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 (e.g. validation of regional Numerical Weather Prediction reanalyses and climate model simulations) and has a high potential for monitoring trends and the 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 tropospheric 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 up by over 280 continuously operating GNSS reference stations, and 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

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generate each week the final EPN solution containing the combined tropospheric estimates with an hourly sampling rate. The coordinates, as a necessary part of this file, are taken from the EPN weekly combined SINEX file (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 means 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 (European Meteorological Services Network) 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 the 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, a 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), for which, using the latest available models and analysis strategy, GNSS data of the entire 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—starting 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 in this century, the ability to estimate ZTDs in Near Real Time has been demonstrated (COST-716, 2005), and the EC 5th FP scientific project TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) was funded. Since 2005, the operational production of tropospheric delays has been...

Promoting 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 to standardise for these applications the conversion method of conversion between propagation delay and atmospheric water vapour \( \text{Saastamoinen, (1973)} \), Bevis et al., \( \text{1992} \), Bock et al. \( \text{2015} \) with respect to climate standards. For climate applications, maintaining the 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 the 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 the northern hemisphere and southern hemisphere as well as in coastal and inland areas. Wang and Zhang (2009) derived GPS Precipitable Water Vapour (PWV or PW) using the International GNSS Service (IGS, \( \text{Dow et al.} \)), tropospheric products at about 400 global sites for the period 1997-2006 and analysed the PWV diurnal variations. Nilsson and Elgered \( \text{2008} \) reported on 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 the GPS Precipitable Water Vapour trend in South Korea for the period 2000-2009 and examined the relationship between GPS PWV and temperature, which is 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 that the validation of PWV is an essential tool for solar-climate studies over a 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 simulations 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
ERA-interimCMWE-GPS, with a standard deviations of 0.98 kg/m² and whereas it is 0.35 kg/m² 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/ per decade in IWV, with a temporal increment correlated with the temporal increase in the surface temperatures levels.

In this scenario Against this background, EPN-Repro2 tropospheric product is a unique dataset for the development of a climate data records of GNSS tropospheric products over Europe, suitable for analysing climate trends and variability, and calibrating/validating independent datasets at global European and regional scales. However, although homogeneously reprocessed, this time series still suffer from site-related inhomogeneities due, for example, to instrumental changes (receivers, cables, antennas, and radomes), changes in the station environment, etc., which might affect the analysis of the long-term variability (Vey et al. 2009). Therefore, to get realistic and reliable water vapour trend estimates climate signals such change points in the time series needs to be detected and corrected for (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. The Summary and recommendations for future reprocessing campaigns are drawn 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 strategy guaranteed that each site was processed by at least three ACs, at least which is an indispensable condition for providing a combined product. The second reprocessing campaign covered all the EPN stations, which were operated from January 1996 through December 2013. Then, the participating ACs decided to extend this period until the end of 2014 for tropospheric products. Data from about 280 stations in the EPN historical database have been considered. As of December 2014, 23% of EPN stations are between 15-18 years old, 26% are between 10-14 years old, 30% between 5-10 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 at least one reprocessed solution at least. One of the goals of the second reprocessing campaign was to test the diversity of the processing methods in order to ensure the verification of the solutions. For this reason, the three main GNSS software packages

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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, in addition, 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), but 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 for the GNSS orbits the 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

