EUREF 2018 NATIONAL REPORT OF BELGIUM

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1. Contribution to the EUREF Permanent Network (EPN)

1.1 Organisation of the EPN Analysis Centres (AC) workshop

The Royal Observatory of Belgium (ROB) organised the tenth EPN Analysis workshop at Brussels, Belgium on Oct. 25-26, 2017. The workshop was very successful and attended by 29 participants from 17 countries. The workshop conclusions (including recommendations to the AC), are available on-line at http://epncb.oma.be/_newseventslinks/workshops/EPNLACWS_2017/.

1.2 EPN Central Bureau

ROB continued to manage the EUREF Permanent Network Central Bureau. Since June 2017, ROB integrated one new station in Portugal in the EPN network.

Next to the core EPN network, ROB also collects and validates the metadata of the EPN densification network. As a result, ROB is today providing access to a unique collection of GNSS metadata for more than 1800 European GNSS stations.

Our web site for the EUREF Permanent Network (EPN, http://www.epncb.oma.be/ or http://www.epncb.eu/), was further extended. The EPN CB team finished the software to create monthly multi-GNSS skyplots based on daily data files in both the RINEX 2 and RINEX 3 format. The results are available for all recent and historical EPN data. Using these new multi-GNSS skyplots, we have been able to detect several new data quality issues at EPN stations and inform the station managers.

In 2017, ROB started the development of our new GNSS station metadata submission and validation system started. It is called "M^{3}G" (Metadata Management and Dissemination System for Multiple GNSS Networks). Even if originally developed in the frame of EPOS[1], the new system will also be used within EUREF because it will have additional functionalities (such as the export of the new GNSS metadata format GeodesyML) compared to the system that we use today at the EPN CB. We released a first (July 25), a second (Oct. 18), and a third (Dec. 13) version of M^{3}G and EPOS data providers are already using this new system today for the submission or their station metadata. For EUREF, the transition from the present EPN on-line site log validation and submission tool will be done one Operational Centre at a time and it is presently on-going.

1.3 Data Analysis

ROB continued to deliver daily rapid and final position and tropospheric zenith path delay estimates to EUREF. As recommended at the EPN AC workshop, ROB started to use the Vienna Mapping

[1] European Plate Observing System integrates European Research Infrastructures for solid Earth science to monitor and understand the dynamic and complex solid-Earth System.

Function (VMF1) together with a priori hydrostatic delays from VMF1 grids (based on atmospheric pressure data from ECMWF[2]), instead of the previously used GMF (Global Mapping Function).
Since mid-2017, ROB is processing two solutions in parallel: a GPS+Glonass solution and a GPS+Glonass+Galileo solution (see Figure 1, left). The last one is only submitted to EUREF for test purposes and it is not used to generate the EUREF products (as recommended at the EPN AC workshop).

ROB also started to submit a dedicated EPN densification solution to EUREF containing also results for non-EPN stations in and around Belgium (see Figure 1, right). This network contains about 250 GNSS stations and the results are used by EUREF densification Working Group to create a dense European velocity field.

Figure 1: 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

Since May 2017, ROB is responsible for the Reference Frame Coordination of the EPN. The responsibility of the reference frame coordinator is to provide the regional densification of the IGS reference frame in Europe in order to maintain of the ETRS89. For this purpose, an EPN multi-year position and velocity solution is computed. 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.

