ROKUBUN

Innovative navigation solutions

Title	**Executive Summary**
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Document number:	Executive Summary
Version:	3.0

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VERSION CHANGE HISTORY

Date	Version	Author	Brief Comment
2018-03-19	0.0	MGF	First version of the template
2018-04-24	1.0	MGF	Completed adding all contributions and final review
2018-05-15	2.0	MGF & BN	Added Acknowledgements
2018-07-02	3.0	MGF	Removed copyright

1 Abstract

The present document is the executive summary for the tasks performed in the Atmosfiller project (ESA/ESTEC contract No. 4000120090/17/NL/AF). The basic goal of this project was the analysis on how the usage of non-conventional data (i.e. "data of opportunity") in conjunction with conventional data could help improving the estimation of parameters for Weather and Space Weather.

By conventional data it is meant data coming from well-known sources such as permanent GNSS receivers (e.g. receivers from IGS or EUREF networks) while non-conventional data is considered to be GNSS data from research vessels or mass-market GNSS receivers (such as smartphones or other single-frequency GNSS chipsets).

The project has been split in two thematic parts, Weather monitoring, for which an illustration is provided in Figure 1 as well as Space Weather, which has been summarized in illustration in Figure 2. The following sections summarize the tasks and results that have been obtained in the context of this project.

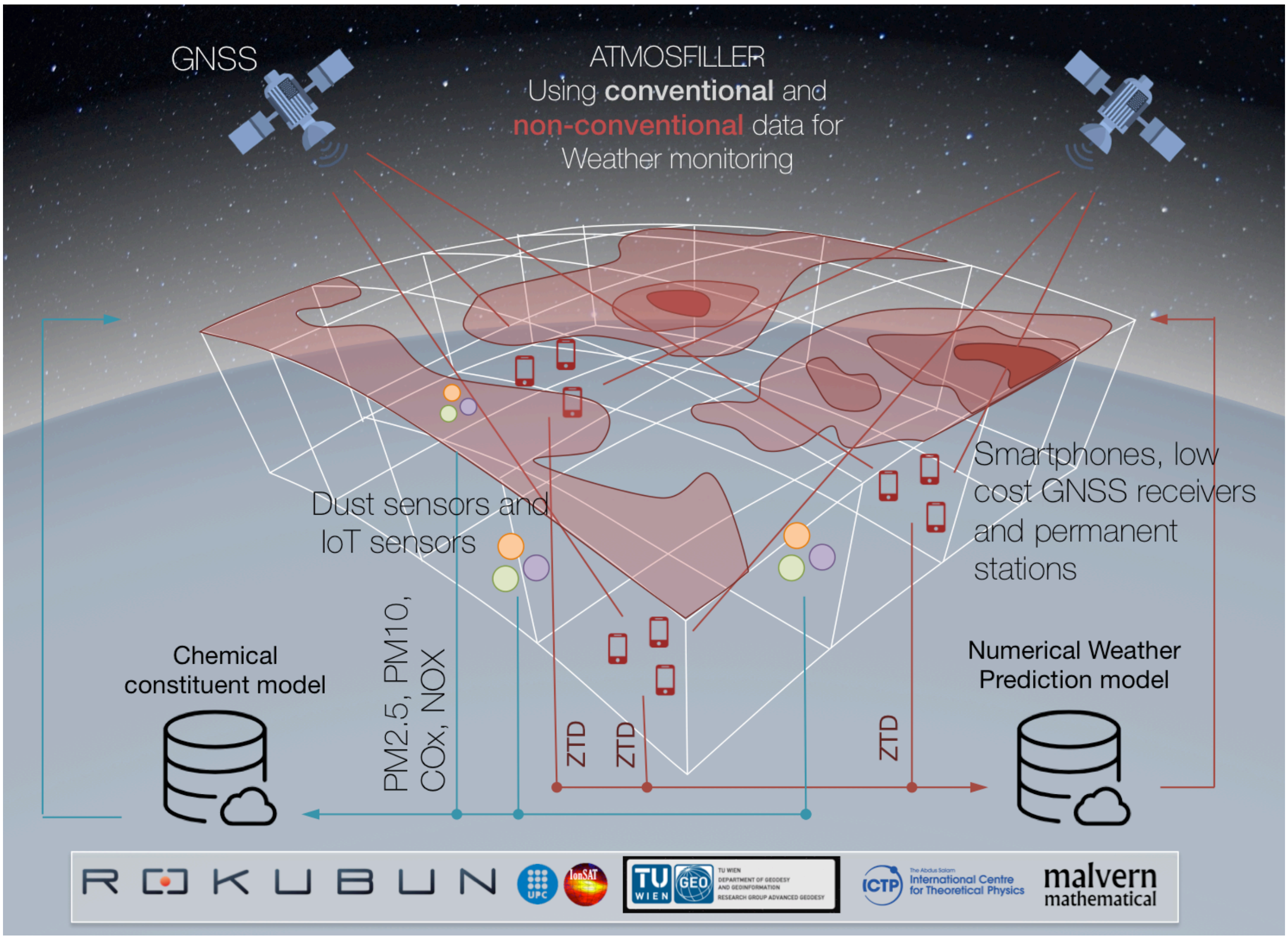

Figure 1 Illustration with the Weather monitoring techniques that have been explored within the Atmosfiller project

