A realistic set of ionospheric profiles based on FORMOSAT-3/COSMIC for radio occultation processor development and testing

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Abstract. The Radio Occultation (RO) instrument on-board the upcoming EPS-SG satellites will be devoted primarily to monitor the neutral atmosphere, it does however also observe the ionosphere up to about 500km altitudes. The RO instrument consists of a GNSS (Global Navigation Satellite System) receiver and two occultation antennae pointing to Earth's limb in velocity and anti-velocity direction. The instrument data will be processed by EUMETSAT (primarily for level 1B bending angle profiles) and by the ROM SAF, using its ROPP processing package software to obtain e.g., level 2 vertical profiles of temperature, water vapour, pressure of the neutral atmosphere. The official ROPP software release has the capability to forward propagate input level 2 data into level 1B profiles (among several other capabilities); this official release was modified in this study to include ionospheric electron density profiles and its impact on the bending angle at the different GNSS frequencies, thus allowing the generating of simulated bending angle profiles that can be used for RO processor and end-to-end data flows, format, etc. testing. The generated test data should be as realistic as possible, making not only use of the neutral atmospheric information provided by an RO instrument, but also including ionospheric information on the different GNSS frequencies. In particular the simulation of the ionospheric impact on radio occultation data required (1) the already mentioned update to ROPP; (2) a selection process to identify suitable ionospheric conditions (very realistic neutral atmospheric data is readily available from NWP models which provide high vertical resolution data in the lower troposphere). In order to identify demanding ionospheric profiles, four representative periods, of high and low ionospheric and geomagnetic activity, were selected. Low level FORMOSAT-3/COSMIC data obtained during these periods has been processed up to ionospheric density with an improved inversion approach. This improved methodology is based on using the *separability hypothesis*, to overcome the spherical symmetry assumption of the Abel inversion as well as a new mechanization of the inversion process, based on a joint processing of all the occultation data via a linear mean square filter, rather than adopting the classical *onion peeling* approach. Additionally, with the development of this realistic data set, a proxy index for scintillation monitoring based on the inverted profiles (Occultation Scintillation Proxy Index or OSPI) has been identified, which shows reasonable correlation with the amplitude scintillation index S_4.

1 Introduction

Sounding the atmosphere (both neutral and the ionosphere) using GNSS data (i.e. Radio Occultations) has been an active topic of research since the GPS/MET mission. Since then, an increasing number of missions (e.g. CHAMP, SAC-C, FORMOSAT-3/COSMIC, ...) have been devoted (either as primary or secondary objective) to this purpose. The GNSS data gathered from antennae pointing to the Earth's limb can be *inverted* with the Abel inversion to analyse the neutral atmosphere ([Kursinski et al. (1997)]) and the ionospheric electron density ([Schreiner et al. (1999)], [Hajj and Romans (1998)], [Hernández-Pajares et al. (2000)], [Garcia-Fernandez et al. (2003)] and references therein).

The EPS-SG (European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Polar System - Second Generation) programme will contain RO (Radio Occultation) payloads whose primary objective is to monitor the Earth's neutral atmosphere, the RO instrument will however also observe data up to 500km altitude on the occultation antennas. The processing chain of the EPS-SG GNSS RO data will be based on a processor developed under EUMETSAT's lead for level 1B data (primarily bending angle ~~over~~as a function of impact parameter), and on the ROM SAF (Radio Occultation Meteorology Satellite Application Facility) and its ROPP (Radio Occultation Processing Package) software for level 2 data (e.g. refractivity, temperature, see [Culverwell et al. (2015)]), which will allow to obtain the neutral-atmosphere-related products. In the current version of the ROPP software, the ionospheric effects (needed to estimate the bending angle of the neutral atmosphere) are modelled with an analytical formula. This ~~analytical~~ formula (called *Zorro* formula, see [Culverwell and Healy (2015)]) is the ~~analytic integration of the ionospheric delay~~ approximation of the numeric integral along the line of sight considering that the vertical profiles of electron density follow a Chapman layer model.

The current EUMETSAT RO data obtained by the GRAS (GNSS Receiver for Atmospheric Sounding) instrument on-board the EPS satellites observes occultation data only up to about 80km. In preparation for the new EPS-SG instrument capabilities, EUMETSAT initiated the ROPE study (Radio Occultation Profiling Evaluation, ITT number 15/210697) which included, as main objectives, the generation of realistic ionospheric test data for processor and end-to-end testing (another main objective was the modification of the ROPP Forward Model (FM) code so that it could accept an arbitrary electron density profile to model the ionospheric delay).

In the process of defining this realistic ionospheric profiles, a data driven (empirical) model of the ionosphere has been developed, using real-time VTEC (vertical total electron content) data as provided by the Global Ionospheric Maps in IONEX format (see Hernández-Pajares et al. (2009) or Schaer et al. (1996)), and a representative data set of shape functions, describing the vertical variability, obtained from FORMOSAT-3/COSMIC data under different geomagnetic and ionospheric conditions.

Note that the purpose of this work is not to develop a generic climatological model such as the International Reference Ionosphere (IRI). Rather, this work aims at developing a data-driven methodology to provide realistic ionospheric data set (also referred to as "model" in this article). This data set might also become useful for an improved understanding of the ionospheric impact on neutral bending angles, as well as an input source for simulation studies of RO data.

As an additional result of this effort, a new scintillation index based on the analysis of the vertical profile of electron density has been developed. Typically, when raw GNSS data is available, scintillation can be monitored using the C/N0 values (S_4

index, see [Kintner et al. (2007)]) or the carrier-phase measurements (σ_ϕ or its lower-sampling rate version Rate of TEC Index, see [Prikryl et al. (2013)]). In this work, the Occultation Scintillation Proxy Index (OSPI) is being computed using the inverted profile, by analysing the variation in the topside of the vertical profile of electron density.

