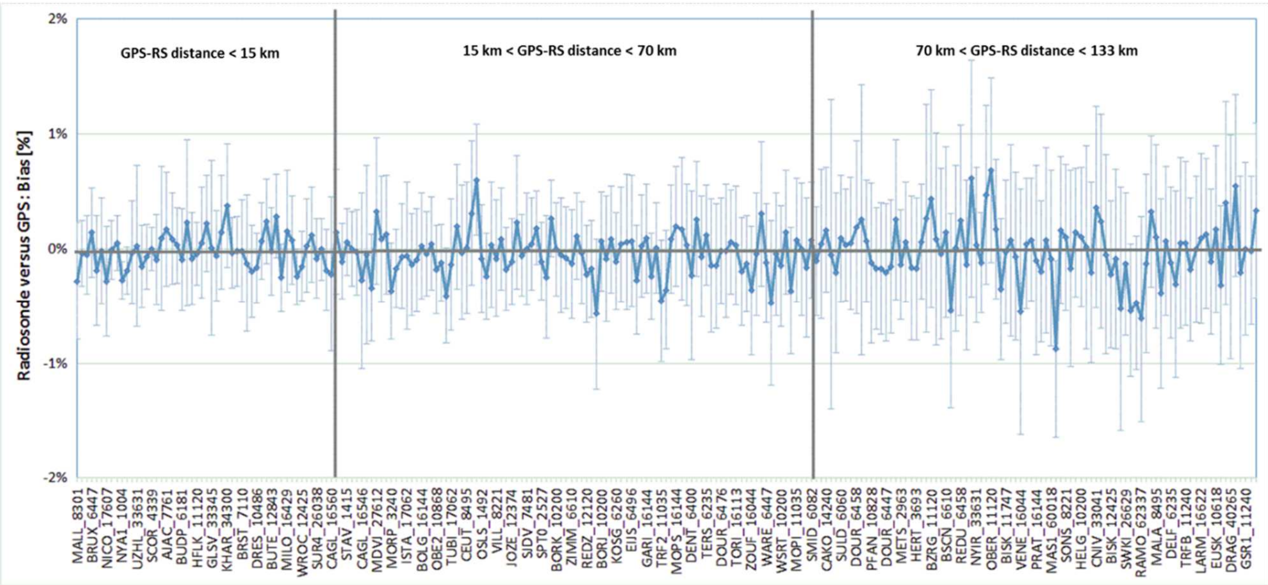

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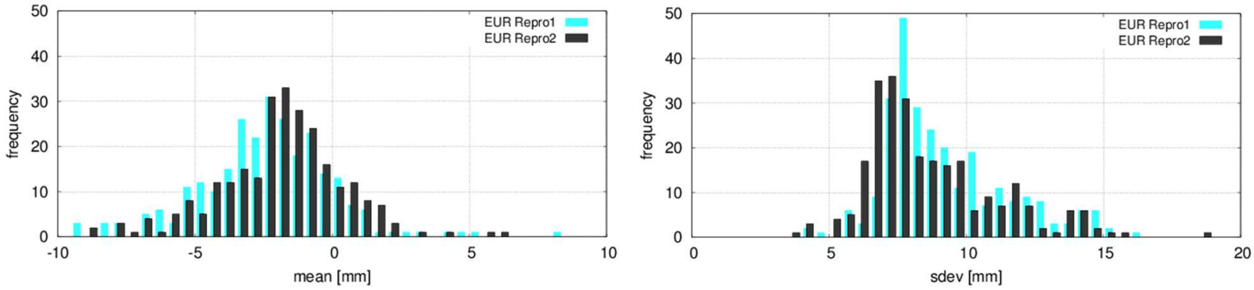