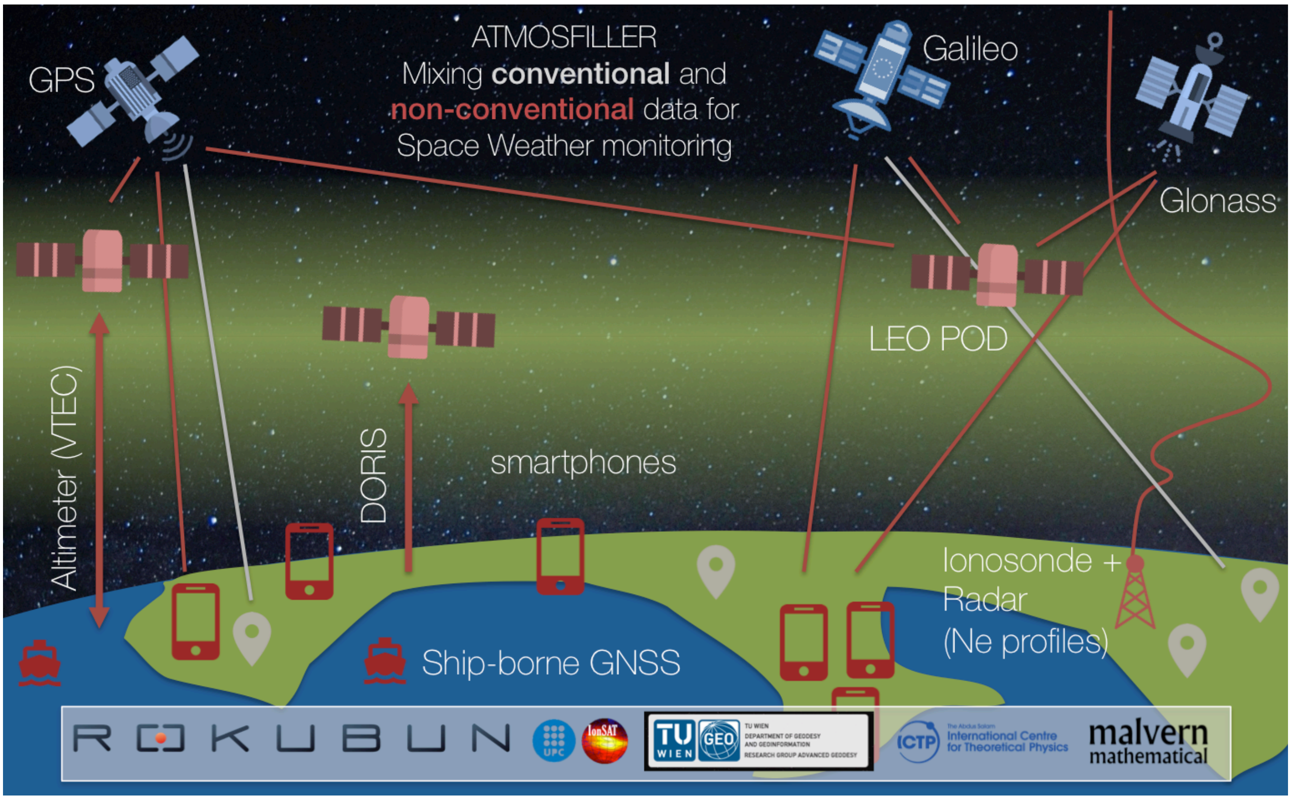

Figure 2 Illustration for the conventional (in grey) and non-conventional (red) sources used for Space Weather (ionospheric) monitoring that has been done during the Atmosfiller project.

2 Weather monitoring

2.1 Numerical Weather Prediction model

The main contribution regarding the Weather monitoring in the Atmosfiller project was to provide data editing algorithms for the non-conventional observation data mainly based on time series analyses and comparison to the GPT2w model. Moreover monitoring algorithms in order to assimilate non-conventional data into the Numerical Weather Prediction (NWP) and atmospheric chemistry models have to be delivered.

Two assimilation tests of the non-conventional ZTD observations, using the 3DVar WRF Data Assimilation system, have been conducted. The initial assimilation run regards the assimilation of ZTDs derived from single-frequency (SF) observation data provided for the GEONET network (Japan). During this approach huge difference between the heights of the observation sites and model heights (up to 1200 m) were discovered. Since the hydrostatic part of ZTD strongly depends on the observation height, most of the observations have been rejected in the assimilation process. To overcome this problem the testing domain has been shifted to a less mountainous area in Europe (EUREF Permanent GNSS Network and Austrian EPOSA stations). Based on formal errors of +/-20mm for phase and code data derived ZTDs as well as +/-100mm for SF code derived ZTDs a 3 sigma editing threshold has been chosen for all datasets in the assimilation process.

Assimilation of SF code-phase based ZTDs show reasonable variations in the derived pressure and temperature fields. On the other hand a comparison of Relative Humidity (RH) calculated from forecasts 6 hours after ZTD assimilation against radiosonde observations yielded in serious discrepancies for the assimilation of SF code + phase observations up to a height level of 4km and moderate differences to the reference model above that height level. To limit the impact on the state of the model the weight of SF derived ZTDs has to be decreased.

In case of the atmospheric chemistry model, the Gridpoint Statistical Interpolation (GSI v3.6) assimilation system to assimilate PM2.5 and PM10 has been used.

Real-time data provided by the World Air Quality Index Project for the Austrian domain has been utilised as a test case. This domain covers 146 stations providing information about chemical constituents (e.g. PM2.5, PM10, NO2, CO, SO2, and O3), and meteorological data (e.g. temperature, pressure, and humidity), depending on the station.