The paper is organized as follows: the following section includes a description of the ionospheric model and the data used for the generation of the model and different scenarios. The second section includes a description of the OSPI index, its generation and some comparison with current scintillation indices. The paper ends with a conclusions section.

2 Model generation

This section includes the description of the processing model to invert the observation profiles as well as post-processing tests and checks to automate the screening and discard unphysical or unrealistic profiles.

2.1 Profile inversion

The processing model described here uses the raw GNSS observables (i.e. dual-frequency pseudoranges and carrier phases), not the already processed profiles inverted through Abel transform by analysis centers such as e.g. UCAR ([Kuo et al. (2004)]).

In order to obtain the vertical profiles of electron density from the GPS Global Positioning System raw data, a modified *onion peeling* ~~mechanization~~method of the Abel inversion has been used. This mechanization consists of:

- Applying the *Separability Hypothesis* [Garcia-Fernandez et al. (2003)], which is a technique that uses Vertical Total Electron Content (VTEC) to account for the horizontal gradients of the ionosphere. Essentially, this hypothesis assumes that the electron density (3D field) can be *separated* into a horizontal component (the VTEC) and a vertical descriptor of the ionosphere (F(h) function or *Shape Function*)

$$N_e(\lambda, \phi, h) = VTEC(\lambda, \phi) \cdot F(h)$$

  The shape functions $F(h)$ can be understood as normalized N_e profiles, with higher spatial and temporal correlation, as shown in Figure 1.

- Using Linear Mean Square (LMS) (instead of the iterative method) so that one can jointly process all occultation measurements with additional features such as phase bias estimation and bottomside constraints. See Figure 2 for an example of profiles inverted with LMS and Separability Hypothesis. The additional advantage of the LMS approach is the possibility to re-run various iteration, thus refining the estimation of ancillary parameters (such as phase bias or topside electron content).

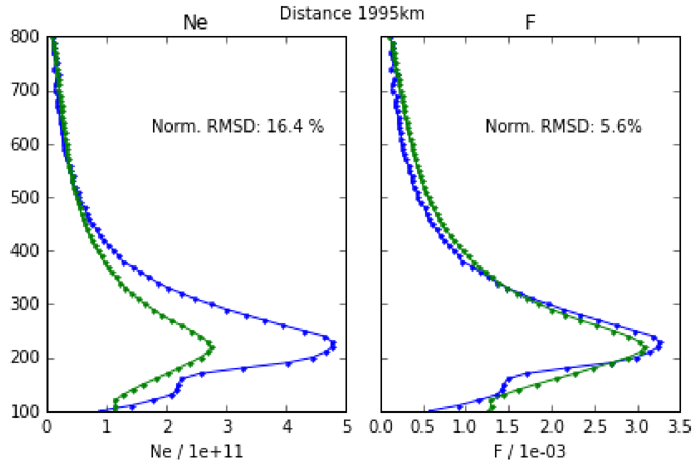

Figure 1. Separability hypothesis generates shape functions ($F(h)$) instead of electron density profiles. The plot shows two inverted occultations that are ca. 2000km apart. The similarity between both Shape Functions is higher than the corresponding electron density profiles (obtained assuming spherical symmetry).

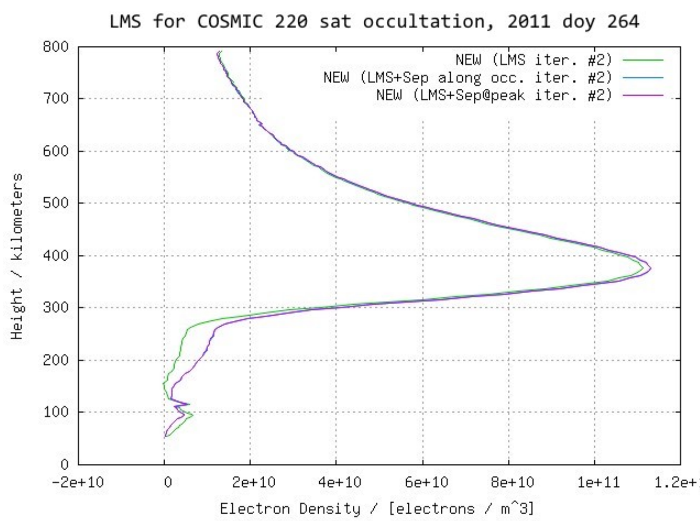

Figure 2. Example of LMS inversion for a FORMOSAT-3/COSMIC occultation in combination of Separability Hypothesis. Green line corresponds to the LMS using sherical symmetry (i.e. without accounting for the horizontal gradients). Blue line corresponds to the LMS with separability hypothesis, where the electron density corresponds to each of the points of the observation with lowest distance to the Earth's surface. Red line is same as blue, but the electron density profile is the vertical profile taking as reference the point where the peak of electron density occurs (NmF2).

2.2 Profile screening ~~and selection~~

~~After a first COSMIC RO GNSS raw data check and editing,~~After a basic data check, editing and cycle-slip detection using the dual-frequency observables of the FORMOSAT-3/COSMIC (hereafter "COSMIC") RO GNSS data, a (typically) large set of inverted profiles are available. However, not all these profiles are suited to build a profile database: some are incomplete, have artifacts or large noise or are outright unphysical. Therefore they have to undergo a quality check, as already suggested by several authors (e.g. [Uma et al. (2016)]). In order to perform this quality check in an automated way:

- The profiles shall have a minimum height range, at least covering the main layers of the ionosphere (~~E,~~ F1, F2, which translates in a typical height range between 150km to 500km)

- Ideally, the integrated shape function ($F(h)$) along the vertical should in theory be 1 (i.e. $\int_0^\infty F(h)dh = 1$) so that the integrated electron density (N_e) along the vertical profile yields the VTEC. In practice this does rarely hold because the profile does not usually account for the topside ionosphere. It should be, however, close to 1 (i.e. larger than 0.75). Despite this fact, this is mitigated by taking the POD data of the LEO to assess the topside content as well as making an extrapolation of the profile by means of the Vary-Chap model, as proposed in Hernández-Pajares et al. (2017).