During the reprocessing period, the Russian satellite system GLONASS (Global'naja Navigacionnaja Sputnikovaja Sistema) became operational, and GLONASS observations are available since 2003. However, only from 2008 onwards the amount of GLONASS data (see Figure 1) is significant. 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. As a matter of fact, GPS data (from the American satellite system) 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, but different 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 100 000 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 and newly added for all systems. This result is a positive sign that the impact of GLONASS data is not as significant as one might expect.
that climate trends can be determined independently of the satellite systems used in the processing. For instance, in the 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 and thus our study here points out that the ZTD trends might be determined independently of the satellite systems used in the processing, hopefully, and therefore might 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, when available. 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 only (Schmid et al., 2015) while only others use with IGS type mean plus EPN individual antenna calibration models. Therefore, 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, but characteristics except the different antenna calibration models: the first solution first one used the IGS type mean models only, and the second one used the individual calibrations whenever it was possible and the IGS type mean for the rest of the antennas. An example of the time series of the ZTD differences obtained between applying ‘Individual’ and ‘Type Mean’ antenna calibration models for the EPN station KLOP (Kloppenheim, Frankfurt, Germany) is shown in Figure 2. KLOP station is included in the EPN network since June, 2nd 2002. When a TRM29659.00 antenna with no radome was installed. In the forthcoming years, two major 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, and the second change 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 at 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 was mentioned by Araszkiewicz and Voelksen (2016), and as a consequence as well as in their ZTD time series. Depending on the antenna model, the offset at station KLOP in the up
component (vertical displacement) 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, values were obtained between solutions calculated for all stations/antennas for which individual calibration models are available. The corresponding offset in the ZTD has the opposite sign for the antennas with an offset in the up component larger than 5 mm (16 antennas) and, generally, does not exceeding 2 mm for ZTD. Such inconsistencies in the ZTD time series are not large enough to be captured during the combination process (see Section 3), where a 10 mm threshold in the ZTD bias (about 1.5 kg/m² 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 without a non-tidal atmospheric loading model, have been compared for the year 2013. In the last one, the solution with the model, 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 non-tidal atmospheric loading correction 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 ZTDs seems to be negligible. Generally, it causes a difference below 0.5 mm with a scattering standard deviation 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 ZTDs and the up components between two solutions obtained with and without non-tidal atmospheric loading for two EPN stations: KIR0 (Kiruna, Sweden) and RIGA (Riga, Latvia).
Furthermore, there is also no correlation between the values of estimated differences and vertical displacements caused by non-tidal atmospheric loading. Correlation coefficients for the 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 the reading and checking of the SINEX TRO files delivered by the ACs. At this stage, gross errors (i.e., ZTD estimates with formal standard deviations $\sigma$ 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 becomes 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) as input. 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 shown). As far as the standard deviation is concerned, it is generally below 2.5 mm, with a clear seasonal behaviour (larger for larger ZTD values), 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 above-mentioned limits. To investigate these outliers, the time series of site/AC specific biases have been studied, since this analysis might be a useful tool to detect bad data periods of data and provide useful information 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 G01 are not shown but are very close to GO4). In the first years of the acquisition, the station VENE experienced tracking issues were experienced at VENE, which are clearly mirrored in both the bias and standard deviation time series.

All the site/AC specific biases are divided into three groups: the red group contains site/AC specific biases with 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 [15 mm, 25 mm].
[10 mm, 15 mm]. In Table 3, the summaries for each contributing solution are summarized. 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 the AS0 solution, while the percentage of biases in the red group ranges from 3% for the MU4 solution to 22% for the IG0 solution.

The final 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 has already been shown described 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 had improved significantly with respect to the preliminary combination (not shown here), due to the removal of outliers detected during this earlier combination. The standard deviation is below 3 mm before from GPS week 2215 to 1055 and 2 mm thereafter. This is somehow related to the worse quality of data and products during the first years of the EPN/IGS activities.

The final tropospheric combination is consistent with 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 the cases where the differences were larger than 16 mm in the up component (vertical displacement), the station was eliminated and the whole combination process was repeated, up to three times, if necessary. This ensures the consistency of the 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 T2D 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., 2016). As shown in Figure 7, only at one site, MOPI (Modra Piesok, Slovakia), exceed this threshold is exceeded on the long term. As reported at the EPN Central Bureau, MOPI has been excluded several times from the routine combined solutions because it has very bad observation periods of observations in the past due to a radome manipulation that caused jumps in the height component. However, this 9 mm threshold has been temporarily exceeded at several stations exceeded it temporarily during bad periods, an example is given shown in Figure 8 for VENE (Venezia, Italy).
4. Evaluation of the ZTD Combined Products with respect to independent data sets

The evaluation with respect to other sources or products, such as \textsuperscript{t}Radiosonde data from the EGVAP 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 \textsuperscript{t}Radiosonde (RS) comparisons at the EPN collocated sites, we used profiles from the World Meteorological Organization (WMO) provided by EUMETNET in the framework of the Memorandum of Understanding between EUREF and EUMETNET. Radiosonde profiles are processed using the software by Haase et al. (2003) that checks the quality of the profiles, converts the dew point temperatures to specific humidity, \textit{shifts} transforms the radiosonde profile to correct for the altitude offset between the GPS and the radiosonde sites, and determines the ZTD, \textit{Zenit Wet Delay} and IWV compensating for the change of the gravitational acceleration, \textit{g}, with height.

