# ~~EPN Repro2~~EPN-Repro2: A reference GNSS tropospheric dataset over Europe.

Rosa Pacione [(1)], Andrzej Araszkiewicz [(2)], Elmar Brockmann [(3)], Jan Dousa [(4)]

(1) e-GEOS S.p.A, ASI/CGS, Italy
(2) Military University of Technology, Poland
(3) Swiss Federal Office of topography swisstopo
(4) New Technologies for the Information Society, Geodetic Observatory Pecný, RIGTC, Czech Republic

*Correspondence to*: Rosa Pacione (rosa.pacione@e-geos.it)

**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 troposphe~~ric~~ice 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~~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

**Comment [g1]:** The aconoym ZTD is havi two different explanations here. Please be consistent and choose one.

**Comment [g2]:** See comment 1.

generate each week the final EPN solution containing the combined tropospheric~~e~~ 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, that~~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~~ focuses~~d~~ on the tropospheric products obtained in the framework of the second EPN Reprocessing campaign (hereafter EPN-Repro2), for which~~where~~, using the latest available models and analysis strategy, GNSS data of the entire~~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~~, starting~~ed~~ 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~~s~~ ZTDs in Near Real Time has been~~was~~ 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

**Comment [g3]:** Add a date here.

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.

PromotingTo 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 to standardise for these applications the conversion 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 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 itsthe 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,), Dow et al., (2009), tropospheric products at about 400 global sites for the period 1997-2006 and analysed the PWV diurnal variations. Nilsson and Elgered (2008) showed 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 studied also the relationship between GPS PWV and temperature, which is the one of the climatic elements. Better information about A more thorough knowledge of 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 onpointed out that the validation of PWV ais 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-interim~~CMWF~~-GPS, with ~~a~~ standard deviations of 0.98 kg/m$^2$ and ~~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~~/~~ per decade in IWV, with a temporal increment correlated with the temporal increase in the surface temperatures ~~levels~~.

**Comment [g4]:** To be checked if my modifications are indeed true.

~~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 homogenously reprocessed, this time series still suffer from site-related inhomogeneities~~y~~ due, for example, to instrumental changes (receivers, cables, antennas, and radomes), changes in the station environment, etc. which might~~can~~ 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 need~~s~~ 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 solution~~s~~ is evaluated w.r.t. r~~R~~adiosonde and ERA-Interim data. The s~~S~~ummary and recommendations for future reprocessing campaigns are dra~~o~~wn 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 guarantee~~ds~~ that each site wa~~i~~s 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~~ed~~ ACs decided to extend this period until the end of 2014 for tropospheric~~e~~ 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~~18-15~~ years old, 26% are between 10-14~~14-10~~ years old, 30% between 5-10~~10-5~~ years old, and 21% less than 5 years old. Only five, over sixteen, EPN ACs (see Table 1~~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

**Formatted:** Font: Not Italic, Check spelling and grammar

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 softwares 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~~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 I~~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~~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~~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~~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 and~~re~~ newly added for all systems. ~~This result is a positive sign~~

**Formatted:** Font color: Text 1, English

**Formatted:** Font: Not Italic, Font color: Text 1, English (U.K.)

**Formatted:** Font color: Text 1, English

**Formatted:** Font: Not Italic, Font color: Text 1, English (U.K.)

**Comment [g5]:** Write out this acronym.

**Comment [g6]:** Write out this acronym.

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

~~that climate trends can be determined independently of the satellite systems used in the processing.~~ For instance, i~~I~~n 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~~but~~ 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~~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, when available. Currently, individual antenna calibration models are available at about 70 EPN stations. As reported in Table 2~~Table 2~~, there are individual solutions carried out with IGS type mean antenna calibration models only (Schmid et al., 2015) while~~ only and~~ 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~~while~~ 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 3~~Figure 3~~. 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, t~~T~~wo 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 a~~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~~it~~ 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

**Formatted:** Font color: Text 1, English

**Formatted:** Font: Not Italic, Font color: Text 1, English (U.K.)

**Formatted:** Font: Not Italic, Check spelling and grammar

**Comment [g7]:** Add a bookmark here explaining that TRM55971.00 points to the provider and the type of the antenna. Simila for TZGD radome.

**Comment [g8]:** Another TZGD radome?

**Comment [g9]:** For all of them: do you me antennas AND radomes??? Please be more specific.

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 exceed~~ing~~ 2 mm~~ for ZTD~~. Such inconsistenc~~y~~ies 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/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 with~~out~~ 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~~Figure 4~~ shows time series of the differences of the ZTDs and the up components between two ~~t~~solutions~~ime series~~ obtained with and without non-tidal atmospheric loading for two EPN stations: KIR0 (Kiruna, Sweden) and RIGA (Riga, Latvia).

**Comment [g10]:** What does the S1 and S2 stand for? Could you just say "surface pressu… oscillations with diurnal, semidiurnal variabi… and even higher harmonics?"

**Comment [g11]:** Same comment as here above.

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

Furthermore, t~~T~~here is ~~also~~ no correlation between the values of estimated differences and vertical displacements caused by non-tidal atmospheric loading, as~~.~~ c~~C~~orrelation 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 devaitions~~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~~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 show~~ned~~n). ~~T~~~~As far as t~~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 ~~ab~~efore mentioned limits. To investigate these outliers, the time series of site/AC specific biases ha~~ves~~ been studied, since ~~it can~~ this analysis might be a useful tool to detect bad data periods ~~of data~~ and provide useful information ~~useful~~ for cleaning the EPN historical archive. An example is given in Figure 5~~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 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

**Formatted:** Font: Not Italic, Check spellir and grammar

**Comment [g12]:** I assume?

**Formatted:** Font: Not Italic, Check spellir and grammar

**Comment [g13]:** I assume?

[10 mm, 15 mm]. In Table 3~~Table 3~~ the~~summarizes~~ percentages of red, orange and yellow biases 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 ~~EPN Repro2~~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~~ 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~~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 early combination. The standard deviation is below 3 mm before~~from~~ GPS week ~~835~~ 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 ~~EPN Repro2~~EPN-Repro2 tropospheric combination is consistent with~~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 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~~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~~Figure 7~~, only at one site, MOPI (Modra Piesok, Slovakia), ~~exceed~~ this threshold is exceeded on the~~a~~ long term. As reported at the EPN Central Bureau, MOPI has been excluded several times from the routine combined solutions because it~~. MOPI~~ has very bad observation periods ~~of observations~~ in the past due to a radome manipulation that caused jumps in the height component. However, this 9mm threshold has been temporary exceeded at several stations ~~exceeded it temporary~~ during bad periods, an example is given ~~s shown~~ in Figure 8~~Figure 8~~ for VENE (Venezia, Italy).



**Formatted:** Font: Font color: Black, Engli (U.K.)

**Formatted:** Font: Not Italic, Font color: Black, English (U.K.), Check spelling and grammar

**Comment [g14]:** On which grounds? Plea comment!

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

**Comment [g15]:** Height component = up component,? If not, please explain the difference. Please use a consistent term (up component or height component) in order t not mislead less GNSS experienced readers.

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

**Comment [g16]:** So, it turns out that the threshold is 9 mm in the up comment (see a Fig. 7). So, why are so speaking about this 16mm differences in the up component? Th is totally not clear to me. Please explain.

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

**Formatted:** Font: Font color: Black

**Formatted:** Font: Not Italic, Font color: Black, Check spelling and grammar

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

The evaluation with respect to other sources or products, such as r~~R~~adiosonde 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 r~~R~~adiosonde (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 a~~the~~ software by ~~(~~Haase et al.~~,~~ (2003) that checks the quality of the profiles, converts the dew point temperatures to specific humidit~~y~~ies, shifts~~transforms~~ the radiosonde profile to correct for the altitude offset between the GPS and the radiosonde sites, and determines the ZTD, Zenit Wet Delay and IWV compensating for the change of the gravitational acceleration~~,~~ g~~,~~ with height.