[2] ECMWF: European Centre for Medium-range Weather Forecasting

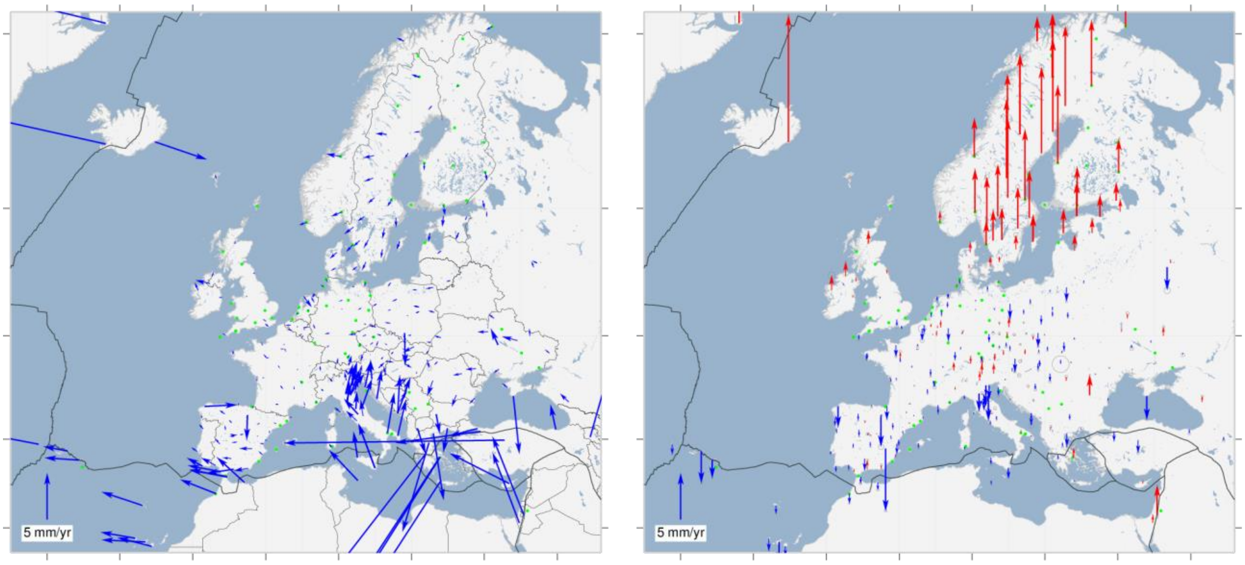


Figure 2: ETRF2014 horizontal (left) and vertical (right) velocity field derived from the EPN cumulative solution C1980. In the ETRF2014, the horizontal velocities are expressed with respect to the Eurasian plate. The Eurasian plate rotation model from ITRF2014 (Altamimi et al., 2017) has been used. The uplift is indicated red, subsidence with blue arrows. The green dots on the map indicate the youngest sites (less than 3 years of observations), which have unrealistic velocities.

Since the last symposium, several multi-year EPN solutions have been published (C1950, C1965, C1980) and C1995 is in preparation. 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, and some plots like the ETRF2014 velocity fields (Figure 2) 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 to the time series of the official product, extended time series are updated every day by adding the recent EPN daily combined solutions not yet included in the final combined EPN solution. 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.