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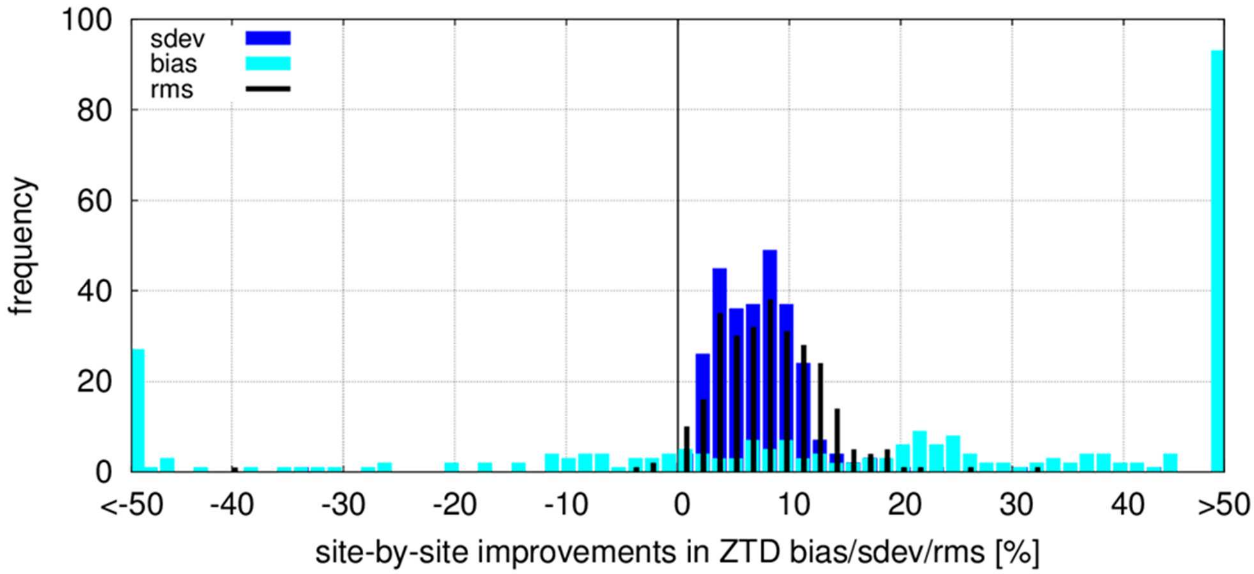
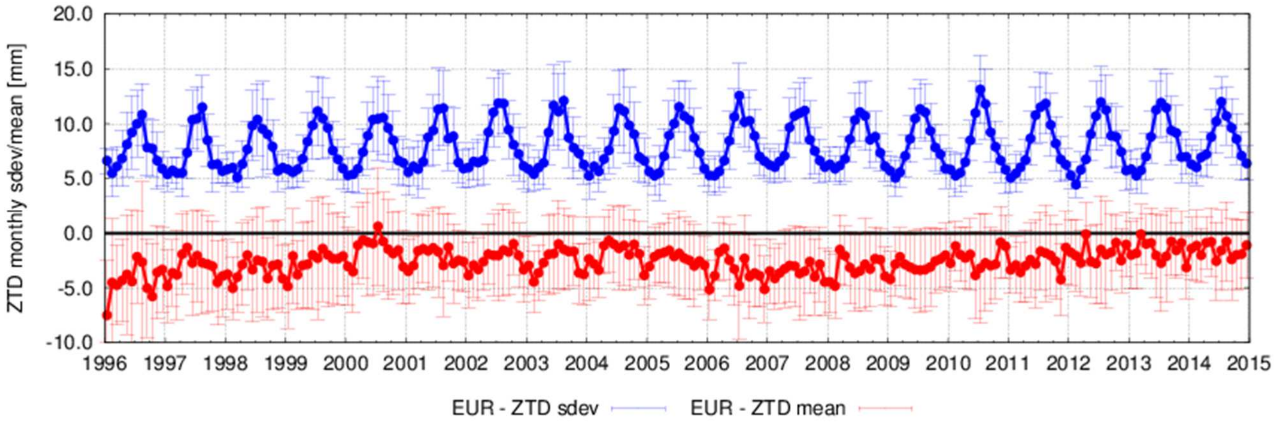