A comparision of the GNSS and radiosonde ZTD time series for the EPN site CAGL (Cagliari, Sardinia Island, Italy) is shown in Figure 9~~Figure 9~~, with the mean biases and standard deviations reported in the Figure. ~~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~~Figure 10~~). In this figure, t~~T~~he sites are sorted with~~according to the~~ increasing distance~~s~~ from the nearest r~~R~~adiosonde launch site. For instance, MALL (Palma de Mallorca, Spain) is the closest (0.5 km to the r~~R~~adiosonde site with WMO code ~~code~~ 8301) while GRAZ (Graz, Austria) is the most distant (133 km to ~~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 r~~R~~adiosonde 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, at~~nd~~ a distance of 96.5 km from the RS WMO ~~Radiosonde launch site 96.5 km, Radiosonde code~~ 33946 station) to 0.~~,~~68%, which corresponds to 15.~~,~~4 mm~~,~~ (at OBER, Germany at~~, and 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.~~,~~6 mm with a standard deviation of 4.9 mm. For ~~the~~ more than

**Comment [g17]:** The ZWD is for the first time used here. Please explain how it is defined or calculated. If not, just do not mention it.

**Formatted:** Font: Font color: Black, Engli (U.K.)

**Formatted:** Font: Not Italic, Font color: Black, English (U.K.), Check spelling and grammar

**Comment [g18]:** In Fig. 9, the bias is defin at RS ZTD minus GNSS ZTD. I assume that yo also used this definition of the bias througho the entire paper?

**Formatted:** Font: Not Italic, Font color: Black, English (U.K.)

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~~s~~ 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~~and~~ 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 r~~R~~adiosondes, in the sense that ~~. In contrast to them,~~ we found~~received~~ a small negative bias -1.19 mm for Vaisala r~~R~~adiosondes, 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 r~~R~~adiosonde types, which represent 4.6%, 3.4% and 3.0% of the compared r~~R~~adiosondes 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~~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 ZTD standard deviation generally increases with the distance from the r~~R~~adiosonde launch site. It is in the range of [0.~~,~~16; 0.~~,~~76] % ,which corresponds to [3; 18] mm in ZTD, till 15 km (first band in Figure 10); in [0.~~,~~29; 0.~~,~~78] % , ~~which~~ corresponding~~s~~ 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 are~~is~~ comparable with previous studies. Haase et al. (2001) showed a very good agreement with biases less than 5 mm in ZTD and a~~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 them~~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 r~~R~~adiosonde 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 ty Vaisala RS90.

**Comment [g20]:** M2K2 is a radiosonde typ that Olivier Bock has assessed in his AMT pa (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) repor about a dry bias in PW of the radiosondes w respect to the GNSS retrievals of 1.08 mm (drier in the radiosondes). If the information Fig. 9 is correct and your bias is also calculat 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 a (2007) results. By the way, a description of t origin and references of the dry biases in Vaisala radiosondes can also be found in ou AMT 2014 paper (doi:10.5194/amt-7-2487- 2014) . The reference document is https://www.wmo.int/pages/prog/www/IM /publications/IOM-107_Yangjiang.pdf

**Comment [g22]:** VRS80L is the radiosond 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 fr RS80 to RS90 in August 2007. You are hence comparing BRUS with RS80 and RS90/RS92, while comparing BRUX only with RS92. This have a non-neglible effect on the compariso and is hence not related only to the change the GPS station!

and ~~R~~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~~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 calculed 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 ~~NWM~~ERA-interim re-analysis. The evaluation of GNSS and ~~NWM~~ERA-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 ~~NWM~~ERA-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~~s~~ 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 (~~NWM~~ERA-interim) principally reflect~~s~~ the quality of the products. No vertical corrections were applied since ~~NWM~~ERA-interim variables~~parameters~~ were estimated for the long-term antenna reference position of each station.

Table 4~~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

**Formatted:** Font: Not Italic, Check spellir and grammar for individual solutions only. In Table 4~~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 ~~NWM~~ERA-interim ZTDs~~products~~, but with the~~for~~ IG0 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 ~~— 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 explained by ~~considered~~ 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~~ of the EPN stations, ~~which were~~ properly selected according to the station quality, hereby~~thus~~ making it difficult ~~a difficulty~~ to interpret thise difference with respect to those solutions processing the full EPN.

The comparison of tropospheric linear horizontal gradients (East and North) from GNSS and ~~NWM~~ERA-interim revealed a problem with the MU2 solution (see Table 4). This solution shows~~ing~~ 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 or magnitude higher compared to all other solutions~~s~~. A g~~G~~eographical plot (not shown here~~ed~~) confirmed this site-specific systematic effect, ~~but in~~ both in positive and negative senses~~s~~. The impact was however not observed in the MU2 ZTD results. Additionally, the GO4 solution performed slightly worse than the others. This~~It~~ was identified as a consequence of estimating 6-hour gradients using a~~the~~ piece-wise linear function ~~and~~ without any absolute or relative constraints. In such case, higher correlations with other parameters occurred and increased the~~raising~~ uncertainties of the estimates. For this purpose, the GO6 solution (not shown~~ed~~) 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 that appl~~ied~~ying 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~~ed~~ ~~to the~~ ERA-Interim horizontal gradients. Looking for s~~S~~ystematic behaviour in monthly mean

**Formatted:** Font: Not Italic, Check spelling and grammar

**Comment [g24]:** Please specify how the b 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~~also~~ EPN-~~-~~Repro1 ZTD product with respect to ~~the~~ ERA-Interim using the same period, i.e. 1996-2014 (after ~~when~~ completing againg~~ed~~ 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 a~~the~~ 8-9% improvement of EPN-Repro2~~the latter~~ in both overall standard deviation and bias~~systematic error~~. Figure 11~~Figure 11~~ shows the distributions of station mean~~s~~ biases and standard deviations of ~~EPN Repro1~~EPN-Repro1 and ~~EPN Repro2~~EPN-Repro2 ZTDs compared to ~~NWM~~ERA-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~~Figure 11~~, we also illustrate the ~~expressed~~ site-by-site improvements in terms of ZTD bias, standard deviation and RMS in~~(~~Figure 12~~Figure 12)~~. The c~~C~~alculated median improvements for these statistics ~~s~~ reached 21.1 %, 6.8 % and 8.0 %, respectively, which corresponds to the abovementioned improvement of 8-9 %. A~~The~~ degradation of the 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). These 3 stations ~~all of them~~ provid~~eing~~ much less data compared to other stations~~s~~, 1%, 30% and 3%, respectively. All other stations (290) showed improvements. We ~~also~~ found 72 stations with increased absolute bias in EPN~~UREF-~~-Repro2~~1~~ compared to Repro1~~2~~ while a~~the other~~ll ~~others,~~ 221 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~~is~~ shown~~ed~~ in Figure 13~~Figure 13~~. The small negative bias slowly decreases towards 2014, but the~~a~~ high uncertainty of the mean bias indicates a site-specific behaviour, depending mainly on latitude and altitude of the EPN station and the quality of both ~~NWM~~ERA-interim and GNSS products. There is almost no seasonal signal observed in the time series of ZTD mean biases or ~~the~~ uncertainties~~y~~, but clearly in the ZTD mean standard deviation and the uncertainties~~y~~. The s~~S~~lightly 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~~a~~ variability in monthly mean biases, however, site-specific errors then contribute more to higher values of standard deviation.

**Formatted:** Font: Not Italic

**Formatted:** Font: Not Italic

**Formatted:** Font: Not Italic

**Comment [g26]:** 1 or 3% less data compa to the other stations is not very significant, So, what is the main reason that those static have larger standard deviations for Repro2 - ERA-interim versus Repro1 – ERA-interim?? Please explain.

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

**Formatted:** Font: Not Italic

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

Figure 14~~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 03-03-2096) and WTZR (Bad Koetzting, 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.

