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1. Contribution to the EUREF Permanent Network (EPN)

1.1 EPN Central Bureau

ROB continued to manage the EUREF Permanent Network Central Bureau. Since June 2019, ROB integrated 21 new EPN stations in the EPN network. Details are given in the presentation Bruyninx et al., 2019.

Next to the core EPN network, ROB also collects and validates the metadata of the EPN densification network. This is done using the new "M^{3}G" (Metadata Management and Dissemination System for Multiple GNSS Networks, https://gnss-metadata.eu) that was developed by ROB. Since the fall of 2018, this system is operationally used in EUREF. The advantage of M^{3}G is that it manages in a consistent way the metadata of the EPN, EPN densification, as well as EPOS (European Plate Observing System) GNSS stations. As a result, ROB is today providing access to a unique collection of GNSS metadata for 2056 European GNSS stations (see Figure 1).

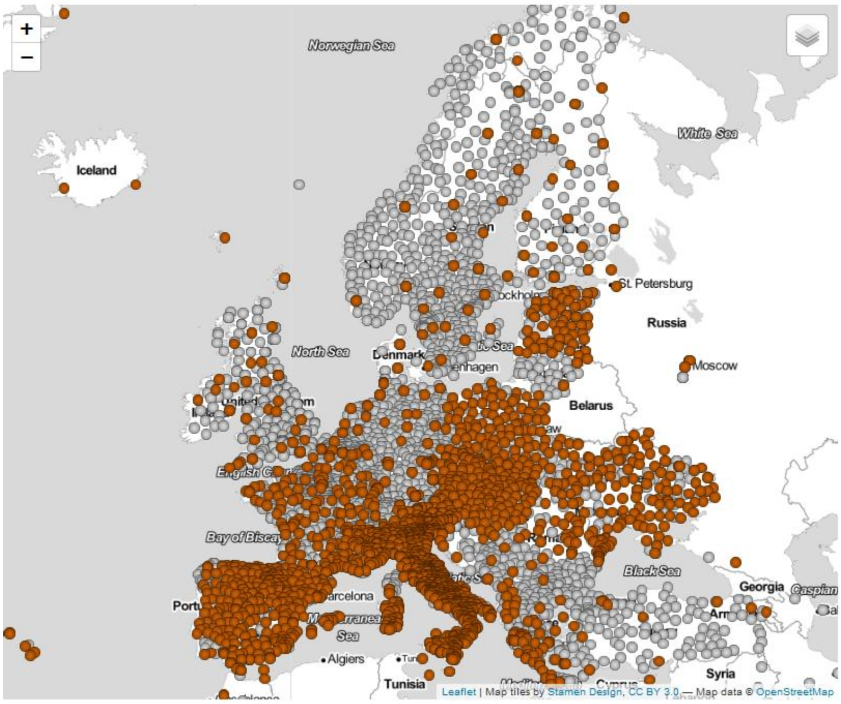

Figure 1: Network of GNSS stations involved in the EPN, EPN densification, EPOS or E-GVAP projects. Stations indicated in brown provide centralized metadata through M^{3}G.

Our continuous efforts to reliably trigger alarms for EPN stations with degraded data quality have resulted in the need to reanalyse the data quality of 23 years of historical EPN data and look in to the detailed results (available from http://www.epncb.oma.be/). We demonstrated the improvement of low elevation tracking since the start of the EPN. This could be explained by the fact that older receivers had a limited number of channels and consequently EPN guidelines did request tracking down to zero degrees of elevation. For GLONASS, a general degradation of the dual frequency tracking is seen since 2016. This degradation is caused by the fact that some GLONASS satellites have an impaired L2 frequency. Today, concerning Galileo and BeiDou, we noticed that fewer satellites are tracked at low elevations compared to GPS and GLONASS. This problem is especially seen for receivers, which have a lower number of channels. The signals of the new BDS-3 satellites (declared healthy since Dec. 2018) are also not fully tracked by a significant number of EPN stations.

Finally, we noticed that, depending on receiver type and RINEX conversion software, RINEX 2 data could have up to 10% less GPS data than RINEX 3. More details are available from Bruyninx et al, 2019.