Based on the EPN multi-year position and velocity solution and its associated residual position time series, the EPN stations are categorized taking into account the station quality and the length of the available observation time span (see Figure 3).

The estimated multi-year position and velocity solutions are compared with respect to several external solutions such as ITRF2014, IGS14, IGS17P21 (which is the IGS multi-year solution up to the GPS week 1950) and the previous EPN solution C1934. The C1950 solution shows a good agreement with the different external solutions. For example, Figure 4 shows the histogram of the position (left) and velocity (right) differences between the EPN multi-year solution C1950 (GPS weeks up to 1950) and the IGS solution for the same GPS week (IGS17P21).

The positions differences are computed for each solution number at the epoch 2010.0. In Figure 4 (left), the histograms including all the estimates are shown in black. When using only stations with the same applied discontinuities and more than 2 years of observation, the RMS is 1.3 mm for the North, 1.7 mm for the East and 5.6 mm for the Up component. The histograms of the position differences for this selection are shown in red.

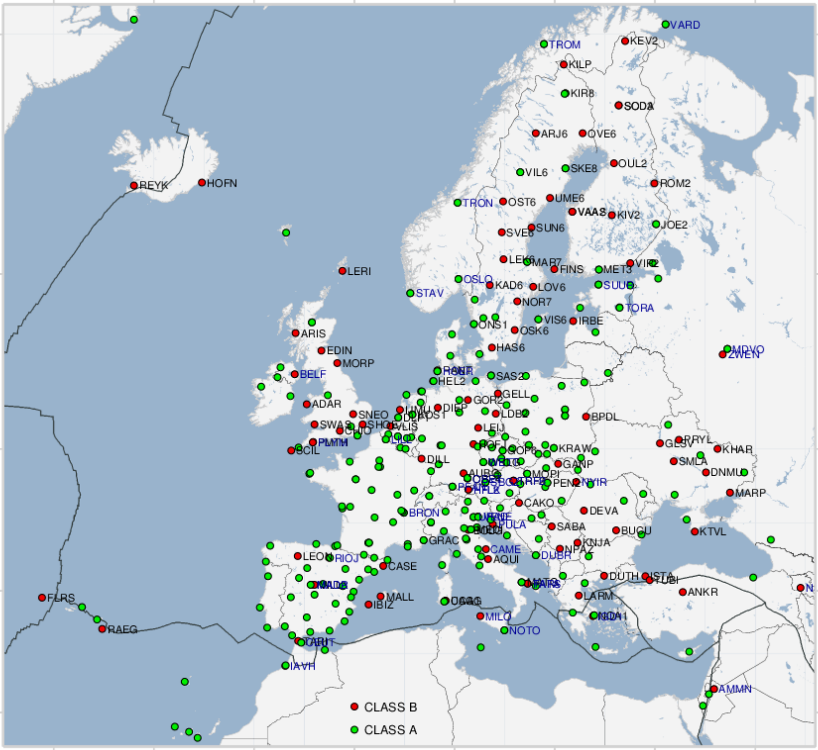
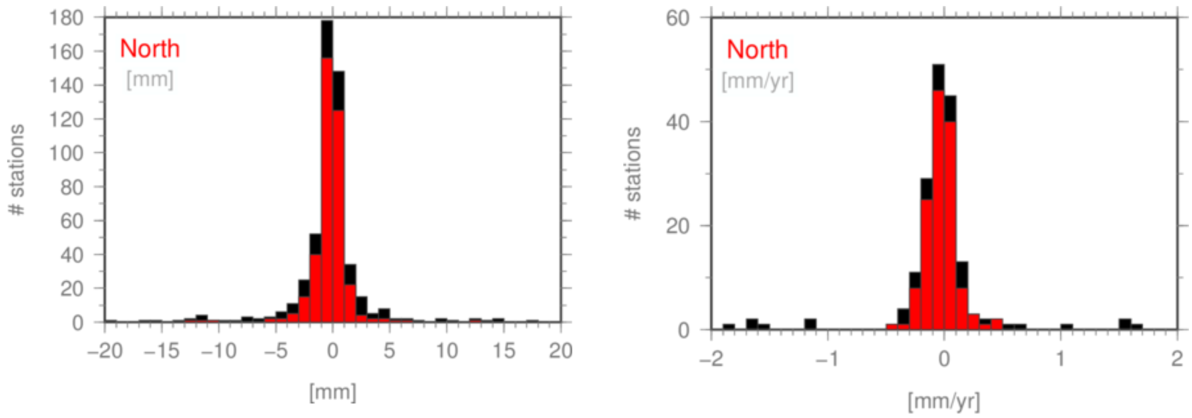