A comparison of the GNSS and radiosonde ZTD time series for the EPN site CAGL (Cagliari, Sardinia Island, Italy) is shown in Figure 9, with the mean biases and standard deviations reported in the Figure. It shows an example for the EPN site CAGL (Cagliari, Sardinia Island, Italy).

Similarly, for all the 183 EPN collocated sites, and using all the data available in the considered period, we computed an overall bias [RS minus GNSS] and standard deviation for all the 183 EPN collocated sites, using all the data available in the considered period (Figure 10). In this figure, the sites are sorted according to the increasing distance from the nearest \textsuperscript{t}Radiosonde launch site. For instance, MALL (Palma de Mallorca, Spain) is the closest (0.5 km to the \textsuperscript{t}Radiosonde site with WMO code code 8301) while GRAZ (Graz, Austria) is the most distant (133 km to \textsuperscript{t}Radiosonde code RS WMO code 14015). The amount of data available for the comparisons varies between sites, depending on the availability of the GPS and \textsuperscript{t}Radiosonde ZTD estimates in the considered epoch, and it ranges from 121 pairs for VIS6 (Visby, Sweden, integrated in the EPN since 22-06-2014) up to 21226 pairs for GOPE (Ondrejov, Czech Republic, integrated in the EPN since 31-12-1995).

The mean bias ranges from -0.87%, which corresponds to -21.2 mm in ZTD, (at EVPA, Ukraine, and a distance of 96.5 km from the \textsuperscript{t}Radiosonde launch site 96.5 km, Radiosonde code 33946 station) to 0.68%, which corresponds to 15.4 mm, (at OBER, Germany at a distance from the Radiosonde launch site 90.8 km from RS WMO-Radiosonde code 11120). The overall mean ZTD bias for all sites is -0.66 mm with a standard deviation of 4.9 mm. For the more than
75% of the stations (178 pairs), the agreement is below 5 mm in ZTD and only 5.5% of the stations
(13 pairs) have ZTD biases higher than 10 mm. The higher biases concern arise mostly for the
paired sites over 50 km away from each other, for which differences in the geographical
representativeness become important. For example, the like GPS stations OBER, OBE2 and OBET
located in Oberpfaffenhofen (Germany) are collocated with the RS WMO Radiosonde
(VRS90L code 11120) at launched from Innsbruck Airport in Austria, on the opposite side of the
North Chain in the Karwendel Alps. Our results are at odds with Wang et al. (2007), in which
where the authors compared PW (not ZTD) from GPS and global radiosondes, in the sense that -in
contrast to them, we found received a 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). It should be however noted
that different Vaisala radiosonde types (e.g. RS80 vs RS90/RS92) are equipped with different
humidity sensors, resulting in e.g. different RS-GPS comparisons in PW (e.g. Van Malderen et al.,
2014 and references therein). For MRZ, GRAW and M2K2 radiosonde types, which represent
4.6%, 3.4% and 3.0% of the compared radiosonde types respectively, we received a 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
(WMO: RS80L 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 ZTD standard deviation generally increases with the
distance from the Radiosonde launch site. It is in the range of [0.16; 0.76] mm, which corresponds
to [3; 18] mm in ZTD, till 15 km (first band in Figure 10); in [0.29; 0.78] mm which correspond
to [7; 19] mm, till 70 km (second band in Figure 10), and in [10; 33] mm till 133
km (third band in Figure 10). The evaluation numbers of the standard deviation area comparable
with previous studies. Haase et al. (2001) showed a very good agreement with biases less than 5
mm in ZTD and the standard deviation of 12 mm for most of the analysed sites in Mediterranean.
Similar results (6.0 mm ± 11.7 mm) were obtained also by Vedel et al. (2001). Both of these studies
were based on non-collocated pairs at sites distant less than 50 km from each other. Pacione et al
(2011), considering 1-year of GPS ZTD and tRadiosonde data over the E-GVAP super sites
network, obtained a standard deviation of 5-14 mm. Dousa et al. 2012 evaluated ZTDs from GNSS

Comment [g19]: This is the radiosonde type: Vaisala RS90.