1.3 Data Analysis

ROB continued to deliver daily rapid and final position and tropospheric zenith path delay estimates for an EPN subnetwork (Figure 2, left) to EUREF. Since GPS week 2044 (March 2019), ROB the final solutions is based on Galileo observations in addition to GPS and GLONASS.
ROB also continued to submit a dedicated EPN densification solution to EUREF containing also results for non-EPN stations in and around Belgium (see Figure 2, right). This network contains about 250 GNSS stations and the results are used by the EPN densification Working Group to create a dense European velocity field.

Figure 2: Left GNSS network processed as a contribution to EPN core products; Right GNSS network processed as a contribution to the EPN densification working group

1.4 Reference Frame Coordination

ROB is responsible for the Reference Frame Coordination of the EUREF. The reference frame coordinator maintains the European densification of the IGS reference frame in order to maintain the ETRS89. For this purpose, an EPN multi-year position and velocity solution is computed and updated each 15 weeks. This solution is estimated with the CATREF software (Altamimi et. al., 2007) and updated each 15 weeks.
Starting with the release of IGS14 (January 2017, GPS week 1934), the EPN multi-year position and velocity solution is based on the daily EPN-Repro2 solutions (from GPS week 834 to GPS week 1772) and the daily EPN routine solutions (from GPS weeks 1773 up to present). This solution has a

revised discontinuity list and incorporates the ITRF2014 post-seismic deformation models (ftp://itrf.ign.fr/pub/itrf/itrf2014/ITRF2014-psd-gnss.dat) for five stations: ANKR00TUR, BUCU00ROU, ISTA00TUR, REYK00ISL, TUBI00TUR (see Legrand et al., 2017). It is consistent with the epn_14.atx ground antenna calibrations and aligned to the IGS14 reference frame. In order to insure the consistency of the daily solutions with the IGS14/epn_14.atx, the positions prior to GPS week 1934 were corrected for the position changes caused by the change from epn_08.atx to epn_14.atx. To maximize the consistency with IGS, when available, the position offsets computed by the IGS for IGS station/antenna pairs were applied. If not available, the latitude-dependent models (IGSMAIL-7399) of the expected position offsets were applied.

Since the last symposium, four multi-year EPN solutions have been published (C1995, C2010, C2025, and C2040). The consistency of the EPN multi-year solution wrt to the IGS14 and the weekly updates of the IGS multi-year solution are monitored at each update by comparing the list of position and velocity discontinuities applied and position/velocity estimates. For example, for GPS Week 2025, 522 position and velocities estimates are common to both solutions (C2025 for EPN and IGS18P44 for the IGS solution). 80% of the position differences are below 0.9, 1.2, and 3.7 mm on resp. the East, North and Up components. In addition, there are no systematic and significant biases as the mean position differences are 0.1, -0.3, 0.4 mm on resp. East, North and Up components. For the velocities, 80% of the differences are below 0.2, 0.2, and 0.5 mm/yr on the East, North and Up components. The mean differences are 0.01, -0.06, and 0.08 mm/yr on the East, North and Up velocity components. Larger differences can mostly be explained by significantly lower data availability in the IGS solution compared to the EPN.

The EPN multi-year product files (including the discontinuity list and associated residual position time series) are available at ftp://epncb.eu/pub/station/coord/EPN/. More details can be found in http://epncb.eu/_productsservices/coordinates/. The residual daily position time series and position time series in IGS14 and ETRF2014 are available online at http://epncb.oma.be/_productsservices/timeseries/. In addition, extended time series are updated every day by completing the EPN multi-year solution with the more recent EPN final and rapid daily combined solutions. Together with the quality check monitoring performed by EPN CB, these quick updates allow to monitor the behaviour of the EPN stations and to react promptly in case of problems.

2. Troposphere

2.1 Tropospheric Products and E-GVAP Analysis Centre

ROB maintained its GNSS analysis centre participating to the E-GVAP program, and provided European meteorological institutes with tropospheric Zenith Path Delay (ZPD) estimates for assimilation in the Numerical Weather Prediction (NWP) models. This 24x7x365 service includes:

1) a hourly European analysis (~ 680 stations, mainly EPN + national densifications),
2) a hourly global analysis (~310 stations, mainly IGS sites) to support global NWP models,
3) a processing running every 15 minutes to support nowcasting applications in the Benelux + U.K. area based on the processing of real-time observations from ~260 EPN and national GNSS stations.

