Royal Observatory of Belgium

Met Office

# GNSS Research and Services at ROB to support Meteorology and Nowcasting Applications


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## Background

For more than a decade, the Royal Observatory of Belgium (ROB) has supported ground-based Global Navigation Satellite System (GNSS) meteorology, participating in European projects such as COST-716, TOUGH and the EUMETNET EIG GNSS Water Vapour Program (E-GVAP I&II). To this aim, ROB contributes by developing and maintaining an operational Analysis Centre (AC) providing meteorologists with Zenith Tropospheric path Delays (ZTD) from a European network of GNSS stations using the Bernese GPS Software V5.0 [2]. This poster presents the status of Research and Developments (R&D) and services at ROB to enhance its support to Numerical Weather Prediction (NWP) and to prepare support to the nowcasting and forecasting of severe weather activities that emerge within E-GVAP and a proposed EU COST Action "Advanced Global Navigation Satellite Systems tropospheric products for monitoring Severe Weather Events and Climate" (GNSS4SWEC, see related Poster P06-14).

## GNSS-Meteorology Requirements

Table 1 summarises the requirements to generate and deliver ZTD products for nowcasting and forecasting (NWP). For each criteria, 3 values are given : the *threshold* (minimum performance to be useful), the *target* (mostly achievable today) and the *optimal* (performance under optimum conditions, needs further developments) value.

| Application | Horizontal Domain | Horizontal Sampling | Observation Cycle | Accuracy/Precision | Timeliness (95%) |
|---|---|---|---|---|---|
| Forecasting (NWP) | Europe/Europe + N. America/Global | 200 / 100 / 30 km | Hourly | 15 / 10 / 5 mm | 2 / 1.5 / 1 hour |
| Nowcasting | Europe / Europe to national / Regional to national | 100 / 50 / 20 km | Sub-Hourly | 15 / 10 / 5 mm | 60 / 30 / 15 min |

*Table 1 : Forecasting and nowcasting requirements for ZTDs as stated in the E-GVAP Product Requirement Document [1].*

## 1. GNSS-Meteorology R&D and Services

At the end of 2011, ROB started to develop a new Hourly-updated GPS-based ZTD solution (ROBT = future ROBH) to enhance its current support to European NWP models. In addition, ROB started in March 2012 to develop a Quick solution (ROBQ) based on the processing of real-time GNSS observations (NTRIP streams) to support assimilation in the emerging rapid-update high-resolution NWP models and nowcasting tools. This is particularly important for monitoring and forecasting severe weather. The development timeline is illustrated in Fig. 1.

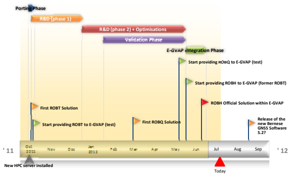

*Figure 1 : Timeline of the recent ROB R&D and services implementation to enhance support to E-GVAP and the future E.U. COST Action GNSS4SWEC.*

### Main Objective:

Satisfy all GNSS-meteorology requirements listed in Table 1, with a focus on (w.r.t. the previous ROB_ contribution to E-GVAP):

1. Improving significantly the horizontal observation domain and sampling (e.g. by adding more GNSS stations and extending the network domain eastward),
2. Improving the timeliness of ROB products (e.g. by speeding up the processing, using real-time GNSS observation streams and preparing to sub-hourly GNSS data processing).

### How was it achieved?

- A new High-Performance Computer infrastructure (2 Intel Xeon CPU X5690 @ 3.47GHz, 6 cores).
- Several strategy changes and optimisations (BPE sequence, options…).
- Heavy parallelisation (BPE scripts, Perl scripts and Fortran code).
- Hourly RINEX dataflow script improvements (improved data latency, redundancy and stability).