Figure 3: EPN Class A and B stations: stations indicated in green are Class A stations (positions with 1 cm accuracy at all epochs of the time span of the used observations), stations indicated in red belong to class B (positions with 1 cm accuracy at the epoch of minimal variance of each station). Former Class B station names are shown in blue. Class A stations are plotted above class B.

One velocity estimate per station has been selected, the histogram of all the velocity differences are shown in black. After rejecting EPN stations with less than 3 years of observations or less than 50% of observation completeness, the rms of the velocity differences of the C1950 wrt the IGS17P21 is 0.19 mm/yr, 0.15 mm/yr, 0.51 mm/yr for resp. the North, East and Up components. The histograms of the velocity differences for this selection are shown in red in Figure 4 (right).

Most of the large position and velocity differences can be explained by different discontinuity handling or different periods of observations (a large data gap or sparse time series affecting the IGS solution). This effect is clearly seen in Figure 5: 33 of the 212 common stations have less than 50% of observations in IGS while the same stations have more than 80% of availability in the EPN.



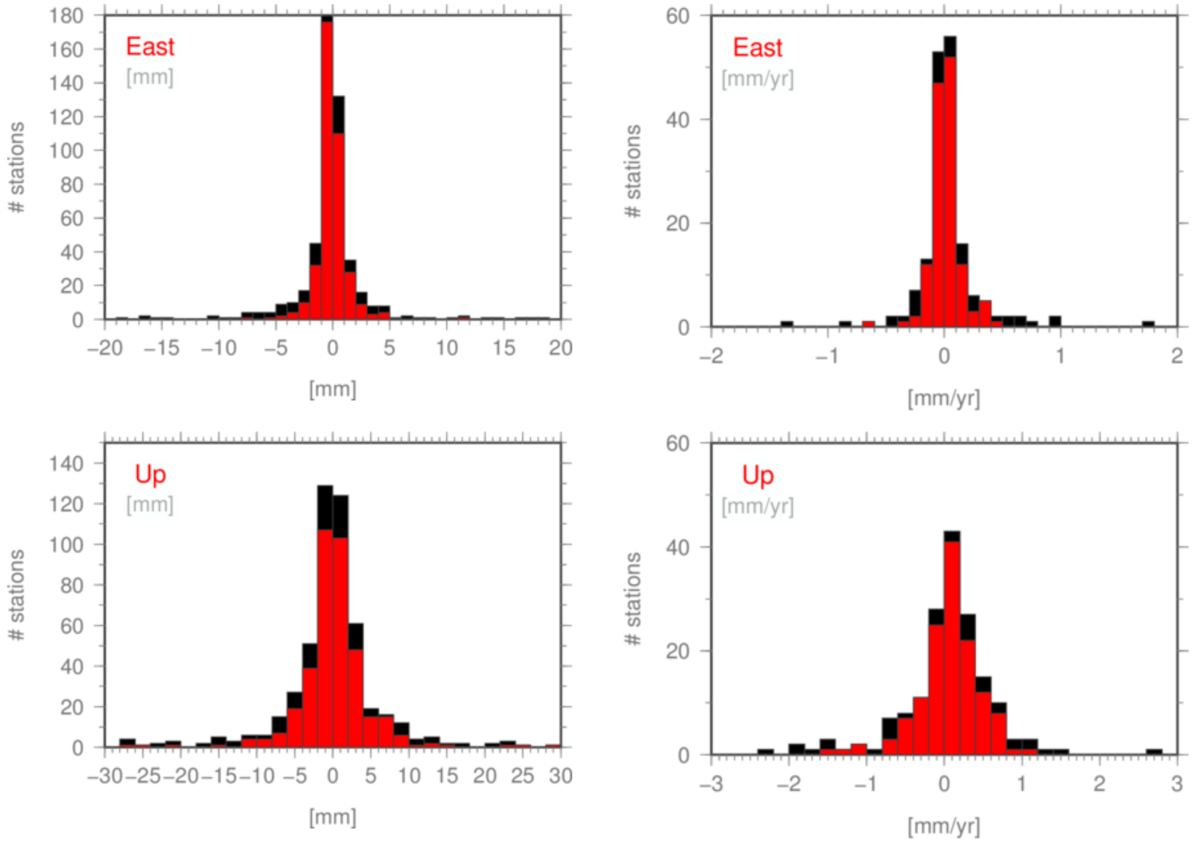


Figure 4: Histogram of the position (left) and velocity (right) differences between the EPN solution C1950 and the IGS solution IGS17P21

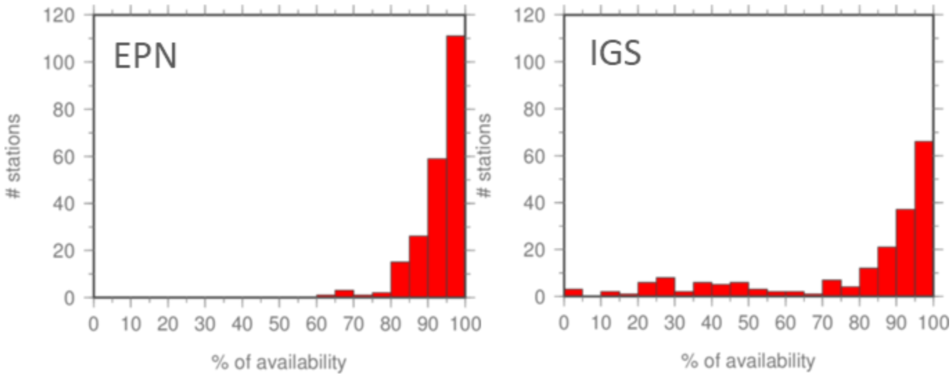


Figure 5: Data availability in the time series (%) in the EPN solution C1950 (left) and the IGS solution IGS17P21 (right) for the 212 common stations with more than 10 weeks of observations in both solutions.

2. Services and Products Based on the EPN

2.1 Ionospheric Products and Space Weather impacts

We continued to maintain the 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 2017, four space weather event were identified and reported (http://gnss.be/ionospheric_event.php).

2.2 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 (~ 600 stations, mainly EPN + national densifications),
2) a hourly global analysis (~300 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 ~230 EPN and national GNSS stations.

Also, we contributed to a paper on the assessment of ground-based GNSS Zenith Total Delay observation errors and their correlations using the Met Office UKV model (Bennit et al., 2017).

3. Research Activities

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

Within the Belgian national project CORDEX.be, ROB collaborated with the Royal Meteorological Institute (RMI) of Belgium to evaluate the water vapour content from the 4 existing high-resolution climate models (ran over Belgium) based on tropospheric products from a reprocessing activity carried by ROB. A paper over the project achievements has been submitted to the journal ‘Climate Services’ (Termonia et al., 2017).

Within the COST Action ES1206 GNSS4SWEC, ROB and RMI collaborated with MUT to organise a workshop on “time series homogenisation” in Warsaw, Poland where the results of the 1st benchmark for existing homogenisation tools on synthetic tropospheric time series has been analysed, discussed, and feedback to homogenisation tool operator was given. A summary of these activities can be found in Van Malderen et al. (2017).

ROB also collaborated with the RMI and ASI in order 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 ‘GNSS observations’ (typical bias < 1 kg/m² of IWV, Figure 6). It also underpins interesting discrepancies when looking in more details, such as the underestimation of the IWV (i.e. a dry bias in the model) during the summer period by ALARO-0 (Figure 7). The latest being tightly link to a precipitation bias. A paper is in preparation and will be submitted in the special issue of the COST Action ES1206 GNSS4SWEC.

ROB collaborated 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 is in preparation (to be submitted to the COST Action ES1206 GNSS4SWEC special issue).