2.2 Long-term Stability of GNSS-based Tropospheric Zenith Path Delays

Within the IAG Working Group 4.3.8, ROB, RMI (Royal Meteorological Institute, Belgium), and MUT (Military University of Technology, Warsaw, Poland) collaborated with other international institutes on the subject of "tropospheric time series homogenisation". During a benchmark campaign, they evaluated the performances of different statistical tools to identify breakpoint/offsets in these time series using synthetic tropospheric time series. During the last year, the results have been analysed, discussed, and feedback to homogenisation tool operator was given. A review presentation on the subject was given at the EGU 2018 and a paper will be submitted in 2019.

ROB continued to collaborate with the RMI and ASI to evaluate the atmospheric water vapour content in the regional (European-wide) climate model ALARO (used by RMI) coupled to the land surface scheme SURFEX based on the EPN repro 2 tropospheric product. The study also uses the ERA-Interim reanalysis as ‘reference model’ for comparison. Results obtained from this large dataset (18 years, 1996-2014) show the very good (global) agreement between the climate models and the water vapour content derived from GNSS observations (typical bias < 1 kg/m², Figure 3). It also underpins interesting discrepancies when looking in more details, such as the underestimation of the water vapour content (i.e. a dry bias in the model) during the summer period by ALARO-0 (Figure 4). The latest being tightly link to a precipitation bias. A paper on these results will be submitted in 2019.

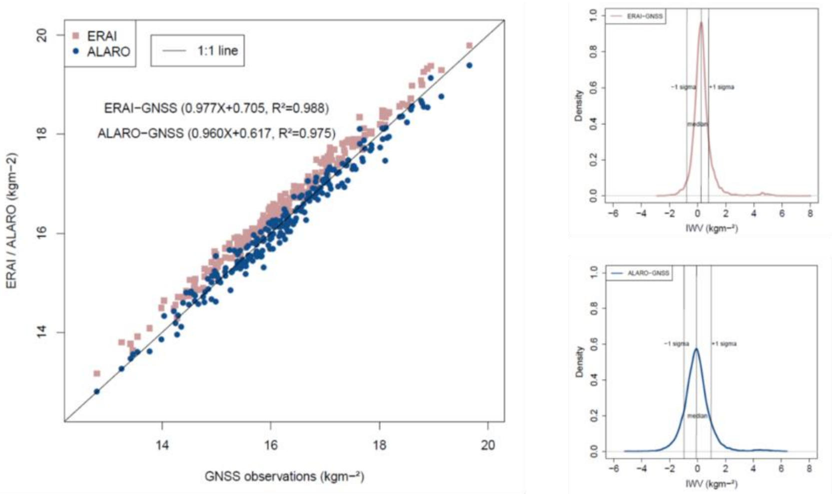

Figure 3:In blue (resp. in brown), agreement between the Integrated Water vapour (IWV) from the climate model ALARO-0 run by RMI (resp. the NWP re-analysis ERA-Interim from ECMWF) and the IWV from the ‘GNSS observations’. (Left): Scatter plots. (Right): Density distribution of the IWV differences. The ERAI shows a slight positive overall bias (i.e. over all stations and over 15 years) while the ALARO-0 has no overall bias.