The ROBQ solution is presently computed hourly and provided within E-GVAP as a prototype. Operationally, it is intended to compute ROBQ solutions every 15min. Finally, ROB carries out also a daily Post-processing name ROBP (with 5 days latency) for precise coordinate and tropospheric products determination, and hence for validation. The meaning of the different solutions and the main processing options of the ROBH/ROBQ/ROBP analysis are summarised below:

- ROB_ = previous solutions based on hourly RINEX.
- ROBH = new solutions based on Hourly RINEX (ROBT acronym was used during the Test phase).
- ROBQ = new Quick solution based on real-time GNSS observations.
- ROBP = new Post-processing solution based on daily RINEX.

| | ROBT=ROBH | ROBQ | ROBP |
|---|---|---|---|
| Software / Mode | Bernese 5.0 / DD* [2] | Bernese 5.0 / DD* [2] | Bernese 5.0 / DD* [2] |
| Network / Nb. Stations | Regional / ~ 373 stations | Regional / ~ 157 stations | Regional / ~ 800 stations |
| Orbits, clocks and EOPs | IGS Ultra-Rapid | IGS Ultra-Rapid | IGS Rapid / Final |
| Sat. Antenna Model | IGS08.ATX | IGS08.ATX | IGS08.ATX |
| Rec. Antenna Model | IGS08.ATX + Indiv. (EPN) | IGS08.ATX + Indiv. (EPN) | IGS08.ATX + Indiv. (EPN) |
| Tropo. Model | STP / NMF | SPT/NMF | SPT/NMF |
| Elev. Cutoff Angle | 10° | 10° | 3° |
| RINEXType | Hourly | High-Rate / NTRIP | Daily |
| Data Time Span | 1 Hour + 6 hour stacking | 1 Hour + 6 hour stacking | 24 hours |
| Data Sampling (in estimation) | 30 sec | 30 sec | 180 sec |
| Estimated Param. | 1 ZTD per 15 min / No gradient | 1 ZTD per 15 min / No gradient | 1 ZTD per hour / 1 gradient per day |
| Ambiguity Resolution | Float | Float | Fixed (QIF) |

*Table 2 : Main processing options used to compute the different ROB contributions to GNSS meteorology.*
*(*) DD stands for double-difference.*

## 2. Requirement Validation

Hereafter, we validate the new ROBH, ROBQ and ROBP solutions w.r.t. the GNSS meteorology requirements listed in Table 1. The validation period covers from 1st January 2012 to 1st July 2012 for ROBH and ROBP, and from 1st March 2012 to 1st July 2012 for ROBQ.

### Horizontal Domain:

The network of GNSS stations processed for ROBH/ROBQ solutions are shown in Fig. 2 and 3. W.r.t. the previous ROB_ solution, ROBH has extended its domain eastward (better support to NWP in eastern countries) and includes ~90% more stations.

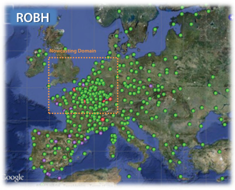


*Figure 2 : Network of ~373 GNSS permanent stations processed by ROB to support assimilation in European NWP models. (Some stations are located outside the represented domain).*

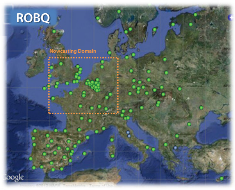


*Figure 3 : Network of ~157 GNSS permanent stations processed by ROB to support nowcasting/forecasting of severe weather. (Some stations are located outside the represented domain).*

### Horizontal Sampling (H.S.):

Fig. 4 shows the horizontal sampling distribution (nearest observation, Delaunay triangulation) within the ROBH network (Fig. 2). 73.49% of them are below 200 km (Table 3). This requirement for European NWP still need to be satisfied as a common effort of all European ACs. In the nowcasting domain, ROBQ (Fig. 3) only performs better for baseline lengths of 20-50 km , i.e. in Belgium. Processing the FLEPOS network will further enhance this difference. In the European domain, ROBH clearly outperforms ROBQ because of lack of real-time GNSS observations.

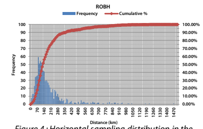

*Figure 4 : Horizontal sampling distribution in the ROBH network of GNSS stations (Fig. 2).*

| | Nowcasting Domain (5°W-10°E, 47°N-53°N) | | | | European NWP Domain (35°W-50°E, 30°N-72°N) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | < 100 km | < 50 km | < 20 km | 95% < | < 200 km | < 100 km | < 30 km | 95% < | Mean H.S. |
| ROB_ (old) | 42.74% | 15.32% | 4.84% | 320 km | 60.87% | 21.71% | 2.90% | 630 km | 214.3 km |
| ROBH (new) | 68.37% | 21.43% | 5.44% | 200 km | 73.49% | 35.71% | 3.72% | 560 km | 180.1 km |
| ROBQ | 56.13% | 38.71% | 3.87% | 470 km | 41.33% | 25.26% | 5.10% | 810 km | 296.7 km |
| ROBP | 78.34% | 48.22% | 12.66% | 250 km | 82.46% | 55.82% | 11.16% | 380 km | 111.8 km |

*Table 3 : Horizontal sampling performances of the past and current ROB solutions contributing to E-GVAP.*

### Latency and Timeliness:

Latency = delivery time (in minutes) of the product (i.e. reference epoch is last GNSS observation processed).
Timeliness = age (in minutes) of the ZTD estimates when disseminated through the GTS (i.e. reference epoch is the epoch of the ZTD estimation).