The main findings found in this aspect can be summarized as follows:

- The accuracy of the non-conventional ZTDs should be assessed properly, to improve the assimilation results.
- ZTDs calculated from pure SF code data are not suitable for ingestion to NWM
- The editing criteria for pressure (p) observations should allow eliminating false measurements at the 12hPa level. Pressure measurements may be tested with respect to the GPT2w model. As the model, pressure may deviate from real pressure at the 1sigma level of +/-6hPa a 2-sigma threshold seems to be suitable.
- T measurements are not essential for ZTD calculation but might be directly assimilated. Nevertheless, a quality of +/-1 K would be required, which is not feasible for cheap sensor equipment.

- Humidity would be a quite interesting quantity for modeling the wet delay. Sensor humidity measurements with 10% accuracy would be sufficient for a valuable contribution for either ZTD (ZWD) calculation or direct assimilation.

Possible lines of work on this respect are the following:

- Comparison of assimilation results with TAWES data (in preparation);
- Testing of the assimilation of the single-frequency code + phase data with a lower weight, for a longer period (e.g. 2 weeks), to observe the impact of assimilation in different weather conditions.

2.2 ZTD estimation with low cost GNSS data

With the advent of portable devices (e.g. smartphones) and the ability to extract raw measurement thanks to the Android Nougat (API v.24) onwards, it is possible (in theory) to not only compute position, but also other parameters such as the Zenith Tropospheric Delay (ZTD). In practice there are several limitations that hinder this possibility as of today: (a) poor antenna and (b) duty cycling (smartphone batteries are turned on an off within a second to save battery life). These two factors combined cause that the carrier phase obtained from smartphones are practically useless as of today for the purpose of e.g. PPP or RTK.

However, other low cost GNSS receivers, such as the ones based on single-frequency GNSS chipsets (e.g. Ublox, NVS), allow the logging of not only pseudorange, but also a good quality carrier-phase if the receiver is equipped with a good RF antenna. This enables the possibility to densify currently existing networks of GNSS receivers.

From the ZTD estimation techniques explored during the Atmosfiller project, it is clear that having a big number of receivers in a localized area does not necessarily improve the ZTD estimation when all this data is jointly processed (i.e. cooperative estimation). The reason is that all the receivers observe more or less the same geometry (i.e. same satellites) and thus having more receivers does not necessarily imply adding more *new* information into the filter. Instead, the main recommendation is to process, whenever possible, using a multi-GNSS strategy. In this case, new information is effectively added to the filter (i.e. more areas of the sky are scanned), thus reducing converge time of the estimation, in particular of the ZTD estimation.

For the case of single frequency processing to obtain the ZTD, the impact of the ionosphere model and orbits and clocks used was also assessed. It was found that the reduction of ZTD estimation error (when compared with a full-fledged dual-frequency PPP solution) of using precise orbits and clocks (rather than broadcast ephemeris) is much greater than using a ionosphere model such as GIM delivered in IONEX format (rather than the Klobuchar model).

3 Space-Weather monitoring

3.1 Ionospheric data assimilation

The ionosphere is a complex and rapidly changing environment with complex statistical properties. In the last 15 years a wide range of ionospheric data assimilation models have been developed. They employ a number of different background models and assimilation techniques. In all cases they have been implemented with the aim of making a prediction of the current state of the ionosphere and then to update this prediction with data.

3.1.1 Data Assimilation

Data assimilation is a process whereby data is combined with a model in a mathematically optimal way to form an "analysis". The process is said to be optimal as it uses estimates of the errors in the data and the model to weight their combination and thereby produce an analysis that is closer to the true state of the system.

In this project we have implemented a new ionospheric data assimilation model (TRAIN) that is based on the Malvern Maths Data Assimilation Model (MMaDAM). MMaDAM is a generalised data assimilation system, which provides a hybrid approach combining two forms of data assimilation – the local ensemble transforms Kalman filter (LETKF) and the particle filter (PF). However, currently TRAIN only uses the LETKF part of the algorithm. TRAIN has been designed in order to take advantage of "traditional" measurements (such as total electron content, TEC, from dual frequency, static, ground-based geodetic GPS receivers in the IGS network) and "non-traditional" measurements (such as single frequency TEC measurements and measurements from shipborne receivers).

It comprises four main components:

- **The background model.** This is provided by the NeQuick model which is a monthly median, ionospheric electron density model [Nava et al., 2008]. After NeQuick has been run, an ensemble is created by multiplying the 3D grid of electron density by a set of random numbers drawn from a Gaussian distribution. This results in an ensemble of models where, at each voxel, the mean electron density is given by NeQuick and the standard deviation is half the electron density; i.e. the assumed electron density uncertainty is largest where the electron density is largest.
- **An observation operator.** Currently an observation operator for assimilating slant TEC from a variety of systems (ground, ship and space based) is implemented. Currently each measurement must be a calibrated TEC (i.e. any differential code biases must have been removed) and the observation operator consists of integration through each member of the background model ensemble.
- **The data assimilation algorithm.** The Local Ensemble Transform Kalman Filter (LETKF) has been used. This is an ensemble method that was developed by Hunt et al. (2007). It is efficient as the computation cost scales with the ensemble size rather than the size of the observation array and this is important when non-conventional data is considered (such as TEC from tens of thousands of mobile handsets). Furthermore, each voxel in the ionospheric grid can be processed independently so that the algorithm lends itself to parallelisation.