- The maximum variation of the first order profile derivative should be less than 2000%. This threshold is wide enough to allow for ionospheric features with high variability but tight enough to discard unrealisitic profiles with large jitter due to measurement errors.

- The $hmF2$ (maximum of the F2 layer peak) should be comprised between a physical and reasonable value (e.g. lower than a LEO satellite height but above the bottom E and D ionospheric layers). Reasonable values for hmF2 are considered between 200km and 400km, as supported by Figure 1 of Hernández-Pajares et al. (2017).

- Due to the fact that negative N_e values are unphysical, a strict positivity is required for all points of the profile.

One of the main advantages of these criteria is that it can be applied in an automated way.

2.3 Profile regularization

For the purpose of processing EPS-SG radio occultation data, and in particular for the applicability of the proposed empirical model into the ROPP-FM package of the ROM SAF software, it is necessary to regularize the profile and avoid sudden changes in it. In particular the following points were enforced for every profile that passed the screening test:

- The topside of the profile has been extrapolated up to the EPS-SG orbit height (thus 820km, but could be higher if needed) using an exponential model:

$$N_{e,topside,fit}(h) = \alpha \cdot e^{\beta \cdot (h-h_0)}$$

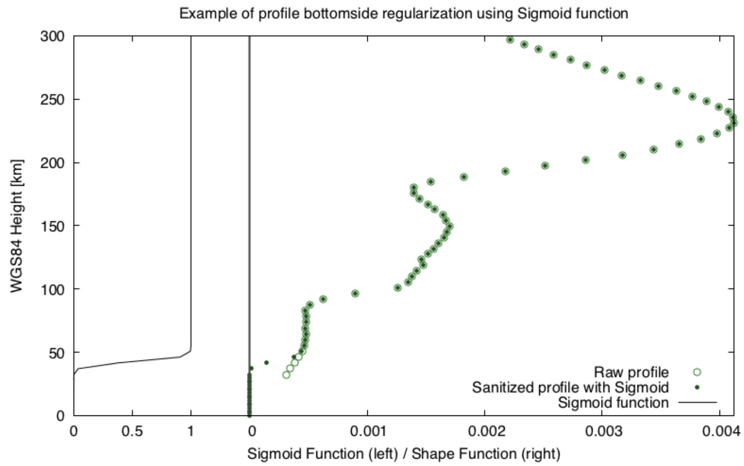

Figure 3. A transition of the bottomside to reach $N_e = 0$ at the bottomside was enforced by means of a masking function.

where the coefficients α, β and h_0 have been computed by fitting the available topside of the profile, beyond the hmF2 (maximum of the electron density peak) plus a certain margin (typically 50km to 100km upwards).

- In order to avoid artifact errors when using the profiles in ROPP-FM, a smooth transition to $N_e = 0$ on the bottomside was enforced. This was done by means of a masking function based on a sigmoid (see Figure 3). This sigmoid function defined a transition zone (from 1 to 0) of 20km that covered the last available samples of the profile bottomside. This approach guarantees a smooth transition to 0 while minimising the modifications to the original profile.

- Removal of *pseudo D layer*. As it is known, using the Abel inversion implies that the error in the N_e estimation increases with decreasing height. This is due to the fact that the retrieval of the lower layers need the estimation of upper layers, thus the error accumulates on the bottomside. This can cause some artifact errors that in some cases might seem a fictitious sporadic layer in the D layer, which is not realistic (see example in Figure 4). To mitigate this effect, if a profile showed a peak under 90km (the upper boundary of the D-layer, see [Mitra (1951)]), this was considered a false D layer peak and thus the samples from 90km downward were removed (preserving, D layer and thus the samples from 90km downward were removed (preserving, however, the rest of the profile). As it is known, the iterative nature of the Abel inversion implies that the error accumulates at the lower heights of the profile, but this does not necessarily imply that the complete profile is incorrect. For this reason, those profiles with suspicious D-layer were left (without its bottom part) rather than completely eliminated. Also, some of these suspicious profiles correspond to some occultations where lower observations start in a region with low electron density, but then end up in high activity areas far from the tangent point.

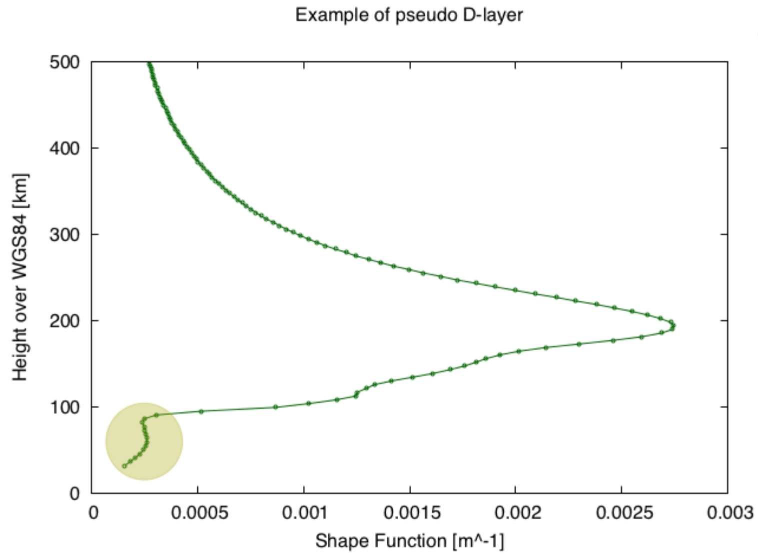

Figure 4. Example of a *pseudo D layer* in an inverted profile. In this case, the samples below 90km are removed. This shape function has been obtained from COSMIC RO data corresponding to August 27th 2008 7:30h UTC, which took place at a mean longitude of 31.1° and mean latitude of 32.4°