Comment [g20]: M2K2 is a radiosonde type that Oliver Bock has assessed in his AMT paper (doi:10.5194/amt-6-2777-2013). Please comment if in this paper also a positive bias has been found.

Comment [g21]: Wang et al. (2007) reported about a dry bias in PW of the radiosondes compared to the GNSS retrievals of 1.08 mm (drier in the radiosondes). If the information in Fig. 9 is correct and your bias is also calculated as RS~GPS, you also find a negative (hence bias for the radiosondes, compared to GNSS). So the results here agree with the Wang et al. (2007) results. By the way, a description of the origin and references of the dry biases in Vaisala radiosondes can also be found in our AMT 2014 paper (doi:10.5194/amt-7-2487-2014). The reference document is https://www.wmo.int/pages/prog/www/IOM/publications/IOM-107_Yangjiang.pdf

Comment [g22]: VRS80L is the radiosonde type: Vaisala RS80.

Comment [g23]: In our AMT2014 paper, section 4.2, we also make the RS-GPS comparison separately for the two (or 3) radiosonde types that have been used at Brussels. As a matter of fact, we switched from RS80 to RS90 in August 2007. You are hence comparing BRUS with RS80 and RS90/R92, while comparing BRUX only with RS92. This have a non-negligible effect on the comparison and is hence not related only to the change of the GPS station!
and radiosondes on a global scale over a 10-month period and reported a standard deviation of 5–16 mm.

If we compare both the EPN-Repro1 ZTD product (completed with the EUREF operational product after 30 December 2006) and the EPN-Repro2 with the radiosonde ZTDs for the same period 1996–2014, we found an improvement of approximately 3-4% in the overall standard deviation for the second processing. The assessment of the EPN Repro1 vs. 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

We also compared the EPN-Repro2 ZTDs with the ZTDs calculated from 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 of a Numerical Weather Prediction (NWP) model and is available every 6 hours (00, 06, 12, 18 UTC) with a horizontal resolution of 1×1 degree and with 60 vertical model levels.

For the period 1996-2014 and for each EPN station, the 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 NWMERA-interim re-analysis. The evaluation of GNSS and NWMERA-interim was performed using the GOP-TropDB (Gyori and Dousa, 2016) by via calculating parameter (ZTD, horizontal gradients, see below) differences for each station pairs of stations, using the values at every 6 hours (00:00, 06:00, 12:00 and 18:00) – as available from the NWMERA-interim model output product. A linear temporal interpolation to those four timestamps from values +/- 30 min was thus necessarily applied for all GNSS products, which are available in providing HH:30 timestamps as required for the combination process. As all compared GNSS products have the same time resolution (1 hour), the interpolation is assumed to affect all products in the same way. Therefore, we assume that all inter-comparisons to a common reference (NWMERA-interim) principally reflects the quality of the products. No vertical corrections were applied since NWMERA-interim variables 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 therefore be evaluated...
for individual solutions only. In Table 4, we can observe a common ZTD bias (GNSS minus ERA-interim) of about -1.8 mm is found for all GNSS solutions compared to the ERA-Interim, however still highly varying for individual stations as obvious from estimated uncertainties but a large station to station variability could be noted, as is obvious from the estimated uncertainties. ZTD standard deviations are generally at the level of 8 mm between GNSS and NWMERA-interim ZTD products, but with the GO4 solution performing about 25% worse than the others as already detected during the combination. Two solutions, AS0 and LP1 are slightly better than GO4 and MU2, with a 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 explained by considering applying a stochastic troposphere modelling using undifference observations sensitive to the absolute tropospheric delays, so that the due to its theoretical better capability of the modelling true dynamics in the troposphere is better taken into account, 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 the EPN stations which were properly selected according to the station quality, hereby making it difficult to interpret this difference with respect to those solutions processing the full EPN.