**Formatted:** Font: Not Italic

**Formatted:** Font: Bold, Font color: Auto, English (U.S.)

**Formatted:** Heading 2, Left, Space After: pt, Adjust space between Latin and Asian text, Adjust space between Asian text an numbers

In Figure 15~~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=0.04mm/year) and WTZR (RMS=0.02mm/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~~ ~~R~~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 ~~Assessment of the EPN Repro1~~EPN-Repro1.~~ and Repro2 with respect to the Radiosonde data has an improvement of approximately 3-4% in the overall standard deviation.~~



**Formatted:** Font: Not Italic, Check spelling and grammar

**Comment [g29]:** Overall RMS between the GPS ZTD trends?

**Comment [g30]:** Add a number here to proof this statement.

**Comment [g31]:** I think this analysis deserves a separate secton and does not belong to the conclusions. In the conclusions you should just give a wrap up, and not describing new research. I also seriously changed the text. Please go through it and check thorougly if you could life with every modification I propose!

The a~~A~~ssessment of the ~~EPN-Repro1~~EPN-Repro2~~1~~ ~~and Repro2 with respect to~~comparison with the ERA-Interim re-analysis showed a~~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 NWM~~ERA-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.

**Comment [RVM32]:** For which paramete

**Comment [g33]:** I think you should investigate some more time on the summar of the most important findings of this paper Do not forget that a lot of readers start by reading the abstract and the conclusions an then make up their mind if they proceed wit the rest. In its current form, this summary is not very attracting. Do not forget to mentio the most important findings of sections 2 an (e.g. one sentence for every subsection of 2

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 Repro1dataset (~~,~~ 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 03-03-2096) 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.

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 en~~to be~~ able 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.

**Acknowledgments**

The authors would like to acknowledge the support provided by COST ~~–~~(~~–~~European Cooperation in Science and Technology) for providing financial assistance for the publication of the paper. The authors thank the members of the EUREF project "EPN reprocessing". e-GEOS work is done under ASI Contract 2015-050-R.0. The assessments of the EUREF combined and individual solutions in the GOP-TropDB were supported by the Ministry of Education, Youth and Science, the Czech Republic (project LH14089). The MUT AC contribution was supported by statutory founds at the Institute of Geodesy, Faculty of Civil Engineering and Geodesy, Military University of Technology (No. PBS/23-933/2016). Finally, we thank the two anonymous referees and the Associate Editor Dr. Roeland Van Malderen for their comments which helped much to improve the paper.

## References

Comment [RVM34]: Please check if the format and journal abbreaviations are compliant with AMT's recommendations


Alshawaf, F., Dick, G., Heise, S., Simeonov, T., Vey, S., Schmidt, T., and Wickert, J.: Decadal variations in atmospheric water vapor time series estimated using ground-based GNSS, Atmos. Meas. Tech. Discuss., doi: 10.5194/amt-2016-151, in review, 2016.

Araszkiewicz, A., and Voelksen, C.: The impact of the antenna phase center models on the coordinates in the EUREF Permanent Network, GPS Solution, doi: 10.1007/s10291-016-0564-7, 2016.

Baldysz, Z., Nykiel, G., Figurski, M., Szafranek, K., and Kroszczynski, K.: Investigation of the 16-year and 18-year ZTD Time Series Derived from GPS Data Processing. Acta Geophys. 63, 1103-1125, DOI: 10.1515/acgeo-2015-0033, 2015.

Baldysz Z., Nykiel G., Araszkiewicz A., Figurski M. and Szafranek K.: Comparison of GPS tropospheric delays derived from two consecutive EPN reprocessing campaigns from the point of view of climate monitoring. Atmos. Meas. Tech., 9, 4861-4877, DOI: 10.5194/amt-9-4861-2016, 2016.

Bastin, S., Bock, O., Chiriaco, M., Conte, D., Dominguez, M., Roehring, R., Drobinski, P., Parracho, A.: Evaluation of MED-CORDEX simulations water cycle at different time scale using long-term GPS-retrieved IWV over Europe, presentation at COST ES1206 workshop, Potsdam (Germany) 1-2 September 2016.

Bevis, M., Businger, S., Herring, T. A., Rocken C., Anthes, R. A., and Ware, R. H.: GPS Meteorology: Remote Sensing of 20 Atmospheric Water Vapour Using the Global Positioning System, J. Geophys. Res., 97, 15787–15801, 1992.

Bevis M., S. Businger, S. Chiswell, T. A. Herring, R. A. Anthes, C. Rocken, and Ware, R. H.: GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water. Journal of Applied Meteorology, 33, 379-386, 1994.

Byun S. H., and Bar-Sever, Y. E.: A new type of troposphere zenith path delay product of the International GNSS Service. J Geodesy, 83(3-4), 1–7, 2009.

Bock, O., P. Bosser, R. Pacione, M., Nuret, N. Fourrie, and Parracho, A.: A high quality reprocessed ground-based GPS dataset for atmospheric process studies, radiosonde and model evaluation, and reanalysis of HYMEX Special Observing Period, Quarterly Journal of the Royal Meteorological Society, doi: 10.1002/qj.2701, 2015.

Boehm, J., and Schuh, H.: Vienna mapping functions in VLBI analyses, Geophys. Res. Lett., 31, L01603, doi: 10.1029/2003GL018984, 2004.

Boehm, J., A. Niell, P. Tregoning, and Schuh, H.: Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data, Geophys. Res. Lett., 33, L07304, doi: 10.1029/2005GL025546, 2006a.

Boehm, J., B. Werl, and Schuh, H.: Troposphere mapping functions for GPS and very long baseline interferometry from European Centre for Medium-Range Weather Forecasts operational analysis data, J. Geophys. Res., 111, B02406, doi: 10.1029/2005JB003629, 2006b.

Bruyninx C, Habrich H, Söhne W, Kenyeres A, Stangl G, Völksen C (2012) Enhancement of the EUREF Permanent Network Services and Products, Geodesy for Planet Earth, IAG Symposia Series, 136: 27–35. doi: 10.1007/978-3-642-20338

Bruyninx, C., A. Araszkiewicz , E. Brockmann, A. Kenyeres, R. Pacione, W. Söhne, G. Stangl, K. Szafranek, and Völksen, C.: EPN Regional Network Associate Analysis Center Technical Report 2015, IGS Technical Report 2015, Editors Yoomin Jean and Rolf Dach, Astronomical Institute, University of Bern, 2015, pp. 101-110, 2015.

COST-716 Exploitation of Ground-Based GPS for Operational Numerical Weather Prediction and Climate Applications – Final Report, in: Elgered, G., Plag, H.-P., Van der Marel, H., et al. (Eds.), EUR 21639, 2005.

Dach, R., Hugentobler, U., Fridez, P., and Meindl, M.: Bernese GPS Software Version 5.0, Journal of Geophysical Research Atmospheres, 119, doi: 10.1002/2013JD021124, 2014.

Dach, R., J. Böhm, S. Lutz, P. Steigenberger and Beutler, G.: Evaluation of the impact of atmospheric pressure loading modeling on GNSS data analysis, J Geod doi: 10.1007/s00190-010-0417-z, 2010.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, and Beljaars, A. C. M.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137(656), 553–597, 2011.

Desai, S. D., W. Bertiger, M. Garcia-Fernandez, B. Haines, N. Harvey, C. Selle, A. Sibthorpe, A. Sibois, and Weiss, J. P.: JPL's Reanalysis of Historical GPS Data from the Second IGS Reanalysis Campaign, AGU Fall Meeting, San Francisco, CA, 2014.

Dow, J.M., Neilan, R. E., and Rizos, C.: The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, Journal of Geodesy 83:191–198, doi: 10.1007/s00190-008-0300-3, 2009.

Dousa, J. and G.V. Bennett: Estimation and Evaluation of Hourly Updated Global GPS Zenith Total Delays over ten Months, GPS Solutions, Online publication date: 12-Oct-2012, doi:10.1007/s10291-012-0291-7, 2012.

Dousa, J. and Vaclavovic P.: The GOP troposphere product from the 2nd European re-processing (1996-2014), 2016 (manuscript prepared for AMT)

Gendt, G. SINEX TRO—Solution (Software/technique) INdependent Exchange Format for combination of TROpospheric estimates Version 0.01, March 1, 1997:https://igscb.jpl.nasa.gov/igscb/data/format/sinex_tropo.txt, 1997.