2.4 Definition of representative scenarios ~~Scenarios~~

As mentioned earlier in the paper, the effort of building a database of profiles was intended to give an empirical model for the ionosphere to correct its delay in the retrieval of neutral atmosphere using the Abel inversion. So far, the ROPP software computed the ~~ionospheric delay~~ bending angle using an analytical integration of the Chapman function (i.e. the so-called *Zorro* equation, see Culverwell and Healy (2015)). With this new option, for a given RO event, a shape function is selected and scaled with the appropriate VTEC value so that an electron density profile is obtained. This profile will represent the ionospheric electron density for the footprint of the occultation, which is then needed for the integral of the bending angle. In order to test this new feature, implemented in the context of the ROPE study, different representative scenarios in terms of ionosphere (geomagnetic conditions, solar activity, season,...) have been prepared. The characteristics of each scenario are summarized in Table 1 and shown in Figure 5. Each scenario comprised several days to include a sufficiently high number of COSMIC occultation events. The range of each scenario has been defined so that it is homogeneous in terms of solar and geomagnetic activity. Each COSMIC occultation of each scenario has been processed according to the methodology outlined above. Therefore, since the resulting product of the inversion are Shape Functions ($F(h)$) rather than electron density profiles, the profiles have to be multiplied by the Vertical Total Electron Content (VTEC) at the appropriate location and time in order to transform it to electron density. This VTEC is obtained by means of the Global Ionospheric Maps in IONEX format (see Hernández-Pajares et al. (2009) or Schaer et al. (1996)). The date (as day of year, and day-of-year) of the IONEX map used to define the scenario is also indicated in Table 1.

Table 1. List of scenarios defined for the ionospheric data set, prepared for EUMETSAT's ROPE study

Ref.	Name	year	doy range	IONEX date	COSMIC occ. count
1	High solar equinox	2011	261-267	2011-263	878
2	High solar solstice	2011	352-358	2011-355	680
3	Low solar	2008	234-240	2008-237	1777
4	Geomagnetic storm	2006	346-352	2006-349	444

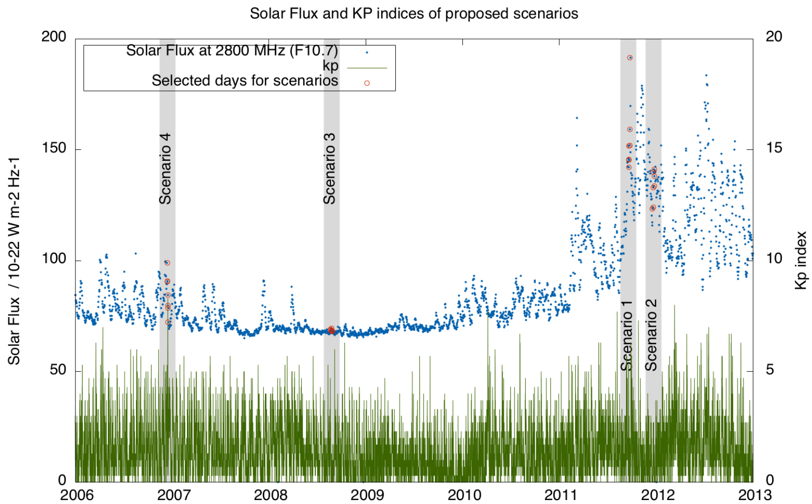

Figure 5. Scenarios of the EUMETSAT's ROPE study. Each period (grey rectangle) is shown against the Solar Flux and the Kp index, to illustrate the geomagnetic and Solar activity conditions of each scenario.

2.5 Profile selection and assignation

Once the database of profiles has been built, the closest profile (shape function) is assigned to a radio occultation event in terms of local time (rather than longitude) and latitude. The reference position of the RO events is taken where the observation has a tangent distance (also called Straight Line Tangent Altitude) to the Earth surface of 450km. Note that for the shape function, the date of the event is not taken into account. In order to provide the actual electron density profile to be used in the inversion process, the VTEC from e.g. IONEX files at the proper time, epoch and location is used. This gives the proper amplitude scaling to the shape function, reflecting the actual variability of the ionosphere.

An interpolation of the shape function, using e.g. a linear model or Kriging, could be performed to account for the height variation (and in particular the hmF2 variation), but this is out of scope of the current work and is considered to be of secondary relevance compared to the VTEC scaling of the shape function to obtain the electron density profile.

3 Scintillation and wave affected profiles

In order to provide a model for the scintillation, as present in the vertical profiles of electron density (or shape functions), the first step is to evaluate its morphology. COSMIC occultations for a single day of Scenario 1 (2011, day of year 264) have been visually inspected (mainly looking at the shape of the F2 layer) to identify those profiles apparently affected by either scintillation (i.e. jitter-like noise in the profile) or wave-like structures.