The comparison of tropospheric linear horizontal gradients (East and North) from GNSS and NWMERA-interim revealed a problem with the MU2 solution (see Table 4). This solution showing a high inconsistency of results over different stations, which is not visible in the total statistics, but mainly in the uncertainties, which are by an order of magnitude higher compared to all other solutions. A geographical plot (not shown here) confirmed this site-specific systematic effect, but in both positive and negative senses. The impact was however not observed in the MU2 ZTD results. Additionally, the GO4 solution performed slightly worse than the others. This 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 and increased uncertainties of the estimates. For this purpose, the GO6 solution (not shown) was derived, fully compliant with the GO4, but stacking tropospheric gradients into 24 hours piece-wise linear modelling. In comparison with the former GO4 solution, By comparing the GO6 (Dousa and Vaclavovic, 2016), the GO6 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 the estimation of the horizontal gradients, which was particularly visible when comparing with the ERA-Interim horizontal gradients. Looking for systematic behaviour in monthly mean

Comment [g24]: Please specify how the bias is calculated.

Comment [g25]: What do you mean by "undifference"?
differences in the gradients therefore 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 also evaluated the EPN-Repro1 ZTD product with respect to the ERA-Interim using the same period, i.e. 1996-2014 (after when completing agained with the EUREF operational product, see above) after GPS week 1407 (December 30, 2006). Comparing EPN Repro1-EPN-Repro1 and EPN Repro2-EPN-Repro2 with the numerical weather model re-analysis showed the 8.9% improvement of EPN-Repro2 the latter in both overall standard deviation and bias systematic error. Figure 11 shows the distributions of station means biases and standard deviations of EPN Repro1-EPN-Repro1 and EPN Repro2-EPN-Repro2 ZTDs compared to NWMERA-interim ZTDs using the whole period 1996-2014. Common reductions of both statistical characteristics are clearly visible for the majority of all stations. From the data of Figure 11, we also illustrate the expressed site-by-site improvements in terms of ZTD bias, standard deviation and RMS in (Figure 12). The calculated median improvements for these statistics reached 21.1%, 6.8% and 8.0%, respectively, which corresponds to the above mentioned improvement of 8.9%. The degradation of the standard deviation was found at three stations: SKE8 (Skellefteå, 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). These 3 stations all of them providing much less data compared to other stations, 1%, 30% and 3%, respectively. All other stations (290) showed improvements. We also found 72 stations with increased absolute bias in EPN-ERA-Rep02 compared to Repro1 while the other 175 stations (75%) had a - resulted in reduced bias with ERA-interim ZTD systematic error.

Time series of monthly mean biases and standard deviations for ZTD differences of EPN Repro2-EPN-Repro2 and the ERA-Interim are shown in Figure 13. The small negative bias slowly decreases towards 2014, but the high uncertainty of the mean bias indicates site-specific behaviour, depending mainly on latitude and altitude of the EPN station and the quality of both NWMERA-interim and GNSS products. There is almost no seasonal signal observed in the time series of ZTD mean biases or the uncertainty, but clearly in the ZTD mean standard deviation and the uncertainty. The 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. A higher number of more stations reduces the variability in monthly mean biases, however, site-specific errors then contribute more to higher values of standard deviation.

Comment [g26]: 1 or 3% less data compared to the other stations is not very significant, so, what is the main reason that those stations have larger standard deviations for Repro2 versus Repro1? Please explain.

Comment [g27]: I guess the order of Repro and Repro 1 should be changed in this sentence (otherwise EPN-Repro1 would be closer to ERA-interim than EPN-Repro2). Please check!!!

Comment [g28]: Explain shortly where this seasonality comes from.
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.

4.3 Evaluation of trends

To illustrate the impact of the new processing on the resulting ZTD trends and uncertainties, we considered 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 03-03-2006) and WTZR (Bad Koeitzing, Germany, integrated in the EPN since 31-12-1995). For these 5 stations, we have computed ZTD trends using EPN-Repro2, EPN-Repro1 (again completed with the EUREF operational products), radiosonde and ERA-Interim data. Furthermore, those 5 stations also belong to the IGS Network, for which IGS Repro1, completed with the IGS operational products, are available and extracted from the GOP-TropDB, so that we could also calculate ZTD trends from this dataset.