Gyori G, and Douša J.: GOP-TropDB developments for tropospheric product evaluation and monitoring – design, functionality and initial results, In: IAG Symposia Series, Rizos Ch. and Willis P. (eds), Springer Vol. 143, pp. 595-602., 2016

Guerova, G., J. Jones, J. Douša, G. Dick, S. de Haan, E. Pottiaux, O. Bock, R. Pacione, G. Elgered, H. Vedel, and M. Bender: Review of the state-of-the-art and future prospective of GNSS Meteorology in Europe, accepted for publication in to Special Issue: Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC), (AMT/ACP/ANGEO inter-journal SI), 2016.

**Comment [RVM35]:** Please use consisten journal abbreviations. You can find a list of t adviced abbreviations on the journal web pa

**Comment [RVM36]:** Same remark as here above.

**Comment [RVM37]:** Submitted to AMT r

IERS Conventions (2010). Gérard Petit and Brian Luzum (eds.). (IERS Technical Note ; 36) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6, 2010.

Ihde, J., Habrich, H., Sacher, M., Söhne, W., Altamimi, Z., Brockmann, E., Bruyninx, C., Caporali, C., Dousa, J., Fernandes, R., Hornik, H., Kenyeres, A., Lidberg, M., Mäkinen, J., Poutanen, M., Stangl, G., Torres, J.A., Völksen, C., (2013). EUREF's contribution to national, European and global geodetic infrastructures. IAG Symposia, vol. 139, pp. 189–196. doi: 10.1007/978-3-642-37222-3_24.

Jin, S.G., J. Park, J. Cho, and P. Park: Seasonal variability of GPS-derived Zenith Tropospheric Delay (1994-2006) and climate implications, J. Geophys. Res., 112, D09110, doi: 10.1029/2006JD007772, 2007.

Haase, J., Calais, E., Talaya, J., Rius, A., Vespe, F., Santangelo, R., Huang, X.-Y., Davila, J. M., Ge, M., Cucurull, L., Flores, A., Sciarretta, C., Pacione, R., Boccolari, M., Pugnaghi, S., Vedel, H., Mogensen, K., Yang, X., and Garate, J.: The contributions of the MAGIC project to the COST 716 objectives of assessing the operational potential of ground-based GPS meteorology on an international scale, Physics and Chemistry of the Earth, Part A, 26, 433–437, 2001.

Haase, J.S., H. Vedel, M. Ge, and E. Calais: GPS zenith troposphteric delay (ZTD) variability in the Mediterranean, Phys Chem Earth (A) 26(6–8):439–443, 2001.

Haase, J., M. Ge, H. Vedel, and Calais, E.: Accuracy and variability of GPS Tropospheric Delay Measurements of Water Vapor in the Western Mediterranean, Journal of Applied Meteorology, 42, 1547-1568, 2003.

King, R., Herring, T., and Mccluscy, S.: Documentation for the GAMIT GPS analysis software 10.4., Tech. rep., Massachusetts Institute of Technology, 2010.

Lutz, S., P. Steigenberger, G. Beutler, S. Schaer, R. Dach, and Jaggi, A.: GNSS orbits and ERPs from CODE's repro2 solutions, IGS Workshop Pasadena (USA), June 23–27, 2014.

Nilsson, T. and Elgered, G.: Long-term trends in the atmospheric water vapor content estimated from ground-based GPS data. J. Geophys. Res., 113, doi: 10.1029/2008JD010110, 2008.

Ning, T., R. Haas, G. Elgered, and. Willén U: Multi-technique comparisons of 10 years of wet delay estimates on the west coast of Sweden, J Geod 86: 565. doi: 10.1007/s00190-011-0527-2, 2012.

Ning, T., J. Wickert, Z. Deng, S. Heise, G. Dick, S. Vey, and Schone, T.: Homogenized time series of the atmospheric water vapor content obtained from the GNSS reprocessed data, Journal of Climate, doi: 10.1175/JCLI-D-15-0158.1, 2016a

Ning, T., J. Wang, G. Elgered, G. Dick, J. Wickert, M. Bradke, M. Sommer, R. Querel, and Smale, D.: The uncertainty of the atmospheric integrated water vapour estimated from GNSS observations Atmos. Meas. Tech., 9, 79-92, doi:10.5194/amt-9-79-2016, 2016b.

Mangiarotti, S., A. Cazenave, L. Soudarin and Crétaux, J. F.: Annual vertical crustal motions predicted from surface mass redistribution and observed by space geodesy, Journal of Geophysical Research, 106, B3, 4277, 2001.

Pacione, R., B. Pace, S.de Haan, H. Vedel, R.Lanotte, and Vespe, F.: Combination Methods of Tropospheric Time Series, Adv. Space Res., 47(2) 323-335 doi: 10.1016/j.asr.2010.07.021, 2011.

**Comment [RVM38]:** For Nilsson and Elge you are using J. Geophys. Res. as journal abbreviation. Be consistent, also with the adviced list of journal abbreviations.

Petrov, L. and Boy, J.-P.: Study of the atmospheric pressure loading signal in very long baseline interferometry observations," J. Geophys. Res., 109, B03405, 14 pp., doi: 10.1029/2003JB002500, 2004.

Ray, R. D. and Ponte, R. M.: Barometric tides from ECMWF operational analyses, Ann. Geophys., 21(8), pp. 1897-1910, doi: 10.5194/angeo-21-1897-2003.

Saastamoinen, J.: Contributions to the theory of atmospheric refraction, Bull. Geodes., 107, 13–34, doi:10.1007/BF02521844, 1973.

Santerre R.: Impact of GPS Satellite sky distribution. Manuscr. Geod., 16, 28-53, 1991.

Schmid R, Dach R, Collilieux X, Jäggi A, Schmitz M, Dilssner F (2015) Absolute IGS antenna phase center model igs08.atx: status and potential improvements. J Geod 90(4):343–364

Sohn, D.-H., and Cho, J.: Trend Analysis of GPS Precipitable Water Vapor Above South Korea Over the Last 10 Years, J. Astron. Space Sci. 27(3), 231-238 (2010), doi: 10.5140/JASS.2010.27.3.231, 2010.

Suparta, W.: Validation of GPS PWV over UKM Bangi Malaysia for climate studies, Procedia Engineering 50, 325 – 332, 2012.

Steigenberger, P., V. Tesmer, M. Krugel, D. Thaller, R. Schmid, S. Vey, and Rothacher, M.: Comparisons of homogeneously reprocessed GPS and VLBI long time-series of troposphere zenith delays and gradients, J. Geod., 81(6-8), 503–514, doi: 10.1007/s00190-006-0124-y, 2007.

Tesmer,V., J. Boehm, R. Heinkelmann and Schuh, H.: Effect of different tropospheric mapping functions on the TRF, CRF and position time-series estimated from VLBI, Journal of Geodesy June 2007, Volume 81, Issue 6, pp 409-421, 2007.

Tregoning, P. and Van Dam, T.: Atmospheric pressure loading corrections applied to GPS data at the observation level, Geophysical Research Letters, 32, 22, 2005.

Tregoning P., Watson C.: Atmospheric effects and spurious signals in GPS analyses. J. Geophys. Res., 114, B09403, doi: 10.1029/2009JB006344, 2009.

Van Dam, T., G. Blewitt, and Heflin, M. B.: Atmospheric pressure loading effects on Global Positioning System coordinate determinations, Journal of Geophysical Research, 99, B12, 23939, 1994.

Vey, S., R. Dietrich, M. Fritsche, A. Rulke, P. Steigenberger, and Rothacher, M.: On the homogeneity and interpretation of precipitable water time series derived from global GPS observations, J. Geophys. Res., 114, D10101, doi: 10.1029/2008JD010415, 2009.

Voelksen, C.: An update on the EPN Reprocessing Project: Current Achievements and Status, Presented at EUREF 2011 Symposium, Chisinau, Republic of Moldova, May 25-28 2011, http://www.epncb.oma.be/_documentation/papers/eurefsymposium2011/an_update_on_epn_reprocessing_project_current_achievement_and_status, 2011.