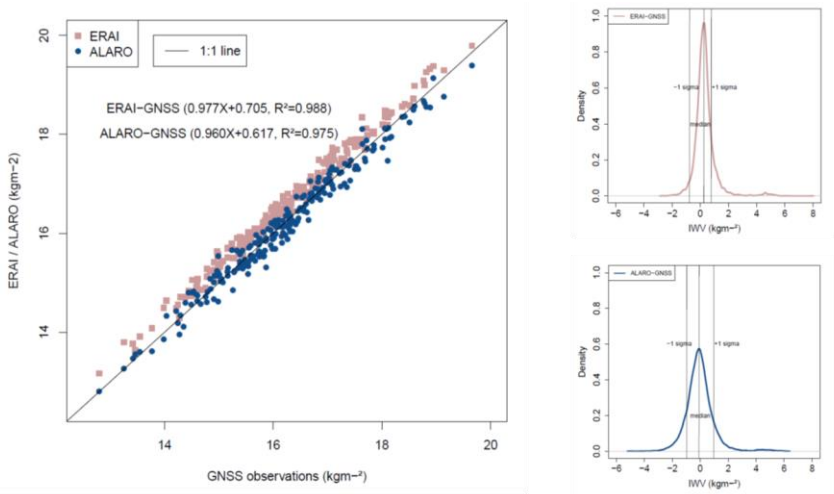


Figure 6: In blue (resp. in brown), agreement between the IWV from the climate model ALARO-0 run by RMI (resp. the NWP re-analysis ERA-Interim from ECMWF) and the IWV from the 'GNSS observations'. (Left): Scatter plots. (Right): Density distribution of the IWV differences. The ERAI shows a slight positive overall bias (i.e. over all stations and over 15 years) while the ALARO-0 has no overall bias.

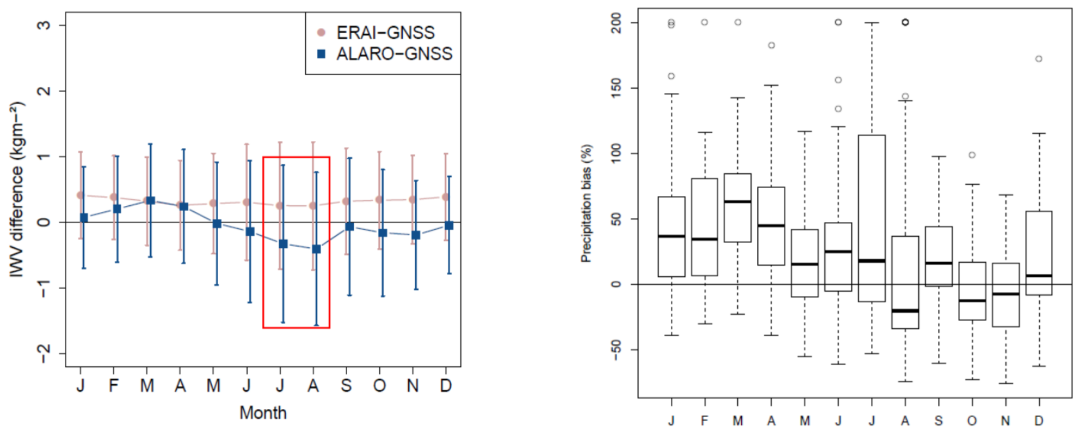


Figure 7: (Left): In blue (resp. in brown) overall agreement between the IWV from the climate model ALARO-0 run by RMI (resp. the NWP re-analysis ERA-Interim run by ECMWF) and the IWV derived from 'GNSS observations' for each month of the year (stacked over 18 years and all stations) emphasizing the 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.

3.2 Research on Space Weather and Ionosphere

Observations of the solar eclipse on 20 March 2015 and its effects on the ionosphere

The ROB-IONO software (Bergeot et al. 2014) was used to re-process GPS and GLONASS data from up to 280 EPN stations available in 2015. The output consists of (European) regional maps of vertical TEC (in TEC units, 1 TECU = 10^{16} el/m^2). Nominally, the maps are produced in near-real time every 15 min on 0.5° x 0.5° grids extending from -20° to +30° in longitude and 32° to 65° in latitude. However, upon necessity, as for this study, higher-cadence (5-min) maps were produced.

Based on this TEC map data set, we calculated the relative difference (Figure 7), $TEC_{rel} = (TEC_{ecl} - TEC_{ref})/TEC_{ref}$ on each grid point from the corresponding TEC values on the eclipse day (TEC_{ecl}) and the reference day (TEC_{ref}). This allowed to note that maximum depletion of above 53% (i.e.

minimum TEC_{rel} < -53%) was reached on a patch over central Europe, where the maximum obscuration was between 70% and 80% rather than in the area of complete obscuration. This is explained by the differences in the umbra crosses the Earth's atmosphere (at a given location) at different solar zenith angles (Stankov ret al. 2017).

Real Time Ionosphere Monitoring Working Group (RTIM-WG)

The EPN data were used to study the impact of the March 17, 2015 event (i.e. the Saint Patrick storm) on the ionosphere (García-Rigo et al. 2017) (Figure 8) in the frame of the new Real Time Ionosphere Monitoring Working Group (RTIM-WG), which is part of IAG's Sub-commission 4.3 on "Atmosphere Remote Sensing". In the future, this WG will develop a procedure to automatically compare available real time ionosphere products.