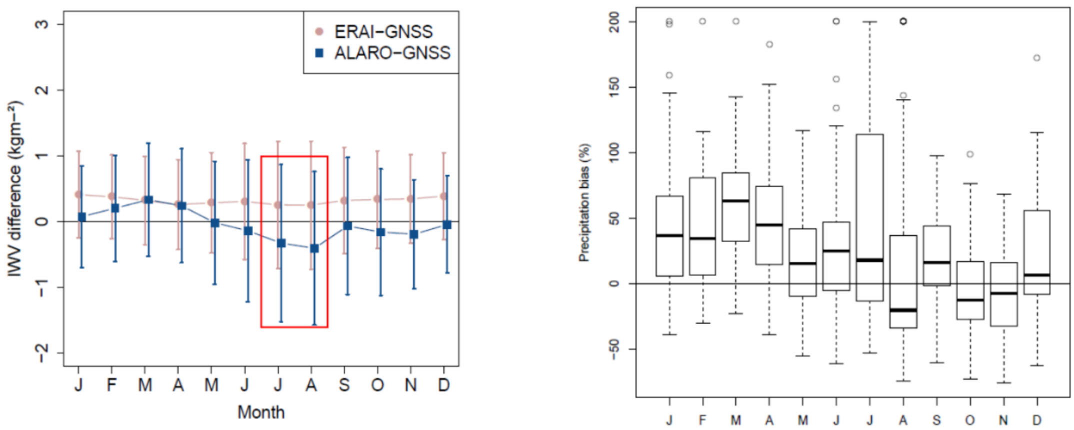

Figure 4: (Left): In blue (resp. in brown) overall agreement between the IWV from the climate model ALARO-0 run by RMI (resp. the NWP re-analysis ERA-Interim run by ECMWF) and the IWV derived from ‘GNSS observations’ for each month of the year (stacked over 18 years and all stations) emphasizing the variations of the bias between model and observations over the months of the year, while the ERA-Interim emphasises almost no variations, but a constant

positive bias. (Right): A very similar variations over the months of the year is visible in the precipitation bias of the ALARO-0 climate model.

ROB continued to collaborate with RMI to study the seasonal variabilities and trends in the atmospheric water vapour at about 100 worldwide IGS station locations based on GNSS, satellite observations (GOME, SCIAMACHY, GOME2), and models (ERA-Interim, NCEP/NCAR). The main drivers of these variabilities have been investigated based on a multiple linear-regression approach and numerous proxies (i.e. circulation, oscillation, and teleconnection patterns; e.g. north Atlantic oscillation, El Niño/La Niña…). A paper on this topic was submitted to the COST Action ES1206 GNSS4SWEC special issue (van Malderen et al., 2018).

3. Ionosphere

3.1 Ionospheric Products and Space Weather impact

ROB continued to maintain its near real-time products dedicated to Space Weather generated by the ROB-IONO software using GNSS data from the EPN. Ionospheric maps and Solar Radio Burst Warnings are displayed online at www.gnss.be and IONEX data are available at ftp://gnss.oma.be.
In 2018, one ionospheric event was reported.

Based on the investigation of the impact of Solar Radio Bursts emitted close to the GNSS frequencies, ROB provides a near-real time 4-level index alert detecting and quantifying solar radio bursts impacting GNSS signal reception of the EPN. No recent solar radio bursts occurred at the GNSS frequencies, but in April 2018 an increase of GPS signal power at L2 frequency at the cost of the L1 frequency was highlighted. This increase was not related to a space weather event, but due to the activation of the anti-jam flex power of the Block IIR-M and IIF satellites by the US government.

ROB is involved in the PECASUS project, a project that addresses Space Weather effects on aviation in Europe. We provide real-time ionospheric vTEC data and alerts, together with real-time alerts for solar radio bursts impacting the GNSS signal reception.

3.2 Inter-hemispheric comparison (Europe – South Africa) of the ionosphere-plasmasphere system

GNSS data (GPS+GLONASS) of the dense EUREF Permanent GNSS Network (EPN) was analyzed together with the South African TRIGNET network as well as IGS stations for the period 1998-2017 in the frame of the BEZA-COM (proposal for the Belgian-South-African Research and Technology Cooperation call). The goal is to provide inter-hemispheric comparison of the ionosphere/plasmasphere system (I/Ps). implying: (1) a characterization of the climatological behavior of the Total Electron Content (TEC) in the I/Ps, over European, South African, Arctic and Antarctica regions; (2) an identification of the mechanisms that regulate inter-hemispheric differences, asymmetries and commonalities in the I/Ps from low to high-latitudes, (3) study of the different responses of the I/Ps during extreme solar events and induced geomagnetic storms in the two hemispheres (presentation at URSI 2018).