Wang, J., Zhang, L., Dai. A.,Van Hove, T.,Van Baelen, J.: A near-global, 2-hourly data set of atmospheric precipitable water dataset from ground-based GPS measurements, J Geophys Res 112(D11107). doi:10.1029/2006JD007529, 2007.

Wang, J. and Zhang, L.: Climate applications of a global, 2-hourly atmospheric precipitable water dataset derived from IGS tropospheric products, J Geod 83: 209. doi: 10.1007/s00190-008-0238-5, 2009.

Webb, F. H., and Zumberge, J.F.: An Introduction to GIPSY/OASIS II. JPL D-11088, 1997.

Vedel, H., K. S. Mogensen, and X.-Y. Huang: Calculation of zenith delays from meteorological data comparison of NWP model, radiosonde and GPS delays, Phys. Chem. Earth Pt. A, 26, 497–502, doi: 10.1016/S1464-1895(01)00091-6, 2001.

Zus, F, Dick, G, Heise, S, Dousa, J, and Wickert J.: The rapid and precise computation of GPS slant total delays and mapping factors utilizing a numerical weather model, Radio Sci, 49(3): 207-216, doi: 10.1002/2013RS005280, 2014.

**Table**

**Table Captions**

Table 1: EPN Analysis Centres providing EPN-Repro2 solutionsTable 1: EPN Analysis Centres providing EPN Repro2EPN-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 2: EPN Repro2EPN-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 biases (see text) for each contributing solutionTable 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 (EGRD = east gradient, NGRD = north gradient)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.

**Formatted:** English (U.K.)

**Formatted:** Font: Not Italic, English (U.K.

**Formatted:** English (U.K.)

**Formatted:** English (U.K.)

**Formatted:** Font: Not Italic, Check spellin and grammar

**Formatted:** Font: Not Italic, Check spellin and grammar

**Formatted:** Font: Not Italic

| 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~~EPN-Repro2 solutions.

| | AS0 | GO0 | GO1 | GO4 | IG0 | LP0 | LP1 | MU2 | MU4 |
|---|---|---|---|---|---|---|---|---|---|
| **software~~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)<br>GRAD (5min) | ZTD (1h)<br>GRAD (6h) | | | ZTD (1h)<br>GRAD (6h) | ZTD (1h)<br>GRAD (24h) | | ZTD (1h)<br>GRAD (24h) | |
| **MAPPING FUNCTION** | VMF1 | GMF | VMF1 | VMF1 | GMF | GMF | VMF1 | VMF1 | |
| **ZTD/GRAD time stamp** | hh:30<br>24 estimates/day | hh:30 (and hh:00)<br>24(+24) estimates/day | | | hh:30<br>24 estimates/day | hh:30 (and hh:00)<br>24(+24) estimates/day | | hh:30<br>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 | |
| **ELE~~VE~~VATION 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~~EPN-Repro2 processing options for each contributing solutions. AS0 solution~~s~~ is provided by ASI/CGS (Matera, Italy), GO0, GO1 and GO4 solutions are provided by GOP (Pecny, Czech Republic), IG0 solution ~~provided~~ by IGE (Madrid, Spain), LP0 and LP1 solutions ~~provided~~ by LPT (Waben, Switzerland), and MU2 and MU4 solutions ~~provided~~ by MUT (Warsaw, Poland).

**Comment [RVM39]:** Please write out, thi incomprehensible for a reader not experien in GPS.

**Comment [RVM40]:** Precise Point Positioning, write out or use a footnote.

**Comment [RVM41]:** Here or in the text: these should be explained at least once.

| 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 biases (see text) 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 (EGRD = east gradient, NGRD = north gradient).

**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 becomes significant starting from 2008.~~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 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 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 differences time series 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 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 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 ZTD biases and standard deviations for the three contributing solutions AS0, GO4 and MU4 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.~~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 ZTD biases (upper part) and standard deviations (lower part) of each contributing solution w.r.t. the final EPN-Repro2 combination.~~Figure 6 Weekly mean bias (upper part) and standard deviation (lower part) of each contribution solutions w.r.t. the final EPN Repro2EPN 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.~~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 (for definition, see Fig. 7) in the up component for the period July 21st, 1996 - July 28, 2007 (GPS weeks 0863-1437).~~Figure 8 VENE~~

**Formatted:** Font color: Auto
**Formatted:** Font: Not Italic, Font color: Auto
**Formatted:** Font color: Auto, Do not che[ck] spelling or grammar
**Formatted:** Font color: Auto
**Formatted:** Font: Not Italic, Font color: Auto, Check spelling and grammar
**Formatted:** Font color: Auto
**Formatted:** Font: Not Italic
**Formatted:** Font: Font color: Black
**Formatted:** Not Superscript/ Subscript
**Formatted:** Not Superscript/ Subscript
**Formatted:** Font color: Auto
**Formatted:** Font: Not Italic, Font color: Auto, Check spelling and grammar
**Formatted:** Font color: Auto
**Formatted:** Font color: Auto, English (U.[K.])
**Formatted:** Font color: Auto
**Formatted:** Font: Italic
**Formatted:** Font: Not Italic
**Formatted:** Not Superscript/ Subscript
**Formatted:** Font: Not Italic, Check spelli[ng] and grammar
**Formatted:** English (U.K.)
**Formatted:** Font: Not Italic, English (U.K.[)], Check spelling and grammar
**Formatted:** English (U.K.)
**Formatted:** English (U.K.)
**Formatted:** Font: Not Italic, English (U.K.[)], Check spelling and grammar
**Formatted:** English (U.K.)
**Formatted:** English (U.K.)
**Formatted:** Not Superscript/ Subscript

~~(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 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 mean ZTD biases (left) and standard deviations (right) of EPN-Repro1 and Repro2 compared to ERA-Interim.~~Figure 11: Distributions of station means (left) and standard deviations (right) of EPN Repro1EPN-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 12: Site-by-site ZTD improvements of EPN Repro2EPN-Repro2 versus EPN Repro1EPN-Repro1 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 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 Repro2EPN-Repro2 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 Repro2EPN-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.~~

**Formatted:** Font: Not Italic, Check spelling and grammar

**Formatted:** English (U.K.)

**Formatted:** Font: Not Italic, English (U.K.)

**Formatted:** Font: Not Italic

**Formatted:** Font: Not Italic, English (U.K.)

**Formatted:** Font: Not Italic, Check spelling and grammar

**Formatted:** Font: Not Italic, Check spelling and grammar

**Formatted:** Font: Not Italic, Check spelling and grammar

**Formatted:** Font: Not Italic, Check spelling and grammar

**Formatted:** Font: Not Italic, Check spelling and grammar

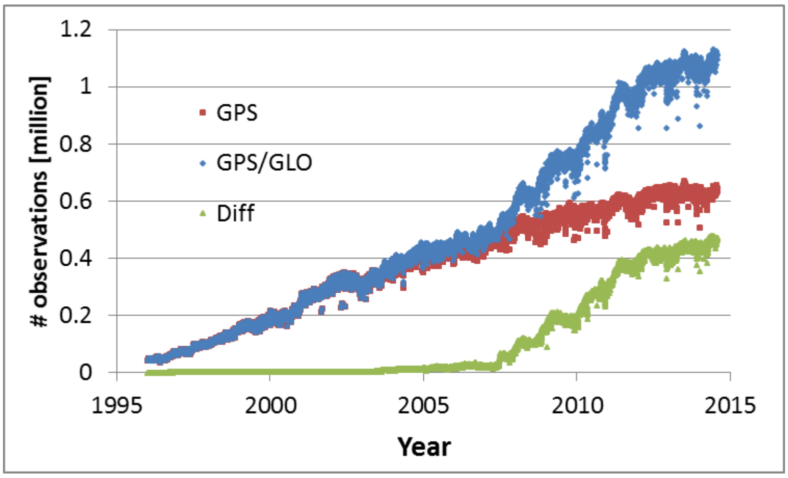


Figure 1. Time series of the number of GNSS observations for the period 1996-2014. GPS observations are shown in red, GPS+GLONASS in blue and their differences in green. The difference becomes~~is~~ significant starting from 2008.