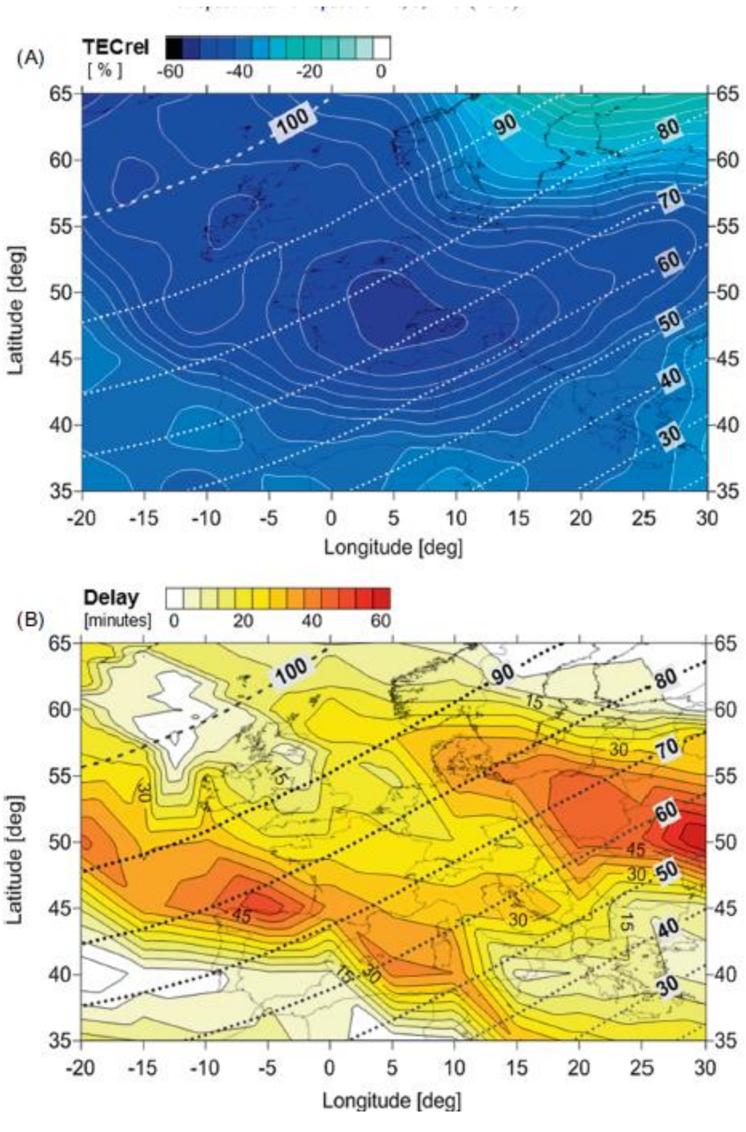


Figure 8: (A) Estimation of the maximum TEC depletion based on the European TEC maps during the 20th March 2015 eclipse, compared with the obscuration (dashed lines) map. (B) Estimation of the TEC depletion delay based on the European TEC maps during the eclipse, comparison with the obscuration map.

Effect of Space Weather on GNSS signals

Intense Solar Radio Bursts (SRBs) emitted at L-band frequencies are a source of Radio Frequency Interferences (RFI) for Global Navigation Satellite Systems (GNSS). During such event, the GNSS signal reception is degraded and fades of carrier to noise density <C/N_0> can be observed at the GNSS receiver level for all satellite tracks.

ROB is now providing a regional (i.e. over Europe) <C/N_0> warning system to alert the users of potential degradation in GNSS based applications due to SRBs (Chevalier and Bergeot 2017a, 2017b and Chevalier et al. 2017). To validate the warning system, we analysed 11 SRB events occurring during the sunlit of Europe from 1999 until 2015 using solar radio flux data at 1415MHz from the Radio Solar Telescope Network (NOAA) and the daily GPS/GLONASS data of the EPN (Figure 9). The estimated <ΔC/N0> is in agreement with the solar flux data above 10^3 SFU. All events were detected apart the one of 1999 (short event, which last 1mn and few EPN stations). Additionally, the warning system is also efficient to detect small event with a <ΔC/N0> of 1dB-Hz fade.