The results of this manual selection are shown in Figure 6. The upper panel of this plot shows the distribution of all inverted profiles from the COSMIC satellites as well as the selected events with scintillation (red) and selected events with waves (green). Wave-like events comprise profiles that might include small scale Travelling Ionospheric Disturbances (TID), with local maxima very different from hmF2. Over all 757 occultations for this day[1], 119 of them have been identified as affected with scintillations and 7 by wave-like structures. In order to illustrate the morphology of scintillating as well as wave-affected profiles, the figure include examples of both in the bottom panels. The distribution of the scintillation events shown in the top panel of Figure 6 (mostly lying at southern hemisphere and high latitudes) is consistent with Figure 1 of Basu and Basu (1989) (on page 134).

[1]This number corresponds to the complete data set of profiles for this day without the quality check based on the solving strategy, described in the paper

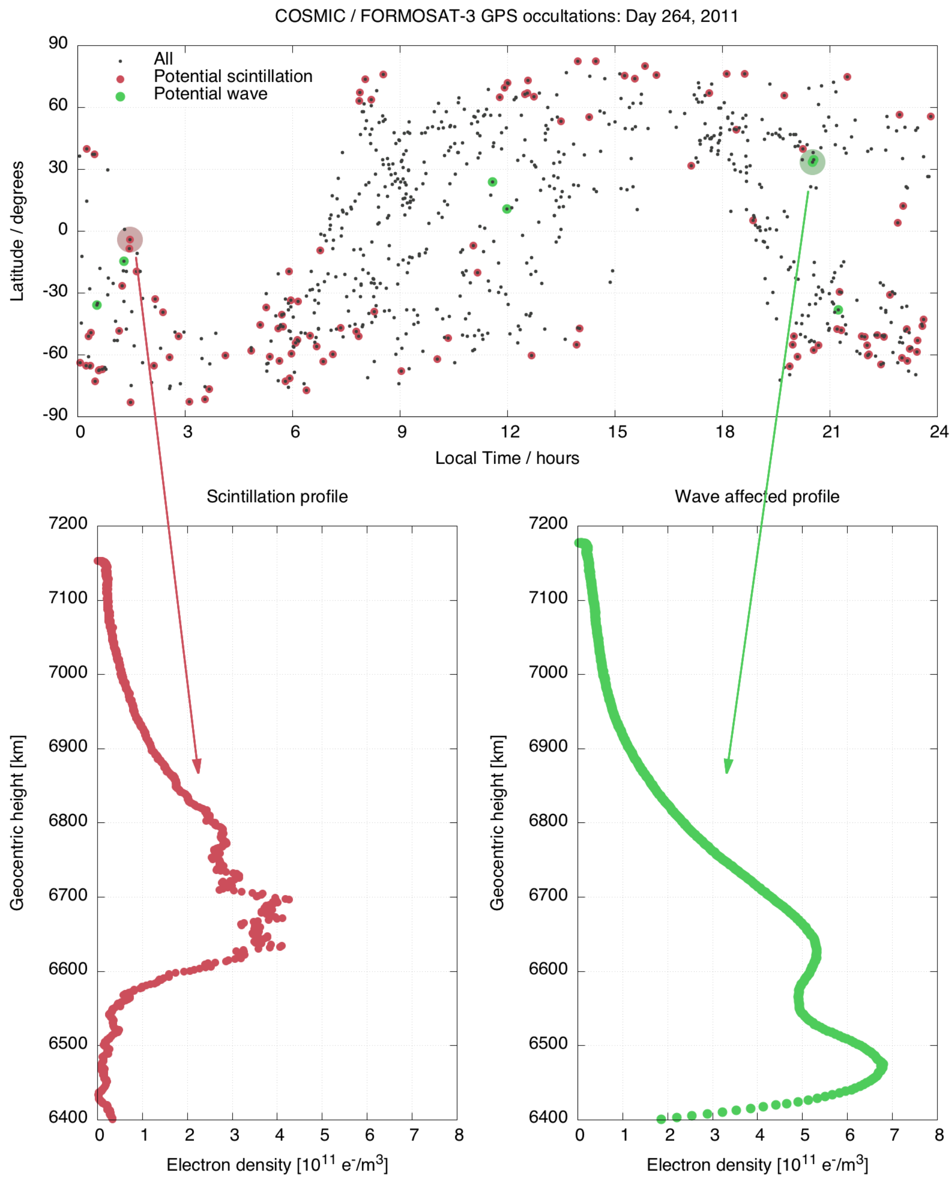

Figure 6. Distribution of occultations (in local time and latitude) for the COSMIC satellites on 2011 doy 264. Manually detected occultations that are scintillation or wave affected are also included in the plot. The bottom panels include two examples of scintillation- and wave-affected profiles.

3.1 Scintillation index

In order to automate the identification of the profiles with scintillations, the Rate of Total Electron Content Index (ROTI), used to identify scintillating environments in the ionosphere, is being adapted to the case of electron density profiles. This proxy index (named Occultation Scintillation Proxy Index, OSPI) is defined as the standard deviation of the variation between consecutive vertical profiles samples (of the topside ionosphere sampled at ca. 1 to 3km) normalized by the value of the profile at the maximum (i.e. $NmF2$). This is expressed by the following formula:

$$OSPI = \frac{\sigma_{\Delta N_e}(h_{topside,min}, h_{topside,max})}{NmF2} \tag{1}$$

where

- σ denotes the standard deviation operator
- ΔN_e is the difference between consecutive samples of the electron density vertical profile. Only the samples of the profile comprised between $h_{topside,min}$ and $h_{topside,max}$ are being considered (typically 550km and 650km above Earth's surface respectively). The sampling rate used to compute these differences is the original sampling of the profile so that it is consistent with the naked-eye analysis
- $NmF2$ is the peak electron density of the profile.