First, we removed the annual signal from the original time series and marked all outliers according to the 3-sigma criterion. Then, we tried to remove all inhomogeneities in the GPS ZTD time series, related to instrumental changes, which might introduce a change in the mean of the ZTD time series and therefore have an impact on the ZTD trends. In particular, for all GPS ZTD data sets we have estimated all documented shifts in the mean related to the antenna replacement. No other unexplained break points has been corrected for, to be sure not to introduce any artificial errors. Based on these cleaned and filtered data, we have used, independently, a linear regression model before and after the considered epoch of the offset. The difference of the mean ZTDs between those two linear regression models is then considered as the offset of the specific epoch is. With this technique, we removed all the estimated offsets from the original GPS ZTD time series. Generally, the amplitudes of the offsets are much lower than the noise level and depend on the applied method of estimation. Therefore, the final ZTD trends and uncertainties presented here are affected by the used methodology and should not be considered in absolute terms. No homogenization has been done for the radiosonde data, since reliable metadata are not available. Also the ERA-interim ZTD time series were not corrected for inhomogeneities. Finally, a Least Squares Estimation method has been applied to estimate the linear trends and the seasonal components.
In Figure 15, the ZTD trends and uncertainties are presented for the 5 sites and for all ZTD datasets. First of all, it should be noted that the trends between the three GPS ZTD data sets are very consistent (as long as the same homogenisation procedure is applied). The overall RMS is 0.02 mm/year. If we now consider all five ZTD sources, the best agreement between the ZTD trends is achieved at ONSA (RMS=0.04 mm/year) and WTZR (RMS=0.02 mm/year). For PENC, we also have a good agreement of the GPS ZTD trends with respect to ERA-Interim (0.05 mm/year), but a large discrepancy with the radiosonde ZTD trend is found (-0.31 mm/year). This large discrepancy is probably due to the distance to the radiosonde launch site (40.7 km, RS WMO 12843) and to the lack of homogenization of the radiosonde data. For the five considered stations, the agreement of GPS ZTD trends with respect to ERA-Interim (RMS = 0.11 mm/year) is better than with respect to radiosondes (RMS = 0.16 mm/year). Even although, for the five considered stations, EPN-Repro2 do not change significantly the value of the ZTD trends with respect to EPN-Repro1.

It has a slightly better agreement with the radiosonde and ERA-Interim ZTD trends. Over Europe, the EPN network also has a better spatial resolution than the IGS and radiosonde networks, which are used today for an observations-based long-term analysis of ZTD/IWV variability over Europe. Taking into account the good consistency among the ZTD trends, EPN-Repro2 can be used for trend detection in areas where other data are not available.

5. Conclusions

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 a 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 means, comparison with 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).

We showed that EPN-Repro2 led to an improvement of approximately 3-4% in the overall standard deviation in the ZTD differences with radiosonde data, as compared with EPN-Repro1 and Repro2 with respect to the radiosonde data has an improvement of approximately 3-4% in the overall standard deviation.
The assessment of the EPN-Repro1, EPN-Repro2, and Repro2 with respect to comparison with the ERA-Interim re-analysis showed the 8-9% improvement of the latter over the former in both the overall ZTD bias and standard deviation with respect to EPN-Repro1 and systematic error which was obvious for the majority of the stations. Comparisons of the GNSS solutions with the NWMERA-interim, 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 example, for the assessment of Euro-CORDEX (Coordinated Regional Climate Downscaling Experiment) climate model simulation, the IGS Repro1 dataset (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 only 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) an additional two years of ZTD data can change the estimated trends up to 10%. Therefore, with 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 the trends 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 03-03-2006) 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:
ONGA (RMS=0.04 mm/year) and WTZR (RMS=0.02 mm/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.

As a matter of fact, a comparison between 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) by the Sofia University,
and ALADIN-Climate IWV simulations conducted by the Hungarian Meteorological Service, is
performed for the period 2003-2008 at the moment. The preliminary results show a tendency of the
model to underestimate IWV. Clearly, a 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 and would enable to improve the consistency of the combined solution.

Prior to any next reprocessing, it was agreed in EUREF to focus on cleaning and documenting the data in the EPN historical archive as it should highly facilitate any future work. For this purpose, all existing information needs 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.

Author Contributions. R. Pacione coordinated the writing of the manuscript and wrote section 1, 2, 3 and 4.1. A. Araszkiewicz wrote section 2.2 and 2.3. E. Brockmann wrote section 2.1. J. Dousa wrote section 4.2. All authors contributed to section 5. All authors approved the final manuscript before its submission.