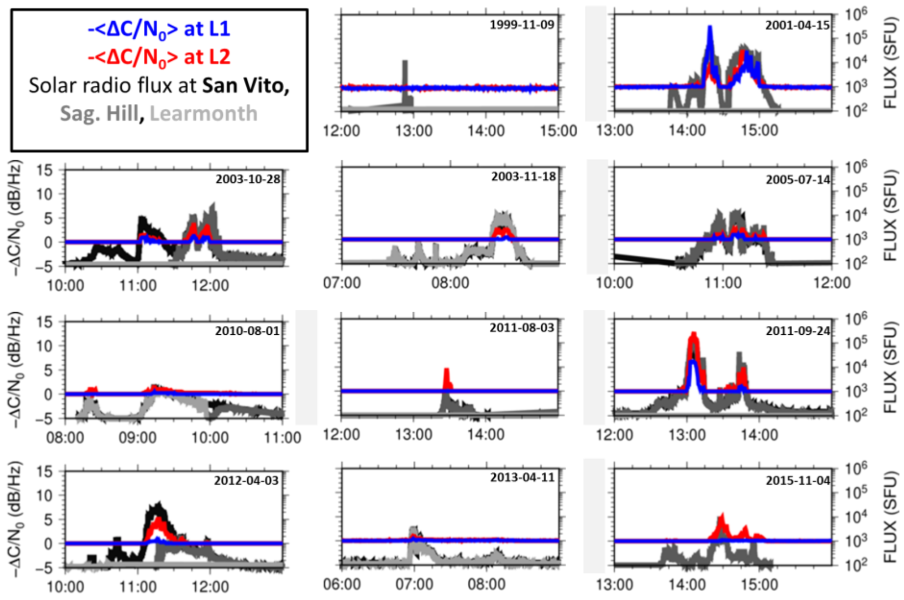


Figure 9: Opposite <CN0> fade estimated at L1 and L2 frequency of the EPN together with the radio flux recorded at the RSTN observatories

3.3 Step-wise Analysis of the Quality of GNSS Network-based Processing

Over the last decades, the number of permanent GNSS stations included in the various ROB's network-based GNSS analysis centres (e.g. for EPN and for E-GVAP) increased significantly. Handling and monitoring the processing of such a big amount of GNSS data and meta-data is the next key challenge that should be achieved to keep all our GNSS products of high quality, reliable, and manageable. For this reason, ROB develops a tool 'ROBER' to monitor and analyse the intermediate and final products of a GNSS network solution produced using the Bernese GNSS software V5.2. The tool extracts the significant Key Performance Indicators (KPI) for each step of the processing, store the metrics and products into databases, carry out statistical analysis, include a web-based user interface to graphically analyse the metrics and provide reports, and cross-check with meta-data. Figure 10 shows operational examples from the user interface. The right part of the figure represents the standard deviation of the geocentric vector of each station as computed from the Single Point Positioning analysis stage (the size of the bubble being the amplitude of the standard deviation). The left part the figure shows how the stations are connected via baselines helping to track how the performance degradation impact neighbouring stations (in this case the percentage of ambiguity resolve is color-coded to draw the baselines). Finally, a number of decision models have been tested to identify and to automatically correct for situation that may cause a degradation of the reliability and the precision of the network solution and final products.

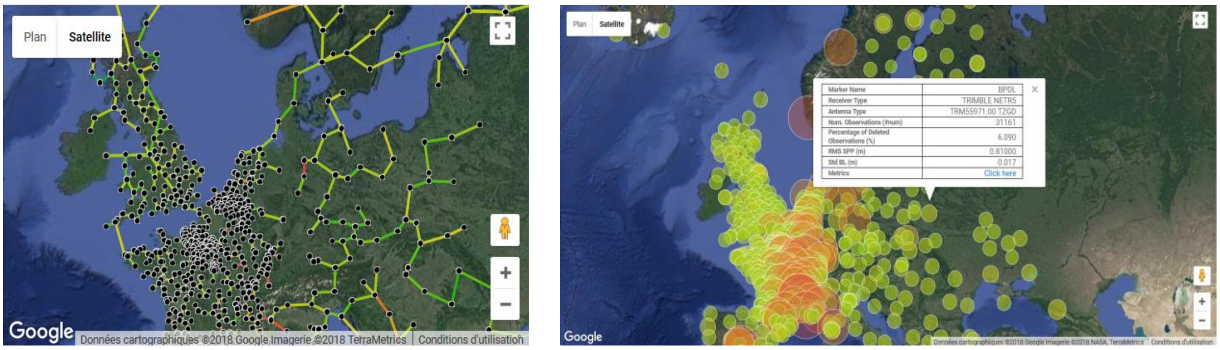


Figure 10: Example of tools provided by the web-based user interface developed for the KPI analysis and for reporting the performances of the GNSS network analysis for the daily E-GVAP operational processing on 29 December 2017. (Left): The figure depicts how the stations are connected together via baselines, which are color-coded to display the percentage of ambiguities resolved for that baseline. It allows studying the spatial distribution of this metrics (ambiguity resolution performance) as well as the tracking of potential problem propagation within the network due this connectivity. (Right): The figure shows color-coded bubbles that represents the standard deviation of the geocentric vector repeatability of each station computed at the Single Point Positioning analysis stage. Such maps can e.g. help in discriminating well performing from badly performing station in our analyses.