- Fig. 6: ROBH (resp. ROBQ) processing starts at H+18min (resp. H+3min) and has a mean processing time of 7±2min (resp. 6±0.5min), i.e. at least two times quicker than ROB_.
- Fig. 6: ROBH/ROBQ deliver almost 100% of their solutions. However, ROBQ has few drops in the number of stations included due to partial/complete real-time data acquisition failure. For both solutions, the processing time increases with the number of stations.
- Fig. 5 and 7 (top): 95% of the ROBH solutions have a latency below 27min and 97% of the ROBH solutions achieve the targeted timeliness requirement for NWP (90min).
- Fig 5 and 7 (bottom): 95% of the ROBQ solutions have a latency below 7min and 100% of the ROBQ solutions achieve the targeted timeliness requirement for NWP and nowcasting (15min), provided that ROBQ solutions are computed every 15min.

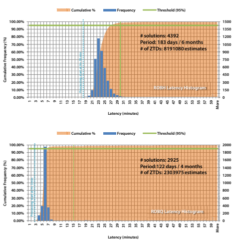

*Figure 5 : Distribution of the latency (upload time on the U.K. Met Office ftp hub) of the ROB solutions. Period: 1 Jan. – 1 Jul. 2012 (Upper graph: ROBH, below graph ROBQ).*

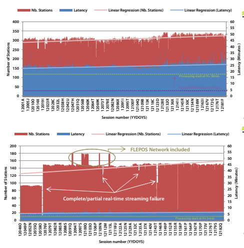


*Figure 6 : Time series of the latency (upload time on the U.K. Met Office ftp hub) of the ROB solutions. Period: 16 Feb. – 1 Jul. 2012 (Upper graph: ROBH, below graph ROBQ).*

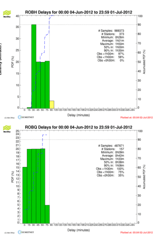

*Figure 7 : Timeliness of the ROB solutions as distributed through the GTS by the U.K. Met Office Period: 4 June – 4 July 2012 (Upper graph: ROBH, below graph ROBQ).*

### Precision:

To validate the precision of the ROBH/ROBQ/ROBP ZTD estimates we compared them to the IGS and EUREF Final Troposphere products [3,8]. Our main findings, summarised in Table 4 and Fig. 8, are :

- Biases are below a few mm (except for some stations for ROBQ) = level impacted by the strategy differences (cut-off angle, mapping functions…).
- The precision of ROBH/ROBQ and ROBP ZTDs is in the range of 2.5-6.5mm and 1.5-4mm respectively. 100% of them achieve the target requirement.
- No clear geographical dependency (except some border effects) could be detected.

### Accuracy:

To validate the accuracy of the ROBH/ROBQ/ROBP ZTD estimates we compared them to the radiosonde (RS) observations and to background field provided by the global U.K. Met Office NWP model [9,10]. Our main findings, summarised in Table 4 and Fig. 9, are :

- 84.20% (resp. 98.09%) of the ROBH ZTDs achieve the optimal (resp. target) accuracy requirement. The same holds true for ROBQ except for a few stations which show a significant bias (probably linked to the ADVNULLANTENNA "issue" of the real-time streams).
- No clear geographical dependency could be detected.