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Table Captions

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

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

Table 3. Percentage of red, orange and yellow biases (see text) 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 (EGRD = east gradient, NGRD = north gradient).
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Table 1: EPN Analysis Centres providing [EPN-Repro2](#) solutions.
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<td>Delivered SNX_TRO Files [from week to week]</td>
<td>0834-1824</td>
<td>0836-1824</td>
<td>0835-1816</td>
<td>0835-1802</td>
<td>0835-1824</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 2: EPN Repro2 processing options for each contributing solutions. AS0 solutions are provided by ASI/CGS (Matera, Italy), GO0, GO1 and GO4 solutions are provided by GOP (Pecny, Czech Republic), IG0 solution is provided by IGE (Madrid, Spain), LP0 and LP1 solutions are provided by LPT (Waben, Switzerland), and MU2 and MU4 solutions are provided by MUT (Warsaw, Poland).
<table>
<thead>
<tr>
<th>Solution</th>
<th>% Red bias</th>
<th>% Orange bias</th>
<th>% Yellow bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS0</td>
<td>17</td>
<td>27</td>
<td>56</td>
</tr>
<tr>
<td>G00</td>
<td>10</td>
<td>22</td>
<td>67</td>
</tr>
<tr>
<td>G01</td>
<td>12</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>G04</td>
<td>12</td>
<td>23</td>
<td>65</td>
</tr>
<tr>
<td>IG0</td>
<td>22</td>
<td>14</td>
<td>64</td>
</tr>
<tr>
<td>LP0</td>
<td>10</td>
<td>12</td>
<td>79</td>
</tr>
<tr>
<td>LP1</td>
<td>10</td>
<td>12</td>
<td>78</td>
</tr>
<tr>
<td>MU2</td>
<td>3</td>
<td>15</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 3. Percentage of red, orange and yellow biases *(see text)* for each contributing solution.
<table>
<thead>
<tr>
<th>Solution</th>
<th>ZTD bias [mm]</th>
<th>ZTD sdev [mm]</th>
<th>EGRD bias [mm]</th>
<th>EGRD sdev [mm]</th>
<th>NGRD bias [mm]</th>
<th>NGRD sdev [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS0 (full EPN)</td>
<td>-1.7±2.0</td>
<td>7.7±1.9</td>
<td>0.00±0.06</td>
<td>0.32±0.09</td>
<td>0.09±0.06</td>
<td>0.33±0.10</td>
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<tr>
<td>GO4 (full EPN)</td>
<td>-1.9±2.4</td>
<td>8.1±2.1</td>
<td>-0.04±0.09</td>
<td>0.38±0.10</td>
<td>0.00±0.09</td>
<td>0.40±0.12</td>
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<tr>
<td>MU2 (full EPN)</td>
<td>-1.8±2.0</td>
<td>8.3±2.1</td>
<td>-0.03±0.32</td>
<td>0.35±2.46</td>
<td>-0.01±0.84</td>
<td>0.34±2.37</td>
</tr>
<tr>
<td>IG0 (part EPN)</td>
<td>-1.6±2.3</td>
<td>10.7±2.2</td>
<td>-0.05±0.09</td>
<td>0.33±0.11</td>
<td>0.04±0.12</td>
<td>0.36±0.12</td>
</tr>
<tr>
<td>LP1 (part EPN)</td>
<td>-1.7±2.4</td>
<td>7.7±1.7</td>
<td>-0.02±0.06</td>
<td>0.28±0.05</td>
<td>0.03±0.09</td>
<td>0.27±0.06</td>
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<tr>
<td>EUR Repro2</td>
<td>-1.8±2.1</td>
<td>7.8±2.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EUR Repro1</td>
<td>-2.2±2.3</td>
<td>8.5±2.1</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
</tbody>
</table>

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 (EGRD = east gradient, NGRD = north gradient).
Figure 7: The final consistency in the up component, calculated as the difference between the EPN-Rep2 combination and the combination performed by the EPN AC coordinator, for all stations. Stations are sorted by name. The final consistency in up component for all stations are shown. Stations are sorted by name.