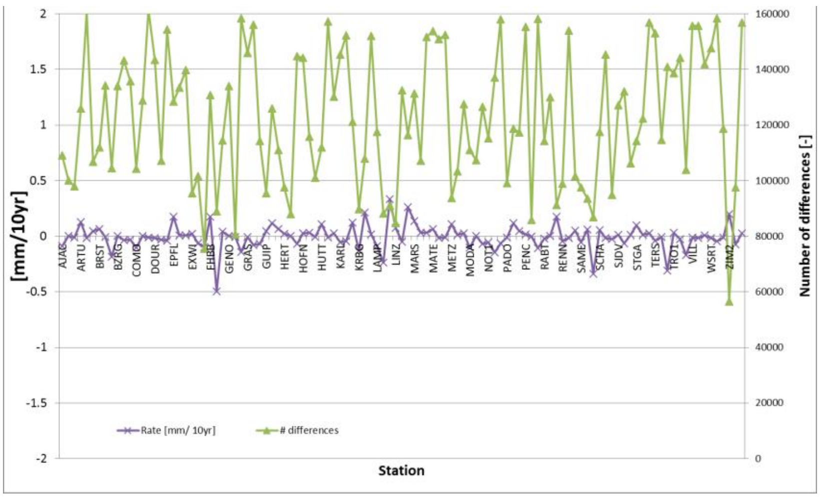


Figure 2. ZTD trend differences between GPS only and —GPS+/GLONASS, computed over 111 sites. The rate is in violet (primary y-axis) and the number of used differences is in green (secondary y-axis).

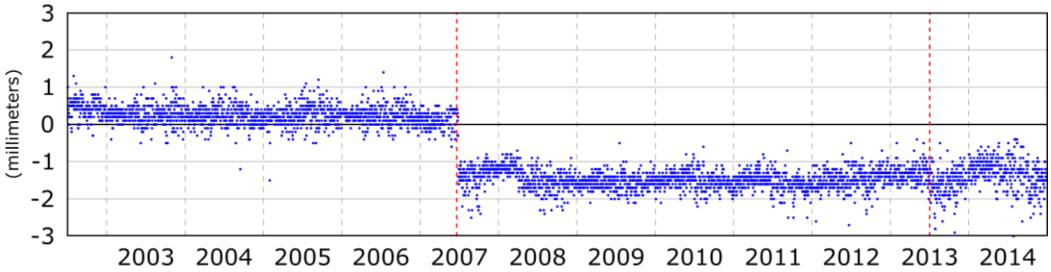


Figure 3. EPN station KLOP (Kloppenheim, Frankfurt, Germany) ZTD differences time series ~~difference~~ between solutions processed with ‘individual’ and ‘type mean’ antenna calibration models. Two instrumentation changes occurred at the station (marked by vertical dashed red lines): the first in June 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.

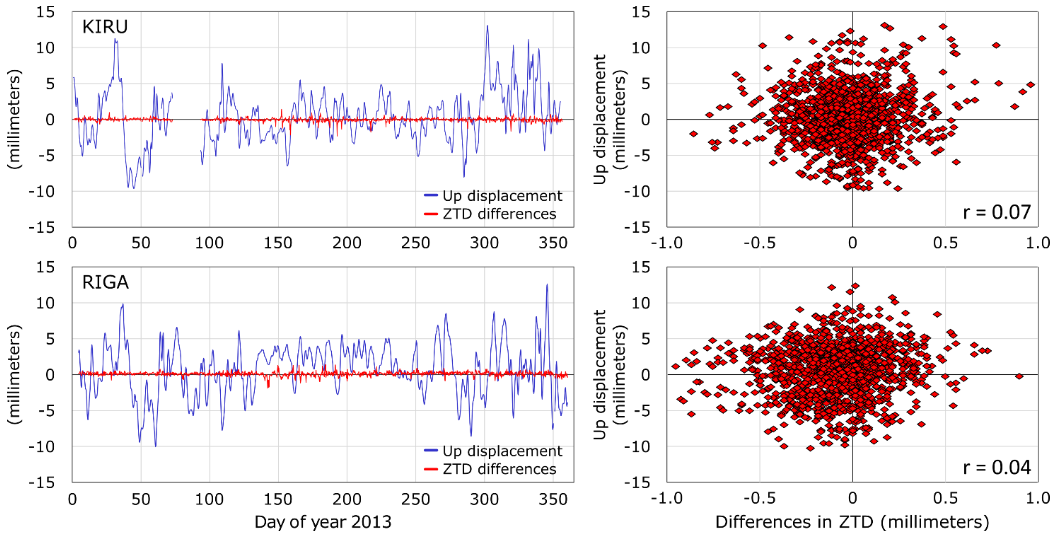


Figure 4. Left part: Time series of the ZTD and up component differences between two time series obtained with and without nNon-tTidal aAtmospheric lLoading for two EPN stations: KIR0 (Kiruna, Sweden) and RIGA (Riga, Latvia). Right part: Scatter plots Correlation between these two parameters.

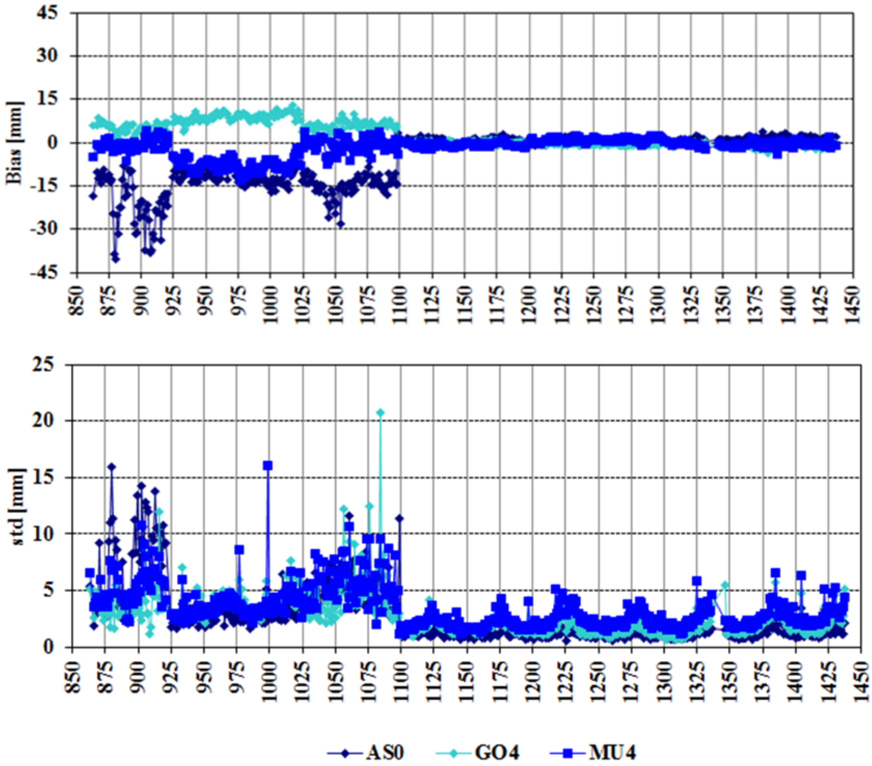


Figure 5: VENE (Venice, Italy) time series of ZTD biases and standard deviations for the three contributing solutions AS0, GO4 and MU4 with the combined solution for the period July 21st, 1996 - July 28, 2007 (GPS weeks 0863-1437). GO0 and GO1 are not shown here, since they are very close to GO4.