- **A forward model (time propagation).** After the assimilation step, TRAIN collapses the analysis ensemble into its mean value at each voxel. Then it is necessary to forward propagate the electron density model after assimilation has taken place. This allows information from previous time steps to remain in the system in a way that would not be possible if the empirical model was simply re-run. TRAIN uses a forward operator based on a propagating NeQuick anchor points.

3.1.2 Forecast model - Electron density propagation in time

A technique to propagate ionospheric electron density in time has been implemented on the basis of the modified NeQuick 2 ionospheric electron density model used as a background. This technique can be used to propagate electron density as far as 24 hours and it includes three different options of diverse computational complexity and execution speed.

The performance of the proposed options has been evaluated in terms of the capability to reconstruct the electron density (profiles) in the ionosphere 15 minutes, one hour and two hours in the future for different heliogeophysical conditions and geographic locations. The relevant statistics on foF2 errors, hmF2 errors and integrated absolute electron density errors has led to the selection of the second option as the most suitable one for data assimilation schemes, being the best tradeoff between accuracy and execution speed. In addition the proposed time propagation algorithm performance has been compared to the NeQuick model used in a climatological (R12 input) and weather-like (f10.7 input) mode. The analysis results indicated that the proposed time propagation algorithm always outperforms the climatological model for 15 minutes and one-hour forecasts. Thus additional efforts would be needed to improve the electron density forecasting beyond two hours. An example of the profiles obtained using propagation options 2, 3 and using NeQuick model with R12 and F10.7 inputs is given in Figure 3.

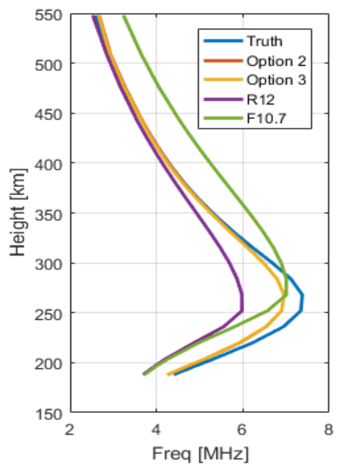

Figure 3 Example of forward propagation of Ne profile with various processing options as well as and NeQuick with R12 and F10.7

3.1.3 Results

The current project has demonstrated that a LETKF can be used to effectively assimilate TEC data into a background model. Furthermore, it has been demonstrated that the use of “non-traditional” data sources (i.e. shipborne GPS TEC) can substantially reduce the edge effects that can occur at localization boundaries when moving from the land into ocean areas (Figure 4). When compared to the peak electron density in the F region (NmF2) from the Dourbes ionosonde the assimilation which includes IGS, shipborne and altimeter data provides the lowest standard deviation of errors and highest correlation with the truth data (Table 1).

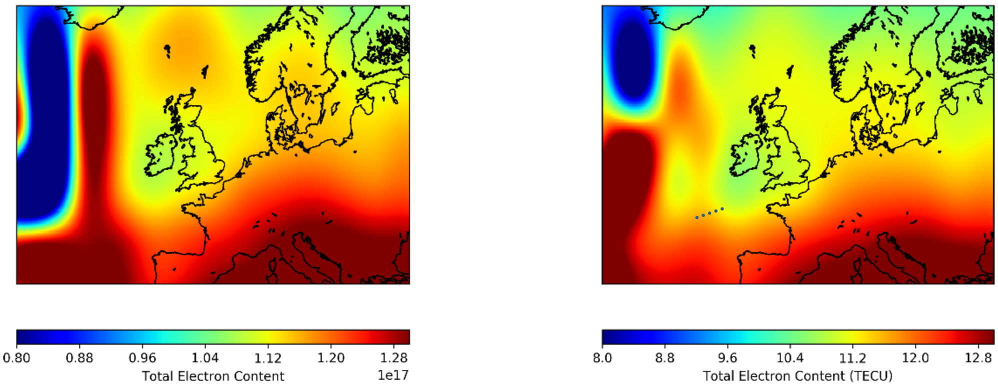

Figure 4. Analysis electron density grid for 1200 UT on June 4th 2017. The left panel shows the analysis when only ground based GPS TEC is assimilated. The large artefact in the western side of the map is due to the edge of a localisation region and the transition from areas of data (over Europe) and no data (in the Atlantic). The right panel show the analysis at the same time, but with the addition of TEC data from a ship (approximate track shown as dotted line) and a space based altimeter.

Model	Mean Error ($e^{-}m^{-3} \times 10^{11}$)	Std dev of Errors ($e^{-}m^{-3} \times 10^{11}$)	Correlation
NeQuick	0.39	0.47	0.87
Just IGS (32 mems)	-0.16	0.48	0.88
IGS+Ship	-0.21	0.44	0.90
IGS+Ship+Altimeter	-0.18	0.43	0.91

Table 1. Comparison of model statistics for June 4th-6th 2017. NmF2 from the Dourbes ionosonde is used as truth. Best performance in each category is highlighted in green and the worst in red.

3.1.4 Recommendations

The following recommendations are made for future work:

1. **Algorithms.** Algorithmic advances should be made to improve representation of height variability in the ensemble; improve the specification of covariances in the ensemble; allow time and spatial variability in the localisation scheme; develop new observation operators for a wider range of data types; and ultimately replace the empirical background model with a physics model.
2. **Data.** Efforts should be made to improve access to high quality, near real time data from a range of sources. More “non-traditional” data should also be sought. Furthermore, the provision of

independent, well maintained and calibrated instrumentation that is operated solely to conduct near real time (i.e. next-day) model assessment should be considered.