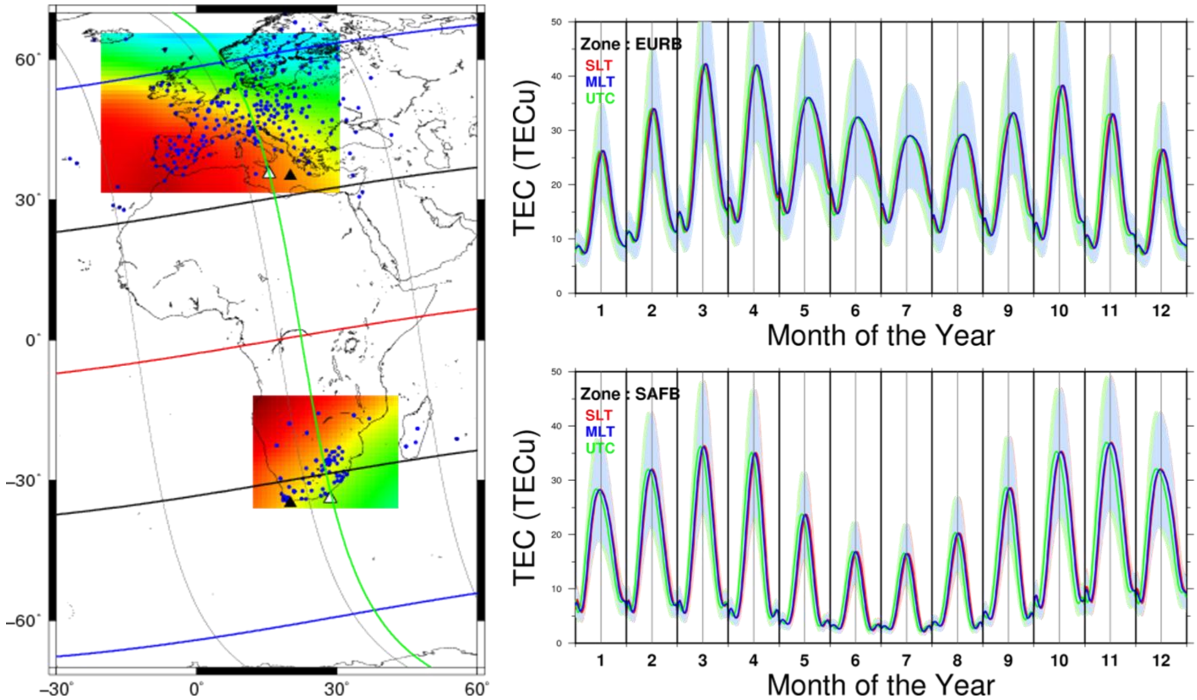

Figure 5: Monthly climatological behavior of the daily TEC for the two hemispheres. Left: GNSS network used. The blue circles are the GNSS stations used for the period 1998-2017. The red, black, blue lines are the geomagnetic latitudes latitudes (0°, ± 30° and ± 60°). The green line represents the geomagnetic longitude E95°. The white and black triangles (geographic and geomagnetic coordinates respectively) are the locations considered for inter-hemispheric comparison. The TEC maps are given for year 2015, DoY 076, time 15:00 UTC. Right: Monthly climatological behavior of the daily TEC for the two hemispheres and different time definitions: SLT (red), UTC (green) and MLT (blue). Right top: for the European location E95° N35° in geomagnetic coordinates. Right bottom: For the South African location E95° S35° in geomagnetic coordinates.

3.3 Time Ionosphere Monitoring Working Group (RTIM-WG)

We continued taking part to the study concerning the comparison of multiple independent near-real time ionospheric approaches as well as the effect of the Saint-Patrick Storm (17 March 2015 event) in the frame of the Real Time Ionosphere Monitoring - Working Group (RTIM-WG) from the International Association of Geodesy (IAG, presentation at EGU 2018).

4. National geodetic reference infrastructure

4.1 AGN (Active Geodetic Network)

Since 2002 we perform a daily and weekly solution for all the permanent GNSS stations in Belgium that are part of the three Belgian RTK networks. We continue doing this work to check the stability of those stations. The results of this monitoring are available at www.ngi.be/agn/.
Since the beginning of 2015 we are taking part in the **EPN Densification project** and we deliver every week a solution to this project from all those permanent GNSS stations. We have been delivering all our weekly solutions starting from week 1656 (2 October 2011) up to week 2050.
The three Belgian RTK providers are in the process of changing their hardware, to make it Galileo compliant. The RTK provider Flepos (Flemish Positioning Service) will gradually do this in the course of 2018 (19 receivers and 3 antennas have already been changed). For GPSBru the hardware of the RTK station in Brussels has been replaced in January this year. Walcors (Wallonia Continuously Operating Reference System) has planned to do the switch in 2019.