| | ROBH vs. EUR | ROBQ vs. EUR | ROBP vs. EUR | ROBH vs. IGS | ROBQ vs. IGS | ROBP vs. IGS | ROBH vs. ROBP | ROBQ vs. ROBP | EUR vs. IGS | ROBH vs. NWP | ROBQ vs. NWP | ROBH vs. RS | ROBQ vs. RS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nr. of Stations | 207 | 117 | 230 | 70 | 36 | 81 | 361 | 158 | 69 | 369 | 152 | 36 | 13 |
| Nr. Of Observations | 551852 | 284955 | 685011 | 864299 | 428949 | 286328 | 1303912 | 494591 | 198500 | 4129295 | 281375 | 113119 | 21022 |
| Mean Bias ± Std. Dev. | -0.97 ± 1.18 mm | -0.67 ± 4.06 mm | -0.17 ± 0.82 mm | -0.94 ± 1.60 mm | 0.31 ± 4.36 mm | -0.11 ± 0.82 mm | -0.22 ± 1.35 mm | -0.44 ± 3.52 mm | 0.22 ± 0.81 mm | 0.5 ± 3.8 mm | 0.1 ± 5.8 mm | 1.86 ± 3.87 mm | 3.62 ± 3.84 mm |
| Std. Dev. ± Std. Dev. | 4.85 ± 0.97 mm | 4.74 ± 1.14 mm | 2.53 ± 0.81 mm | 5.53 ± 1.76 mm | 5.51 ± 1.79 mm | 4.35 ± 1.78 mm | 6.56 ± 1.91 mm | 6.04 ± 1.53 mm | 2.98 ± 1.35 mm | 11.3 ± 4.1 mm | 10.5 ± 2.0 mm | 8.24 ± 2.92 mm | 7.88 ± 1.71 mm |

*Table 4 : Summary of the ROBH, ROBQ and ROBP validation in terms of precision (w.r.t. the EUREF, IGS, ROBP) and accuracy (w.r.t. the U.K. Met Office NWP model).*

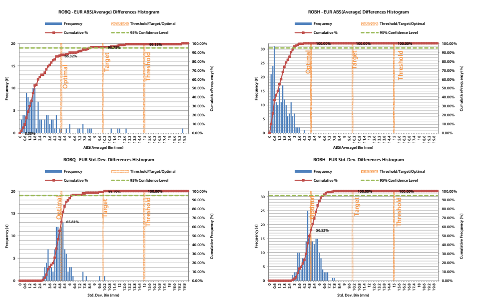

*Figure 8 : Distribution of the mean biases (up graphs) and standard deviations (below graphs) of the ROBQ and ROBH ZTD solutions w.r.t. the EUREF Tropospheric products. Period: 1 Jan. – 1 Jul. 2012 (Left : ROBQ, right: ROBH).*

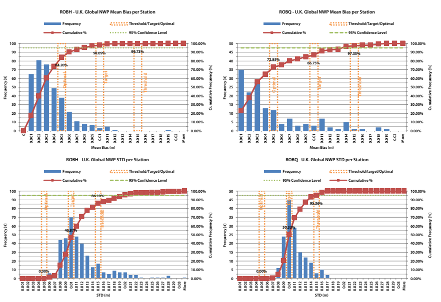

*Figure 9 : Distribution of the mean biases (up graphs) and standard deviations (below graphs) of the ROBH and ROBQ ZTD solutions w.r.t. the U.K. Met Office Global Model. Period: 1 Jan. – 1 Jul. 2012 (Left : ROBH, right ROBQ).*

## 3. European Tropospheric Models

We developed a method based on ordinary krigging interpolation [4,5,6] to model the total & wet tropospheric delay over Europe using ROB's contributions to E-GVAP. The flowchart of the method is illustrated in Fig. 11 and its main characteristics are listed in Table 5. The method consist in :

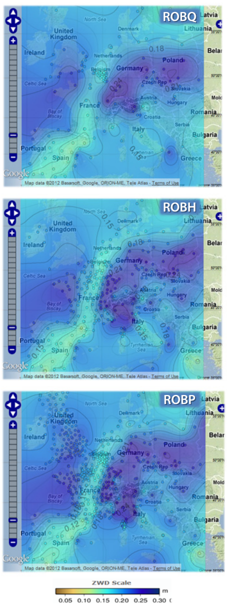


*Figure 10 : Map of the European wet tropospheric delay (ZWD) based on the ROBQ (top), ROBH (middle) and ROBP (bottom) solutions on the 2nd July 2012 at 13:00 UTC.*

- Data selection (with a larger domain than the interpolation domain).
- Robust algorithms for data cleaning and pre-processing (gross error rejection, formal error filtering based on last 3 days…).
- Fully automated/adaptive ordinary krigging method (experimental variogram, adaptive power variogram model, linear variogram fall-back method, statistical monitoring, confidence level) for operational purpose.
- Fully automated graphical representation (based on GMT [7]).
- User-web interface (based on OpenLayer and jQuery).