4. National geodetic reference infrastructure (by the National Geographic Institute)

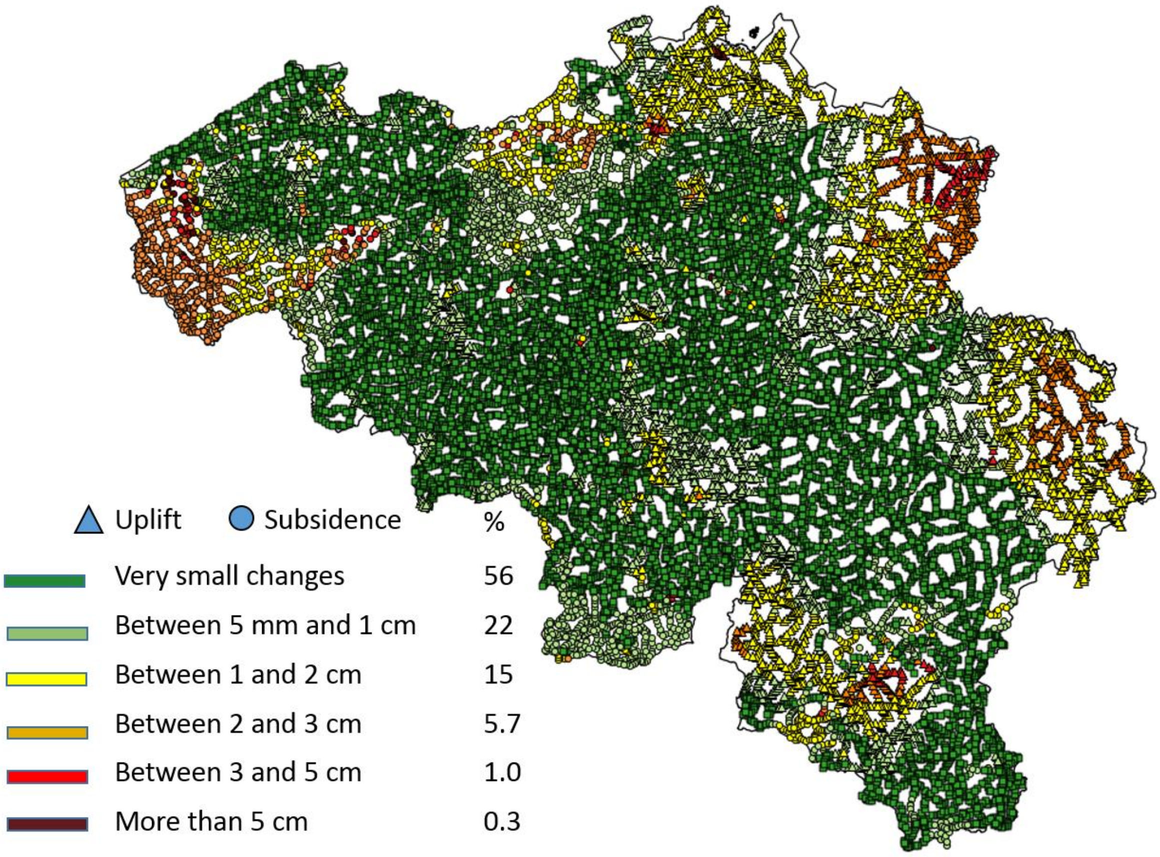
4.1 AGN (Active Geodetic Network)

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 2000.
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 (8 receivers and 2 antennas have already been changed). For GPSBru the hardware of the RTK station in Brussels will also be replaced 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

The models that are disseminated by the NGI to transform ellipsoidal height to 'Ostend height' (levelling reference) were established in 2003, combining gravimetric data and more than 3000 GPS-levelling points. Tests have shown that the standard deviation of this transformation is 2 cm. We think that the accuracy can be augmented through a better analysis of the gravimetric data, which is rather inhomogeneous. Next to that, during the last decade, a new set of GNSS-levelling points, with a better quality, has been observed.

All existing levelling data have been analyzed with software which, compared to the original adjustment, performs better in terms of testing and error detection. Twelve areas were found containing relatively big errors. Thanks to new observations, carried out last year and in the first months of 2018 (675 km in total), we have been able to solve these problems. As a result the new adjustment of the entire levelling network shows to be more homogeneous. Compared to the former values, the height of the markers changes hardly (56% less than 5 mm) or little (78% less than 1 cm). The remaining 22% of the markers are mainly situated in areas which are known to be slightly uplifting (eastern part of Belgium) or subsiding (some parts of the area northwest of the river Schelde). The picture below gives an overview of all height changes.



Based on the new height values, 3760 GNSS/leveling points have been selected to create a new height-conversion model for Belgium. This was done by R Klees and Dc Slobbe at the Delft University of Technology, Delft, The Netherlands (R Klees and DC Slobbe, March 2018*)*.

We are in the process of validating this new hBG18 model. The release of this model will be this year 2018. At the same time the new height's from our least square adjustment will be published.

4.3 3D network

In the future it will not be possible to maintain all our "Plani" and "Alti" points. So we are not going to have any new observations for these points. All the information about these points will still be available on our website www.ngi.be/gdoc . The information can also be consulted via a smartphone.

But we will create 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.

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