3. **Programmatic.** More coordination should be sought with satellite providers to obtain access to data. International cooperation to order to obtain data from trans-oceanic flights and from ships (including future autonomous shipping) should also be sought. Finally, coordination should be sought at a European and international level to ensure a coherent approach to ionospheric model development

3.2 Using GNSS data-of-opportunity for ionospheric monitoring

The following section incorporates the results that have been obtained when incorporating "data-of-opportunity" (non-conventional GNSS data in e.g. research vessels, POD antenna onboard LEO, …) into data-driven models for ionospheric determination. Such data-driven models are used for now-casting and do not attempt to perform a forecast (as opposed to the data assimilation model shown in previous sections). The results hereby summarized are focused on: calibrating single-frequency GNSS data obtained from mass-market receivers, new data editing technique based on Doppler measurement and usage of non-conventional data sources (altimeter, POD and ship borne data) into such models.

1) New usage of mass-market single-frequency GNSS receivers to monitor the ionospheric electron content, up to better than 1 TECU vs dual-frequency receivers.

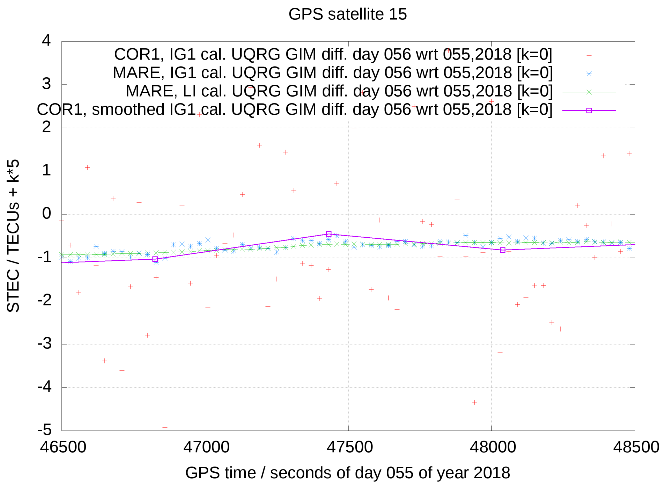

Figure 5 STEC change obtained from UQRG GIM-calibrated dual-frequency LI=L1-L2 (green) and from SIg, single-frequency IG1=(P1-L1)/2, both from MARE geodetic receiver of the ICGC (blue line), close to our single-frequency receiver at COR1, which IG1 is represented in red, and in green after smoothing

The usage of such single-frequency receiver requires a calibration process, whose formulation has been made under this project and has led to a publication (currently under revision):

Hernández-Pajares M. et al, "*Precise ionospheric electron content monitoring from single-frequency GPS receivers*". GPS Solutions (2018). Under revision.

2) Precise detection and fixing of cycle-slips in low-cost single-frequency GNSS receivers by using high-rate Doppler measurements.

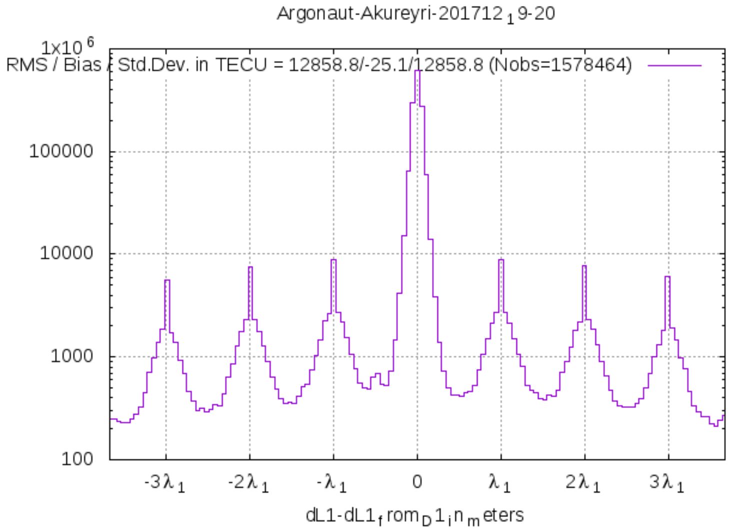

Figure 6 Histogram of the distribution of $\delta L_1+\lambda_1 D_1$ values in wavelength units measured in AKUREx (Akureyri, Iceland, 19-20 Dec 2017), represented for the range of [-3,+3] meters.