The main advantage of the OSPI index compared to e.g. σ_ϕ is that, as the ROTI index, it can be computed with low sampling rate data (e.g. 1Hz rather than 50Hz) and, additionally, OSPI is computed using topside data, which gives a more localized indicator of scintillation events. This is specially relevant for LEO RO data because measurements with low impact parameters traverse various ionospheric regions (height, different line-of-sight geometries at low and high latitudes with regard to the Earth's magnetic field, ...)

As an example, Figure 7 includes the OSPI values for a clean profile (without scintillation after visual inspection) and a profile affected with scintillation. Note that the OSPI values can be one order of magnitude larger depending on the scintillation effect. More generally, the histogram of the OSPI values for clean and scintillating profiles (obtained from COSMIC on 2011 / 264) are shown in Figure 8. Among the 119 profiles that have been manually labeled 'with scintillation', 68 of them yielded an OSPI value greater than 0.003141. This represents a 57% of coincidence. There is a dubious area with OSPI values between 0.001 and 0.0031 with no clear distinction between clean or scintillating profiles. Despite this uncertainty region, this proposed index can constitute a useful tool for ~~automatizing~~automating the detection and selection of scintillation-affected occultations. Further tuning can also improve the performance. This (rather loose) OSPI threshold of 0.0031 ensures a selection of profiles (for Scenario 4) that would include some profiles affected by scintillation and also some others without.

In order to assess the suitability and limitations of the proposed index, a comparison with the amplitude scintillation indices provided by COSMIC is being provided. These indices are the S4 index and the SNR of the L1 carrier amplitude obtained with C/A-aided tracking loop. Figure 9 shows this comparison. The OSPI index has been computed not only at the topside

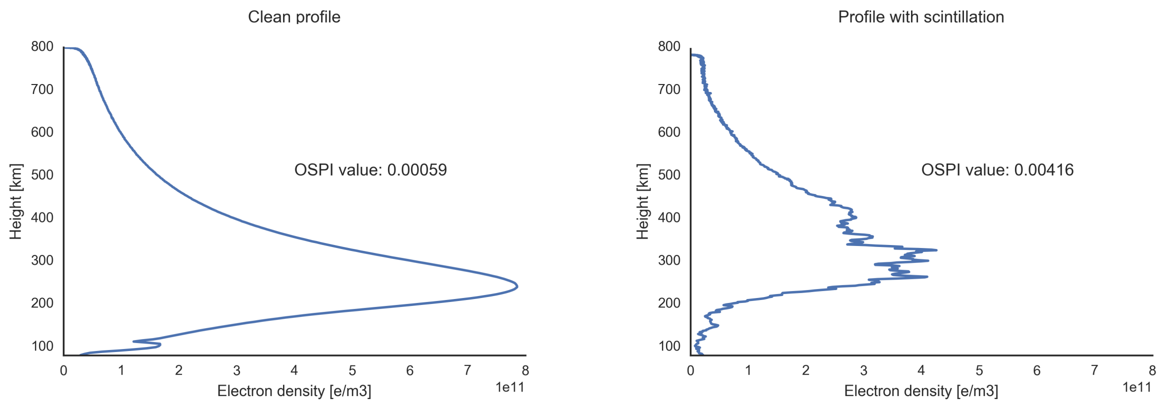

Figure 7. Example of OSPI values for a clean profile (left) and a profile affected by scintillation (right). Left profile corresponds to an occultation event that took place on September 21st 2011 12:20 UTC on mean longitude of 13.9° and mean latitude of 50.2°. Right profile corresponmds to an occultation event on September 21st 2011 13:20 UTC on mean longitude and latitude of 180.3° and 10.2° respectively.

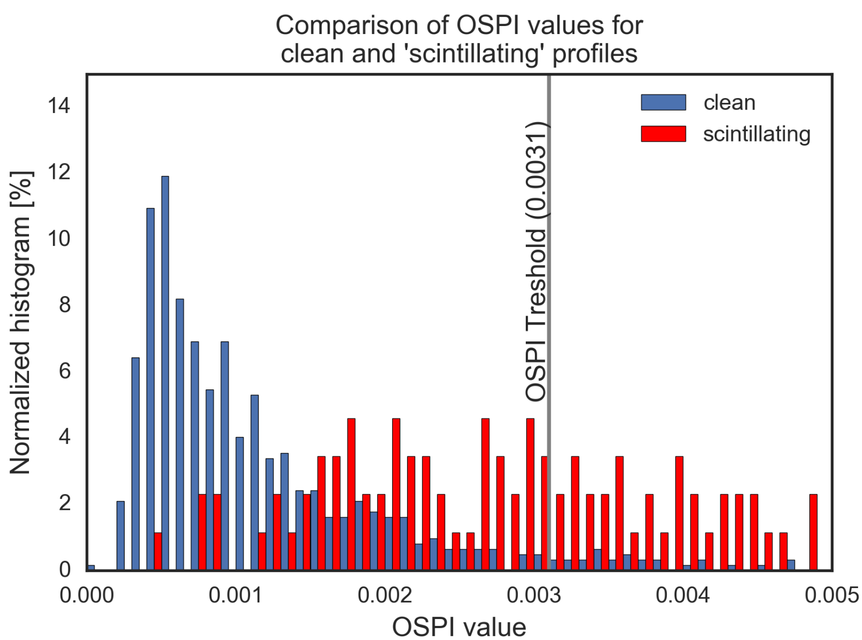

Figure 8. Normalized histograms of the OSPI values for the COSMIC profiles of 2011 / 264. The histograms have been split into OSPI values from clean profiles and OSPI values from profiles affected with scintillation.

level but at every 100km interval of the profile (i.e. x-axis of the Figure) and the COSMIC indices are being provided also at these heights. The y-axis of these figures are the percentage of agreement relative to the profiles labelled as "scintillating" using different methods: (left panel) naked eye and (right panel) OSPI between 550km and 650km. The manual labelling of scintillating events was based on identifying significant jitter in smooth profiles. It is worth noting that:

– The OSPI at 600km (i.e. between 550km and 650km) is the one that provides the best agreement relative to the profiles labelled as scintillating using the naked eye approach, compared to the OSPI at other heights (such as e.g. F2 layer or E layer, at lower height intervals)

– The OSPI index (i.e. standard deviation normalized with the electron density) outperforms other similar index such as the standard deviation of the electron index normalized by the RMS of the electron density along all the profile or the standard deviation of the electron index without normalization.