4.2 Update of the levelling network and a new height conversion model

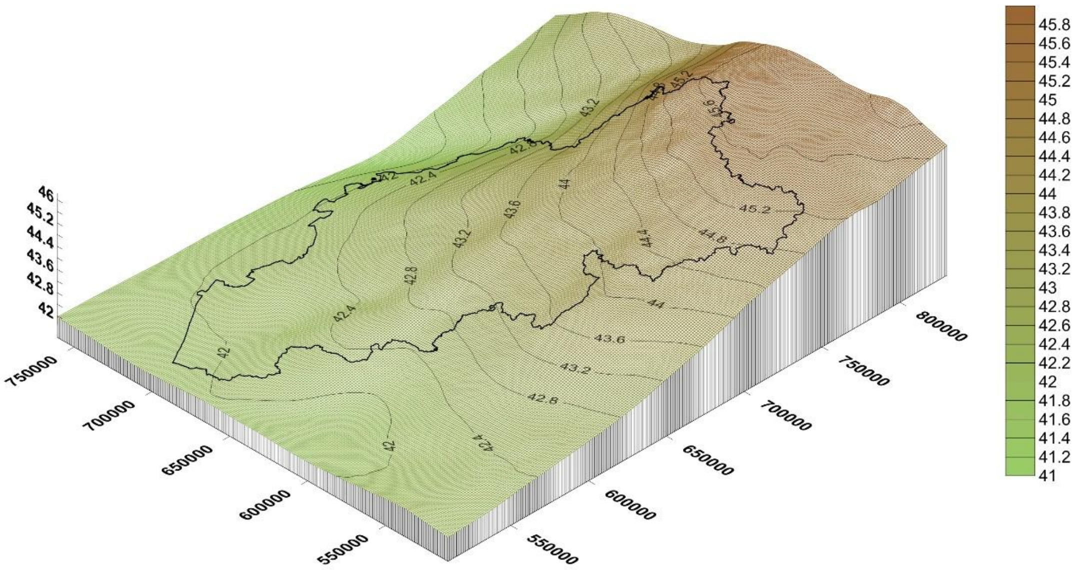

Figure 6: 3-D representation of our new height conversion model hBG18. In x and y we see the coordinates in Lambert2008 (m). In z we see the geoidal height or the N-value (m)

On the 1ste of august 2018 we have replaced our height conversion model hBG03 by a new model **hBG18** and at the same time the new heights for the levelling benchmarks where published.

- This model was made by combining: the quasi-geoid model NLGEO2018grav based on gravity measurements in the Netherlands, Belgium and on the North Sea which was done by R Klees and Dc Slobbe at the Delft University of Technology, Delft, The Netherlands.
- 3707 GNSS/leveling points in Belgium where used to create the new model.

4.3 3D network

As we mentioned last year, it will not be possible to maintain the existing networks of horizontal and vertical benchmarks. So we are not going to perform new observations for these geodetic points, but all valid information will still be available on our website www.ngi.be/gdoc. (Also usable on smartphones).

We started creating a new network with “3D” points. For each of these points we will have GNSS static observations and leveling observations. There will be about 2500 3D points. The distance between the points will be about 5 km. Up to the month of May 2019 about 10% of this work has been done.

4.4 Ground motion Analyses using Radar Interferometry technique

We have started a project with the "Royal Belgian Institute of Natural Sciences Geological Survey of Belgium". The project will provide a cartography of the ground movements in whole Belgium highlighted by radar interferometry. These ground movements will be compared with our levelling points (around 17,800). The main idea consists in characterizing the areas that undergo ground motion and providing a brief analysis of the most probable cause(s). Furthermore, a spatial analysis between each levelling point and the radar interferometry measurements will be realized throughout Belgium.

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