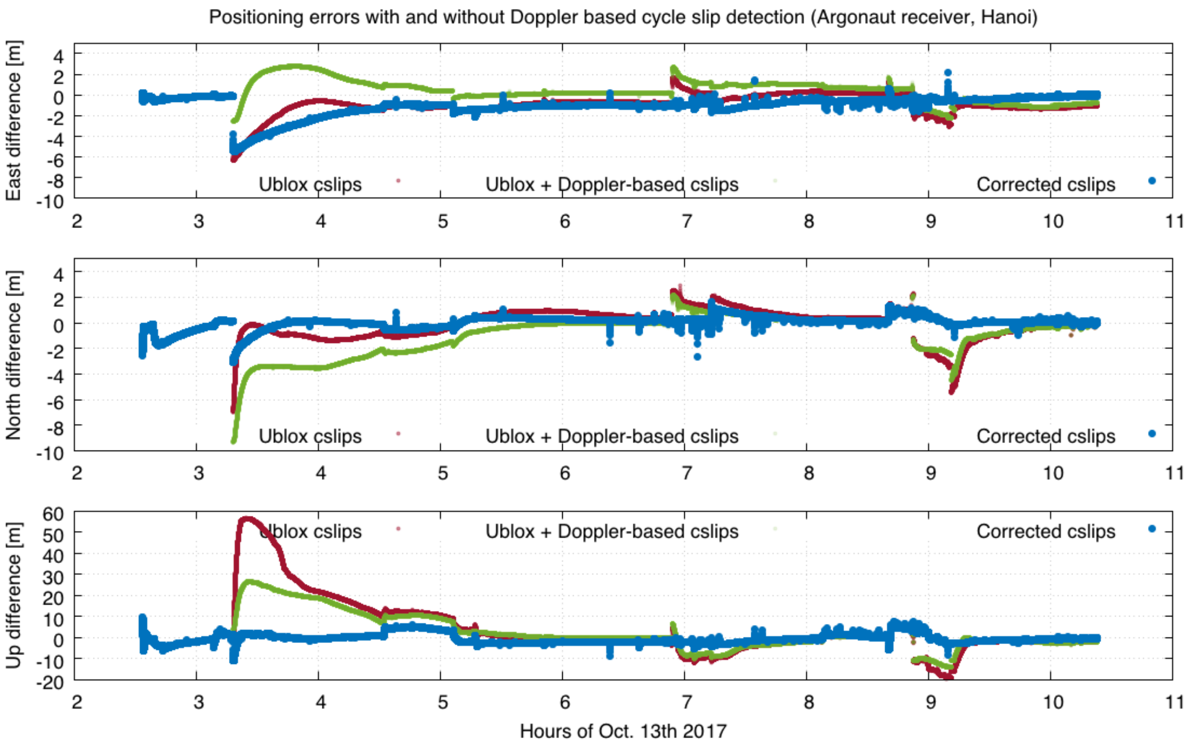

Figure 7 Effect of detecting and correcting cycle-slips in positioning in an affordable (mass market) single-frequency GNSS receiver.

3) Improvements up to 10% of VTEC GIM in areas with lack of permanent receivers by adding dual-frequency GPS measurements taken from vessels

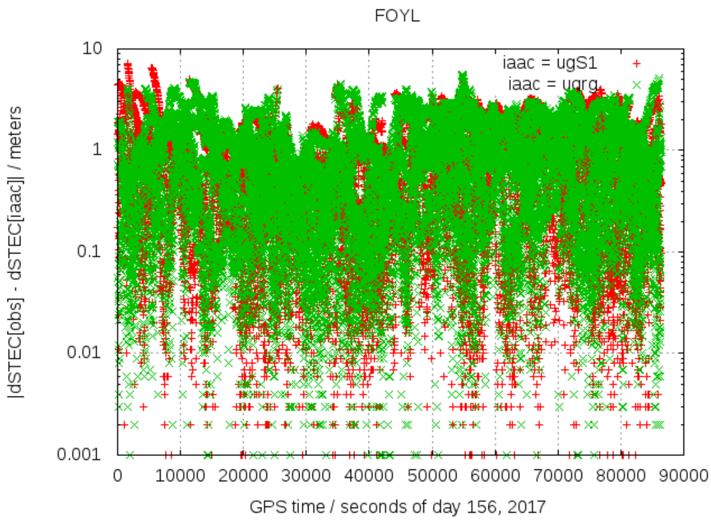

Figure 8 Semilog plot representing the absolute value of the dSTEC error using the +200 GPS receivers and the vessel-onboard MAME receiver (UGS1, red points) and only the permanent GPS receivers (UQRG, green points), for the external GPS receiver FOYL in Ireland.

4) Improvement of the topside electron content determination from ground- and LEO-based GPS measurements up to several TECUs.

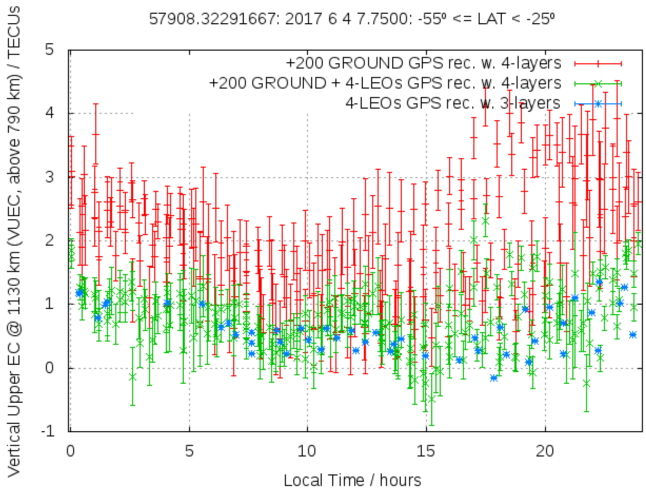

Figure 9 Electron content of the two upper layers [790-1470]km vs local time at south mid-latitudes for scenarios G (ground-GPS only, red), GL (ground and LEO data, green) and L (LEO only, blue), 07:45 day 155, 2017.

5) First assessment of the inclusion of Galileo dual-frequency measurements in the generation of VTEC Global Ionospheric Maps (GIMs), with an improvement of 2%.