Figure 8: VENE (Venice Italy) time series of total consistency (for definition, see Fig. 7) in the up component for the period July 21st, 1996 - July 28, 2007 (GPS weeks 0863-1437).
(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: ZTD differences, calculated as RS minus GPS. 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: RS minus GPS ZTD biases for all GPS-RS station pairs. The error bar is the standard deviation. Sites are sorted with increasing distances from the nearest radiosonde launch site.

Figure 11: Distributions of station mean ZTD biases (left) and standard deviations (right) of EPN-Repro1 and Repro2 compared to ERA-Interim. Figure 11: Distributions of station mean (left) and standard deviations (right) of EPN Repro1, EPN Repr01 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 12: Site by site ZTD improvements of EPN-Repro2 vs EPN-Repro1 compared to EPN-Repro1.

Figure 13: Time series of monthly mean biases (lower part) and standard deviations (upper part) for ZTD differences between EPN-Repro2 and ERA-interim re-analysis (GPS minus ERA-interim?). Uncertainties are calculated over all stations. Figure 13: Time series of monthly mean biases (lower part) and standard deviations (upper part) for ZTD differences of EPN Repro2 vs ERA-Interim and NWMERA interim re-analysis. Uncertainties are calculated over all stations.

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

Figure 15: ZTD trend comparisons at five EPN stations for 5 different ZTD datasets. The error bars are the formal errors of the estimated trend values. Figure 15: ZTD trend comparisons at five EPN stations. The error bars are the formal error of the trend values.
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 becomes significant starting from 2008.
Figure 2. ZTD trend differences between GPS only and GPS + GLONASS, computed over 111 sites. The rate is in violet (primary y-axis) and the number of used differences is in green (secondary y-axis).
Figure 3. EPN station KLOP (Kloppenheim, Frankfurt, Germany) ZTD differences time series. The difference between solutions processed with ‘individual’ and ‘type mean’ antenna calibration models. Two instrumentation changes occurred at the station (marked by vertical dashed red lines): the first in June 27th 2007, when the previous antenna was replaced with a TRM55971.00 and a TZGD radome, and 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). Right part: Scatter plots Correlation between these two parameters.
Figure 5: VENE (Venice, Italy) time series of ZTD biases and standard deviations for the three contributing solutions AS0, GO4 and MU4 \textit{with the combined solution} for the period July 21st, 1996 - July 28, 2007 (GPS weeks 0863-1437). GO0 and GO1 are not shown here, since they are very close to GO4.

\textbf{Comment [RVM42]: I assume?}
Figure 6: Weekly mean ZTD biases (upper part) and standard deviations (lower part) of each contributing solution w.r.t. the final EPN-EPN-Repro2 combination.
Figure 7. The final consistency in the up component, calculated as the difference between the EPN-Repro2 combination and the combination performed by the EPN AC coordinator, for all stations. Stations are sorted by name.

Comment [g43]: Please correct if I got this wrong. In any case, you should explain here how “consistency” is defined or calculated.
Figure 8 VENE (Venice Italy) time series of total consistency (for definition, see Fig. 7) in the up component for the period July 21st, 1996 - July 28, 2007 (GPS weeks 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: ZTD differences, calculated as RS minus GPS.

Comment [g44]: In this figure, you use ZPD instead of ZTD. You do not explain what it stands for and this is also very inconsistent with the rest of the paper. Please change the titles and the label in the figure!
Figure 10: RS minus GPS versus Radiosonde ZTD biases for all GPS-RS station pairs. The error bar is the standard deviation. Sites are sorted according to increasing distances from the nearest Radiosonde launch site. The x-axis reports the GPS station and the Radiosonde site WMO code.
Figure 11: Distributions of station mean $ZTD_{bias}$ (left) and standard deviations (right) of EPN Repro1, EPN-Repro1, and Repro2 $ZTD$s compared to ERA-Interim $ZTD$s.
Figure 12: Site-by-site ZTD improvements of EPN-Rep2 versus EPN-Rep1 compared to ERA-Interim.
Figure 13: Time series of monthly mean biases (lower part) and standard deviations (upper part) for ZTD differences between EPN-Repro2 and NWMERA-interim re-analysis (GPS minus ERA-interim). Uncertainties are calculated over all stations.

Comment [RVM45]: Please confirm or modify.
Figure 14: Geographical distribution 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 for 5 different ZTD datasets. The error bars are the formal errors of the estimated trend values.