**Comment [RVM42]:** I assume?

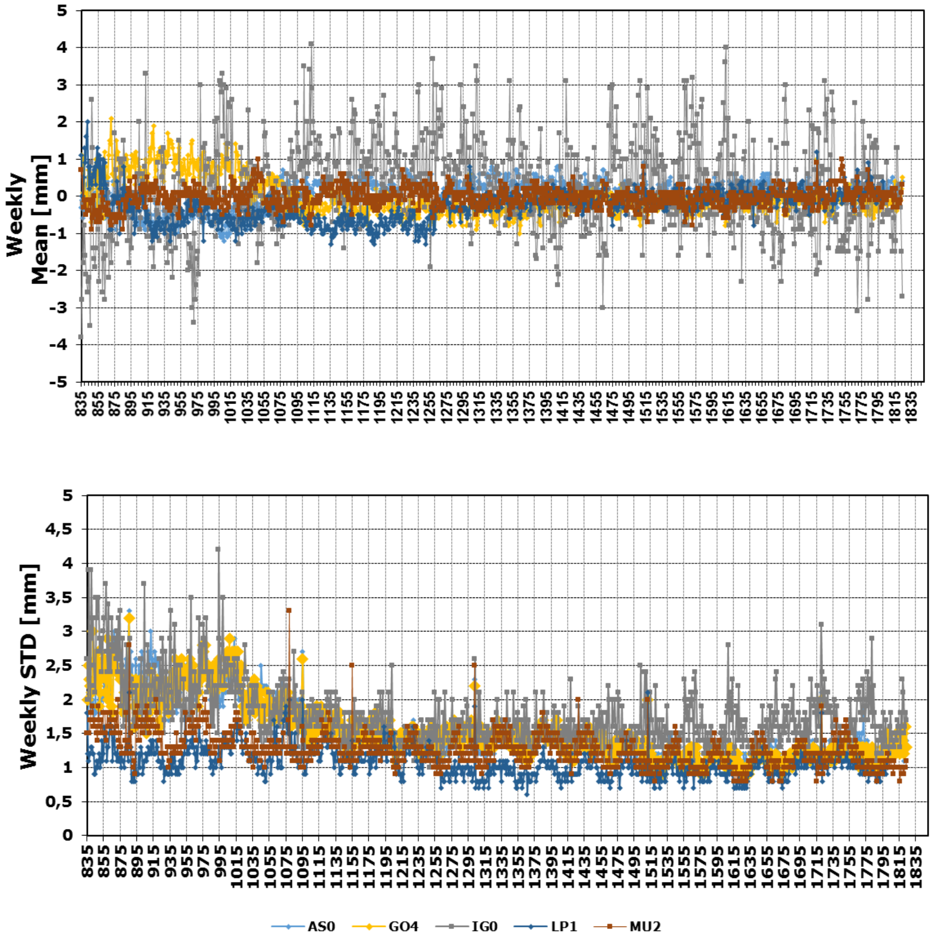


Figure 6: Weekly mean ZTD biases (upper part) and standard deviations (lower part) of each contributingion solutions w.r.t. the final EPN-Repro2EPN-Repro2 combination.

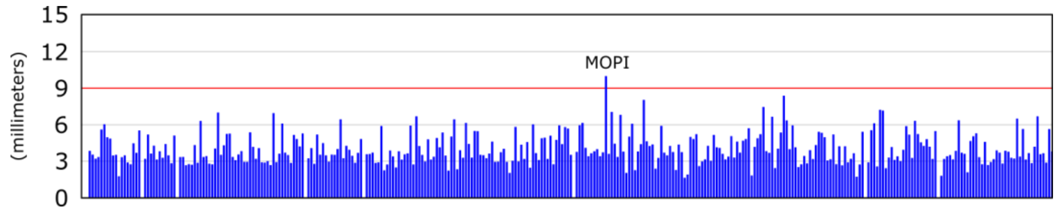


Figure 7. The final consistency in the up component, calculated as the difference between the EPN-Repro2 combination and the combination performed by the EPN AC coordinator, for all stations. Stations are sorted by name.

**Comment [g43]:** Please correct if I got thi wrong. In any case, you should explain here how "consistency" is defined or calculated.

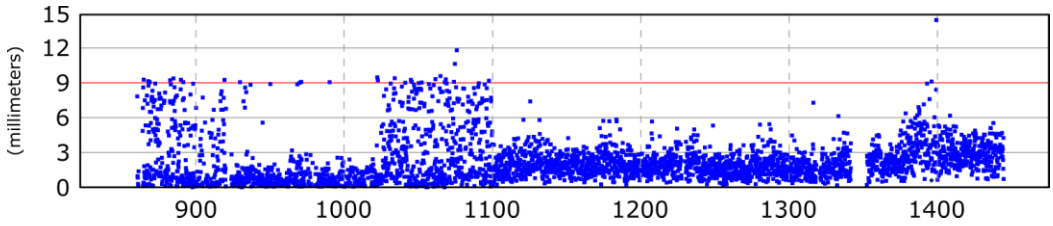


Figure 8 VENE (Venice Italy) time series of total consistency (for definition, see Fig. 7) in the up component for the period July 21st, 1996 - July 28, 2007 (GPS weeks 0863-1437).

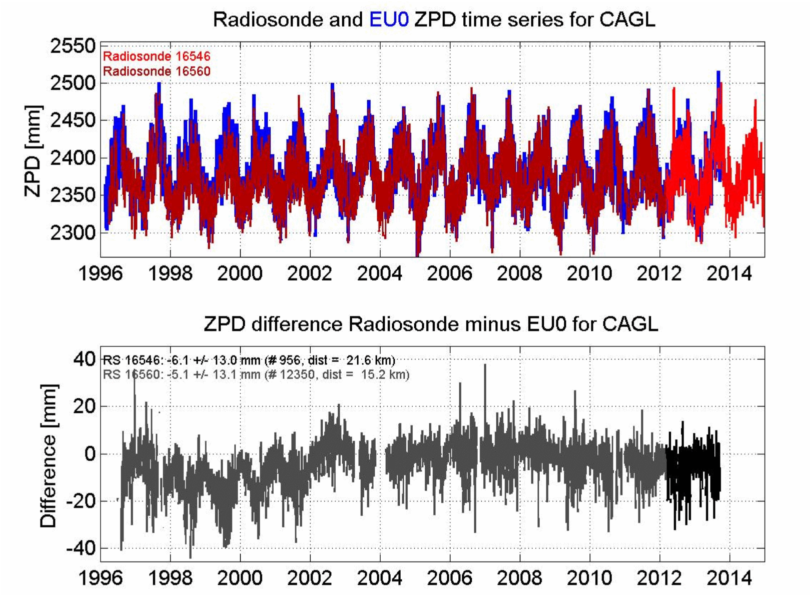


Figure 9 EPN station CAGL (Cagliari, Sardinia Island, Italy). Upper part: Radiosondes (in red) and GPS (in blue) ZTD time series. Lower part: ZTD differences, calculated as RS minus GPS.

**Comment [g44]:** In this figure, you use ZP 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 th titles and the label in the figure!

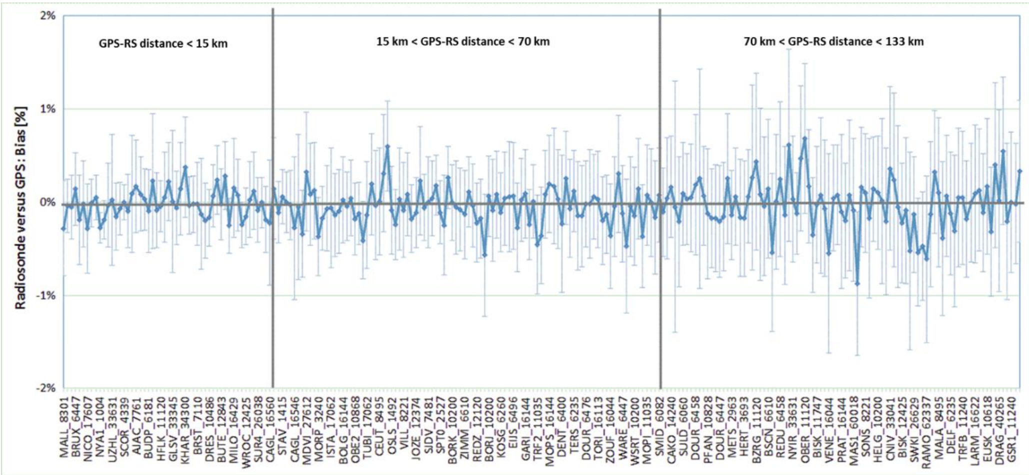


Figure 10~~10~~: RS minus GPS ~~versus Radiosonde~~ZTD b~~B~~iases for all GPS-RS station pairs. The error bar is the standard deviation. Sites are sorted ~~according to the~~with increasing distances from the nearest r~~R~~adiosonde launch site. The x-axis ~~reports~~ shows the GPS station and the r~~R~~adiosonde site WMO code.