– The right panel of Figure 9 shows the consistency between the proposed indices (taking as reference the OSPI at 600km), which is larger compared to the case when taking as reference the naked eye.

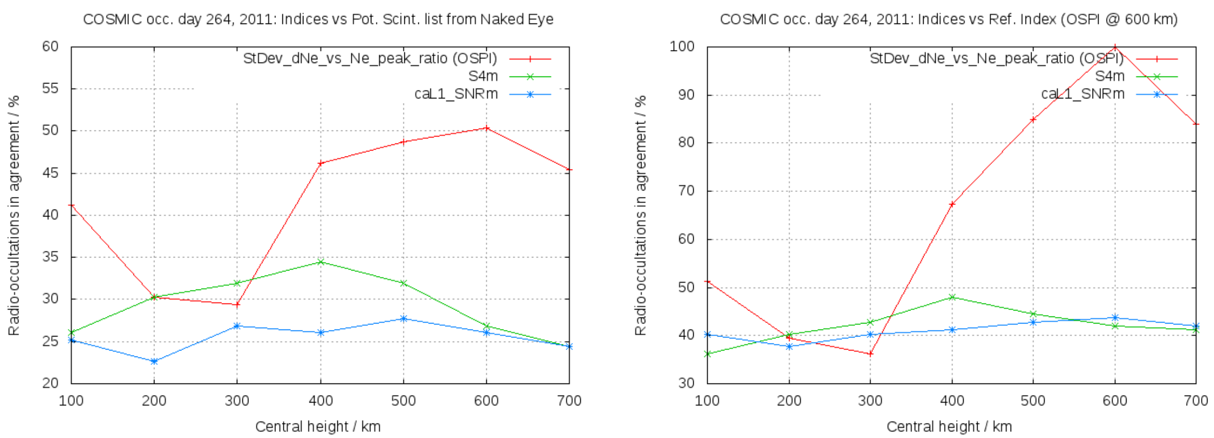

Figure 9. Comparison of OSPI obtained at different height intervals with amplitude scintillation indices provided by COSMIC. Left panel shows the agreement relative to the profiles labelled with "naked eye" while right panel shows the agreement relative to OSPI between 550km and 650km (i.e. OPSI @ 600km).

The correlation check between the scintillation parameters given by COSMIC and the proposed OSPI index is provided in Figure 10. Even though the correlation seems weak between OSPI and S_4 or SNR_{L1}, the upper pictures show that there are some dependency that can be exploited. Note however that a perfect agreement of the S_4 and SNR_{L1} relative to the naked eye profiles or with the OSPI index are not expected because these indices refer to the scintillation in amplitude, rather than the scintillation in phase, which is the one affecting the vertical profiles. No comparative plots between OSPI and σ_ϕ could be performed due to the lack of available data.

4 Conclusions

A data-driven procedure for the generation of realistic electron density profiles has been developed within a EUMETSAT study. The main aim of the study was the generation of realistic neutral and ionospheric atmospheric scenarios that can be used for