Figure 12: Site-by-site ZTD improvements of EPN Repro2 versus EPN Repro1 compared to ERA-Interim



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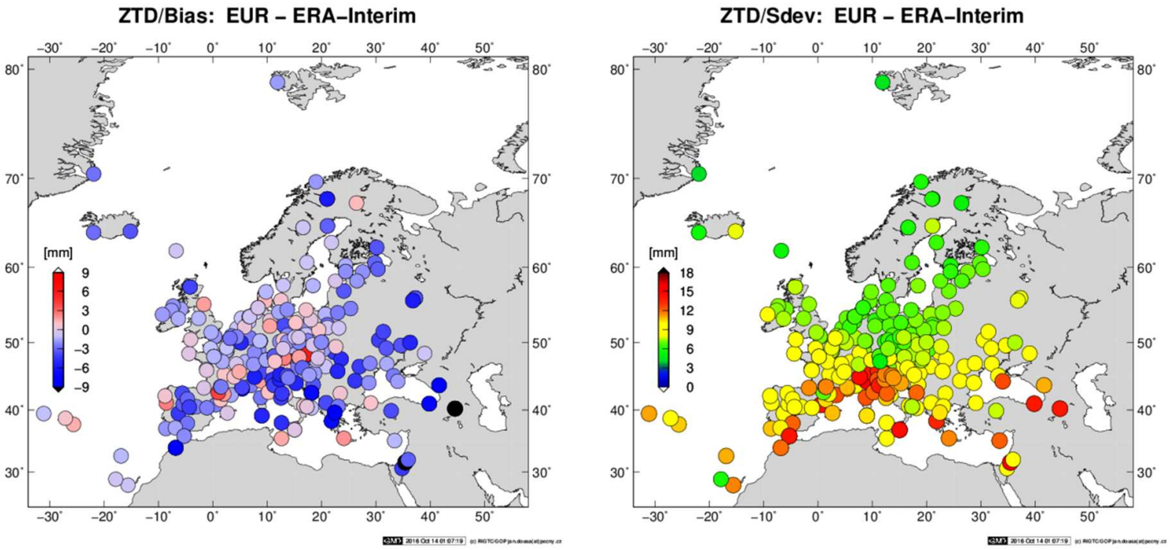

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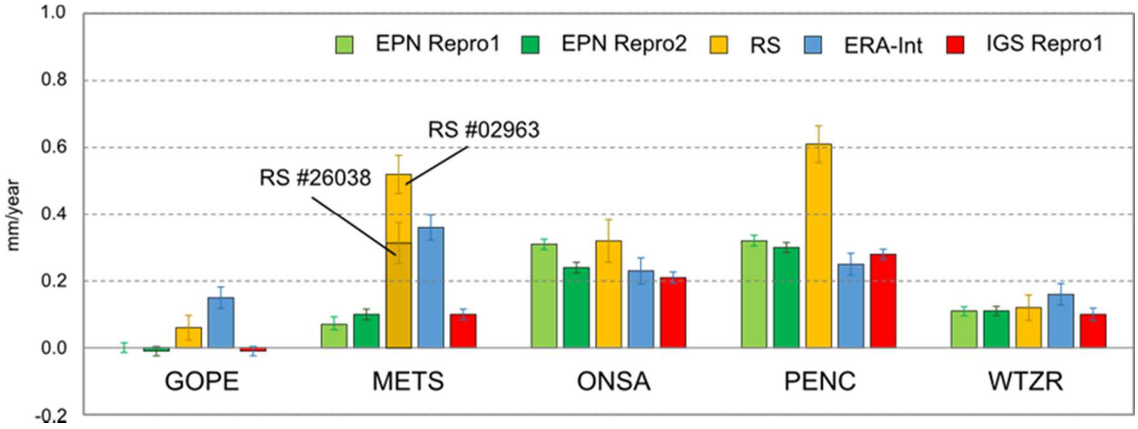

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