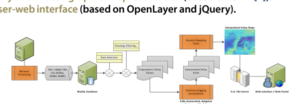

*Figure 11 : Flowchart of the method used to compute the European tropospheric model.*

| | ROBQ | ROBH | ROBP |
|---|---|---|---|
| Space Domain | 35°N-58°N / 11°W – 25°E | | |
| Horizontal Sampling | 0.1° x 0.1° | | |
| Time Resolution | Each 15 min | | Each hour |
| Latency | ~ H + 11min | ~ H + 34 min | ~ 6 days |
| Typical Precision (over countries) | < 5 – 15 mm | | |

*Table 5 : Main characteristics of the European tropospheric model.*

Application of this method to the different ROB solutions is illustrated in Fig. 10. The overall pattern is rendered by the three ROB solutions. However, as the horizontal sampling increases, more small-scale structures can be extracted. This can be seen in several regions in Fig. 10. Fig. 13 shows an example of the variance of the estimations computed during the krigging. Over countries, it generally remains below 5-10mm. In the worst cases, it reaches up 15mm.

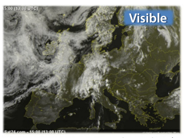


*Figure 12 : Meteosat images taken on the 2nd July 2012 at 13:00 UTC.*

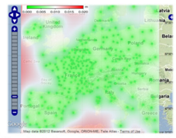

*Figure 13 : Variance of the krigging interpolation based on the ROBH solution on the 19th July 2012 at 6:15 UTC.*

## 4. Development of a Web Portal

We also started the development of a GNSS meteorology web portal. Access is presently internal-only, but future public access is foreseen. The portal aims at providing (current existing features are in bold) :

- Information on the different tropospheric products and services developed by ROB.
- Access to these tropospheric products and services (**ZTD time series, tropospheric delay maps**…).
- A continuous monitoring of all ROB solutions (**network status**, processing output, availability…).
- A continuous validations of the different products against post-processing solutions, **NWP model output**, radiosondes observations…

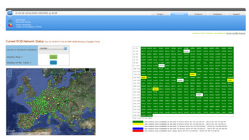

*Figure 14 : Screenshot of the web portal showing the network monitoring of ROBH (status: 10 July 2012 15:30 UTC).*

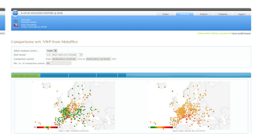

*Figure 15 : Screenshot of the web portal showing the accuracy monitoring of ROBH w.r.t. the U.K. Met Office NAE and Global Models (period: 26 June 2012 15h45 UTC - 3 July 2012 15:45 UTC).*

## Conclusion and Perspectives

### Main conclusions:

1. W.r.t. the old ROB_ solution, the new ROBH solution includes 90% more GNSS stations, extends its domain eastward and improves the horizontal sampling by ~12-25% while lowering the latency of the solution. 96% of the ROBH ZTD estimates have a precision better than 6.5mm (100% of them have a precision better than the 10mm target requirement). 98% of the ROBH solutions have an accuracy better than the 10mm target requirement (w.r.t. NWP model output). Consequently, ROBH is now provided as an official solution within E-GVAP and assimilated operationally at national meteorological services (e.g. at Météo France and the U.K. Met Office).
2. Both ROBH and ROBQ have advantages and disadvantages. ROBQ cannot replace ROBH (e.g. because of the horizontal sampling). ROBQ is now provided on an hourly basis as a prototype solution within E-GVAP. It is expected to further develop ROBQ towards a sub-hourly update rate.

### Main perspectives:

1. Switch to the upcoming version 5.2 of the Bernese software and start a new cycle of R&D: 1) develop enhanced/new processing methods (multi-GNSS, PPP, global analysis…) and 2) develop enhanced/new tropospheric products (horizontal gradients, slant delays…).
2. Search for more GNSS station observations (both hourly RINEX and real-time streams) to further increase the horizontal sampling.
3. Improve the krigging method for the tropospheric modelling with a special focus on Belgium and finalise the web portal.

## References and Acknoledgments


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Solar-Terrestrial Centre of Excellence — International GNSS Service — EUREF — IGN Institut National de l'Information Géographique et Forestière — Région Wallonne — Flemish Geographical Information Agency — Nationaal Geografisch Instituut / Institut Géographique National


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