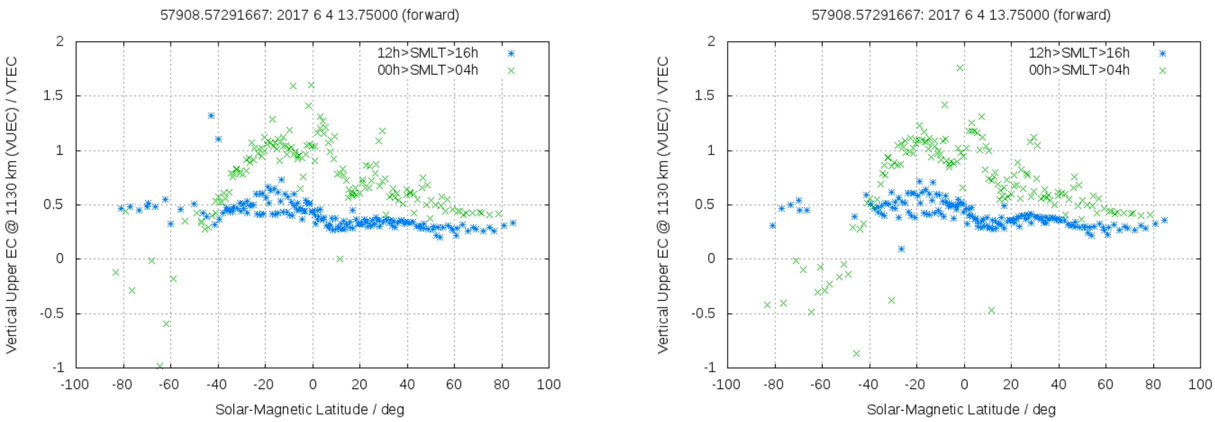

Figure 10 Distribution of the upper layer electron density estimation, normalized by the VTEC (the so called shape function assessed at the top layer): from GPS + Galileo measurements (left), from GPS measurements (right), and vs geomagnetic latitude. The results correspond to the early phase of the Kalman filter convergence of the global ionospheric tomographic model, at 2017 June 4th, 13:45, within the run from 2017 June 4th, 12:00 to June 5th, 24:00.

3.3 Additional ionospheric data

Besides GNSS data onboard and research vessels and VTEC data from altimeter, the project also included ionosonde data to feed to the climatological model as well as single-frequency data from mass-market receivers such as Rokubun GNSS receiver Argonaut (which features a Ublox chipset) or the data logger developed by ICTP.

3.3.1 Ionospheric data

The Atmosfiller project included a review concerning the use of ionosondes to obtain ionospheric information. Several aspects concerning the retrieval of electron density values through ionogram scaling have been considered. They include ionogram inversion, manual vs. automatic scaling, data formatting and archiving and data latency (for possible near-real-time applications).

In accordance to the project necessities, ICTP has supplied hourly manually scaled ionograms obtained from 22+ ionosondes (located all over the world, see Fig. 2) during the days 156, 157 and 158 of year 2017. The data have been provided in terms of plasma frequency profiles (the bottomside is obtained from manually scaled ionograms, edited with SAO-Explorer v 3.5.31; the topside is modeled by SAO-Explorer) and ionosonde characteristics (foF2, foF1, foE, hmF2, hmF1, hmE, M(3000)F2).

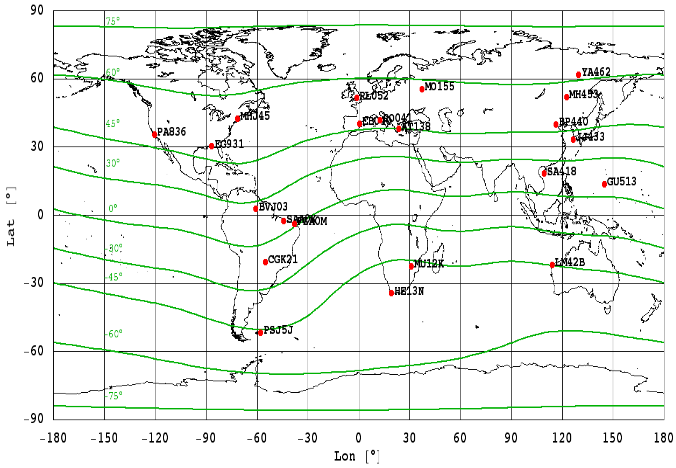

Figure 11 Network of ionosondes used in Atmosfiller. Green lines show the modip isolines

3.3.2 Commercial grade GNSS receiver

A prototype of a low power single frequency multi-constellation GNSS receiver has been developed at the Abdus Salam International Centre for Theoretical Physics. It is based on UBLOX M8T single frequency multi-constellation GNSS receiver that allows acquiring raw data (carrier phase and pseudo-range measurements) for up to 72 satellites from up to 3 different constellations (including GPS, GLONASS, Galileo and Beidou) and with data rate up to 10 Hz. The logging system of the receiver is built on top of the Raspberry Pi 3 minicomputer. An example of the receiver is shown in left panel of Figure 12.

The configuration of the receiver as well as access to the GNSS data can be done in quasi real-time providing an Internet connection is available. The receiver supports two powering options: from a regular 110÷230 V power grid or using solar power system. Therefore, it is suitable for remote areas where power grids are unreliable or not available.

A number of prototypes has been implemented and tested in different parts of the Earth, including low latitude regions (Africa, South America and Asia). An example of the data collected for GPS constellation in Abidjan (Cote d'Ivoire) in terms of the difference between pseudo-range and carrier phase measurements (C1-L1, in TECU) is presented in Fig 4. The C1-L1 difference is leveled to 0 TECU at the highest elevation angle for each satellite arc. The elevation mask used is 25°. Different satellite arcs are presented with different colors. The level of residuals (after removing low frequency fluctuations) is estimated to be ~1.5÷2 TECU in standard deviation.