**Formatted:** English (U.S.)

**Field Code Changed**

**Formatted:** English (U.S.)

**Formatted:** English (U.S.)

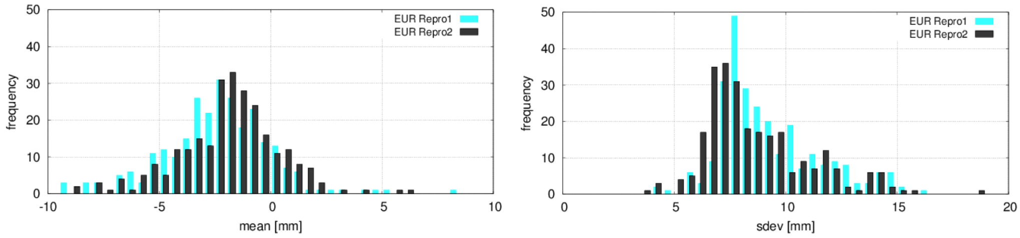


Figure 11: Distributions of station mean ZTD biasess (left) and standard deviations (right) of EPN Repro1EPN-Repro1 and Repro2 ZTDs compared to ERA-Interim ZTDs.

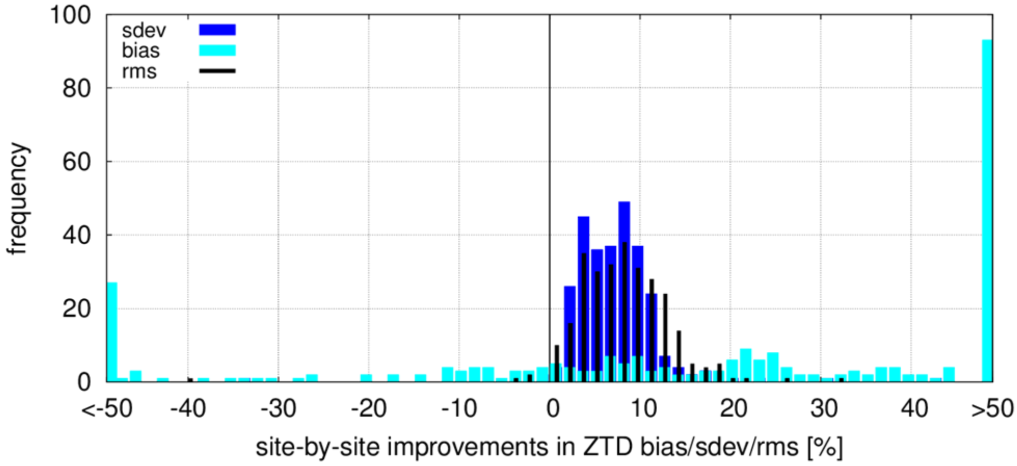


Figure 12: Site-by-site ZTD improvements of EPN Repro2EPN-Repro2 versus EPN Repro1EPN-Repro1 compared to ERA-Interim.

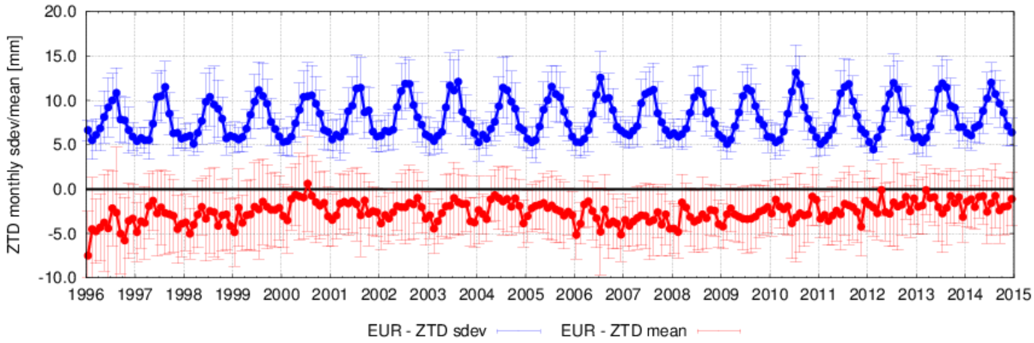


Figure 13: Time series of monthly mean biases (lower part) and standard deviations (upper part) for ZTD differences betweenof EPN Repro2EPN-Repro2 and NWMERA-interim re-analysis (GPS minus ERA-interim?). Uncertainties are calculated over all stations.

**Comment [RVM45]:** Please confirm or modify.

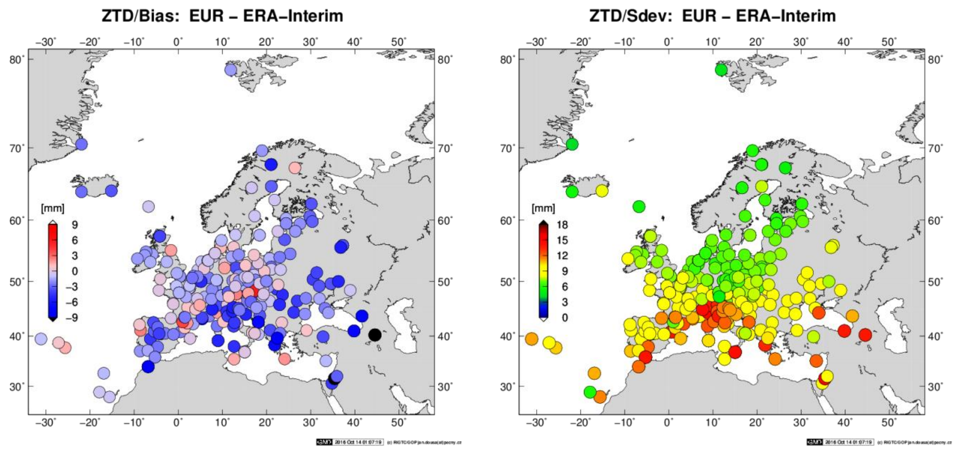


Figure 14: Geographical distribution~~display~~ of ZTD biases (left) and standard deviations (right) for ~~EPN Repro2~~EPN-Repro2~~ products~~ compared to ~~the ~~ERA-Interim.

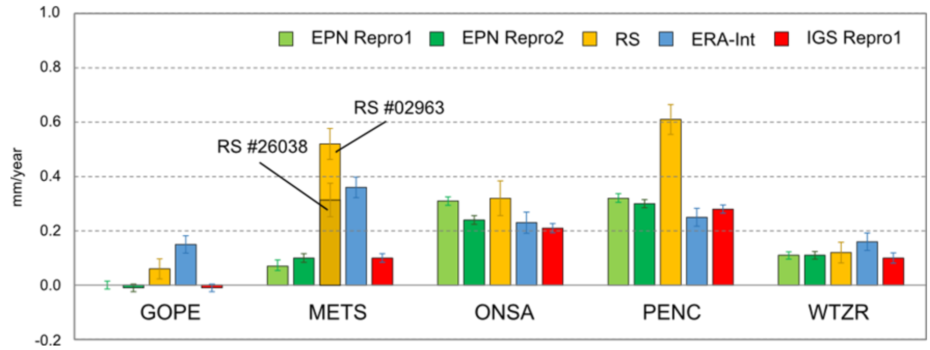


Figure 15: ZTD trend comparisons at five EPN stations for 5 different ZTD datasets. The error bars are the formal errors of the estimated trend values.