Long run tests have been performed on the mentioned prototypes, demonstrating the reliability, scalability and robustness of the proposed approach, which could be therefore considered as a starting point for the implementation of a global single frequency GNSS receiver network for ionospheric monitoring.

In addition, the Argonaut GNSS receiver developed by Rokubun[1] has been also used in several tests throughout the project (single frequency GNSS data calibration, cycle-slip detection based on Doppler, data campaign for the Minerva Uno research vessel in the Mediterranean, …).

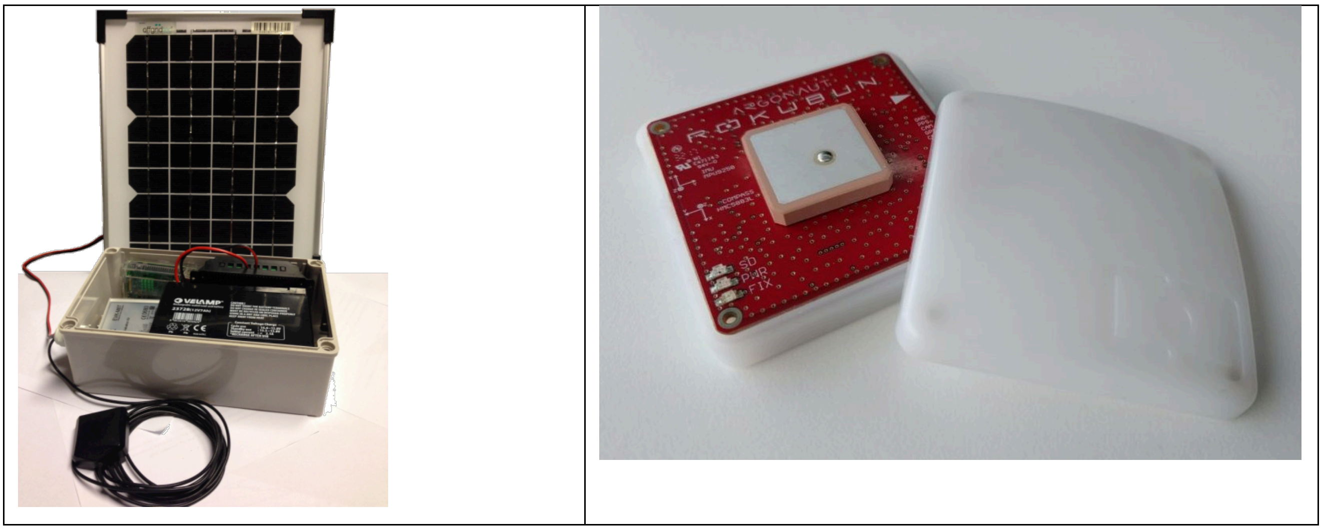

Figure 12 GNSS receivers used in the Atmosfiller project that are based on mass-market GNSS chipset (Ublox). (Left) shows the receiver system developed at ICTP, (Right) is the Argonaut GNSS receiver manufactured by Rokubun

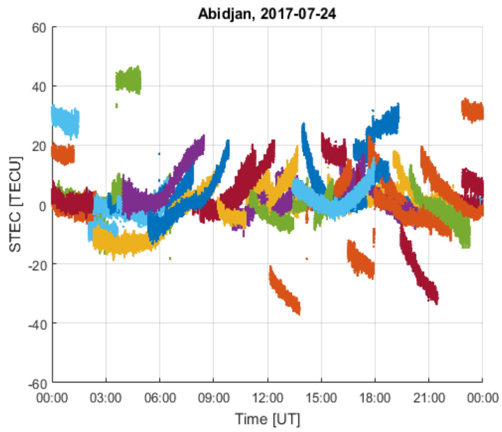

Figure 13 Code-minus-carrier phase observable ("iono" GRAPHIC) obtained from a Ublox GNSS chipset

[1] http://rokubun.cat/wp-content/uploads/2017/12/ARGONAUT_Brochure.pdf

4 References

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Nava, B., P. Coisson, and S. Radicella (2008), A new version of the neQuick ionosphere electron density model, J. Atmos. Solar-Terr. Phys., doi:10.1016/j.jatsp.2008.01.015.

5 Acknowledgements

The consortium of the Atmosfiller project would like to thank the following parties:

- To the crew of the FS Maria D. Merian research vessel and its managing authority, Univ. of Hamburg, for providing both the dual-frequency GNSS data as well as meteorological readings of the vessel instrumentation during the data campaign of the project.
- To Marco Talone, Ph.D. (from JRC) and crew of the Minerva Uno vessel for hosting and operating Rokubun's Argonaut receiver during the data campaign of the project.
- Also, the following parties are also ackowledged for for hosting and operating the UBLOX receivers during the data campaign of the Project:
    - Prof. Babatunde Rabiu, Centre for Atmospheric Research of the National Space Research and Development Agency, Anyigba, Nigeria (ICTP Ublox receiver)
    - Prof. Olivier Obrou, Laboratoire de Physique de l'Atmosphère, Université Félix Houphouet Boigny Cocody, Abidjan, Côte d'Ivoire (ICTP Ublox receiver)
    - MSc Ing. Jorge García Villalobos, CORPAC S.A., Lima, Peru (ICTP Ublox receiver)
    - Dr. Navin Parihar, ICTP Junior Associate, Ranchi, India (ICTP Ublox receiver)
    - Prof. Dr. TA Hai Tung, Dr. LA The Vinh and the staff at the NAVIS center for hosting the data campaign of the Argonaut GNSS Receiver at Hanoi (Vietnam)