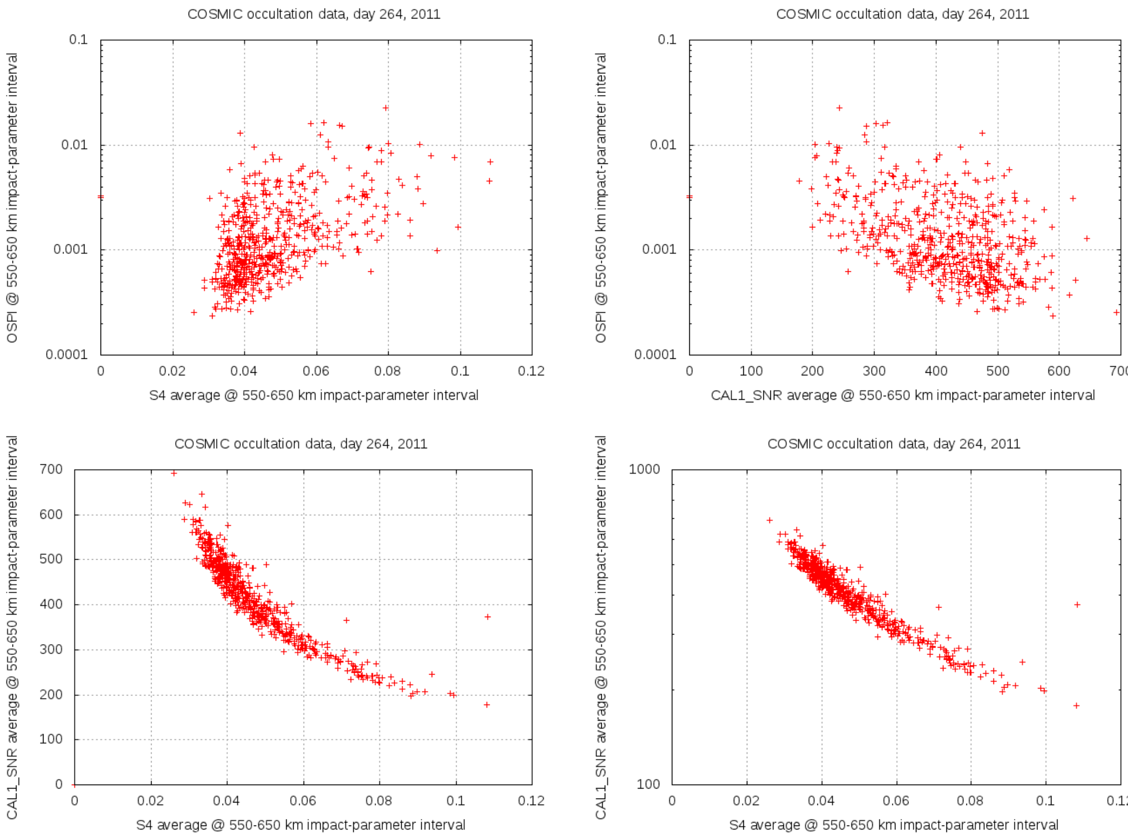

Figure 10. One-to-one comparison between the different scintillation indices provided by COSMIC and OSPI. Upper left shows the OSPI vs. S4, upper right shows OSPI vs. SNR of L1 and lower panels show the correlation between the SNR of L1 and S4 in linear (left) and log (right) scale. The correlation coefficients of the OSPI vs S4 and OSPI vs SNR are 0.42 and -0.38 respectively, which correspond to a linear correlation with positive and negative sign, consistent with the plots.

EPS-SG RO processor and end-to-end performance testing. The presented work describes all the steps adopted to generate this realistic "model". It has been built using low level GNSS data from the FORMOSAT-3/COSMIC constellation, processing this through a modified Abel inversion based on Linear Mean Square (rather than the classic onion peeling approach) and the Separability Hypothesis (which overcomes the spherical symmetry assumption of the Abel inversion, by taking into account VTEC information from global ionospheric maps).

The ionospheric dataset has been developed for 4 characteristic scenarios, covering various states of the ionosphere. Within this study activity to develop this model, an improved inversion strategy to obtain Ne profiles from occultation observations has been developed in case of missing data at the occultation topside or for when occultation measurements do not reach the LEO orbit. In addition to the ionospheric model, a proxy index for scintillation monitoring based on the retrieved profiles of electron density (OSPI) has been proposed. Results have shown that the OSPI has relevant correlation with the S4 amplitude scintillation index.

Even though neither described in this paper nor quantified yet, this data set could be further exploited for an improved understanding of the ionospheric impact on RO measurements, as well as for a better removal of ionospheric contribution to the neutral bending angle retrieval, covering e.g., high geomagnetic activity, sporadic events in the E-layer, travelling ionospheric disturbances.

References

Basu, S. and Basu, S.: Scintillation technique for probing ionospheric irregularities, WITS Handbook, 2, 128–136, 1989.

Culverwell, I. and Healy, S.: Simulation of L1 and L2 bending angles with a model ionosphere, http://www.romsaf.org/general-documents/rsr/rsr_17.pdf, 2015.

Culverwell, I., Lewis, H., Offiler, D., Marquardt, C., and Burrows, C.: The Radio Occultation Processing Package, ROPP, Atmospheric Measurement Techniques, 8, 1887–1899, 2015.

Garcia-Fernandez, M., Hernandez-Pajares, M., Juan, M., and Sanz, J.: Improvement of ionospheric electron density estimation with GPSMET occultations using Abel inversion and VTEC information, Journal of Geophysical Research: Space Physics, 108, 2003.

Hajj, G. A. and Romans, L. J.: Ionospheric electron density profiles obtained with the Global Positioning System: Results from the GPS/MET experiment, Radio Science, 33, 175–190, 1998.

Hernández-Pajares, M., Juan, J., and Sanz, J.: Improving the Abel inversion by adding ground GPS data to LEO radio occultations in ionospheric sounding, Geophysical Research Letters, 27, 2473–2476, 2000.

Hernández-Pajares, M., Juan, J., Sanz, J., Orus, R., Garcia-Rigo, A., Feltens, J., Komjathy, A., Schaer, S., and Krankowski, A.: The IGS VTEC maps: a reliable source of ionospheric information since 1998, Journal of Geodesy, 83, 263–275, 2009.

Hernández-Pajares, M., Garcia-Fernàndez, M., Rius, A., Notarpietro, R., Engeln, A. v., Olivares-Pulido, G., Aragón-Àngel, À., and García-Rigo, A.: Electron density extrapolation above F2 peak by the linear Vary-Chap model supporting new GNSS-LEO occultation missions, Journal of Geophysical Research: Space Physics, doi:10.1002/2017JA023876, 2017.

Kintner, P., Ledvina, B., and De Paula, E.: GPS and ionospheric scintillations, Space weather, 5, 2007.

Kuo, Y.-H., Wee, T.-K., Sokolovskiy, S., Rocken, C., Schreiner, W., Hunt, D., and Anthes, R.: Inversion and error estimation of GPS radio occultation data, Journal of the Meteorological Society of Japan. Ser. II, 82, 507–531, 2004.

Kursinski, E., Hajj, G., Schofield, J., Linfield, R., and Hardy, K. R.: Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System, Journal of Geophysical Research: Atmospheres, 102, 23 429–23 465, 1997.

Mitra, A.: The D-layer of the ionosphere, Journal of Geophysical Research, 56, 373–402, 1951.

Prikryl, P., Ghoddousi-Fard, R., Kunduri, B., Thomas, E., Coster, A., Jayachandran, P., Spanswick, E., and Danskin, D.: GPS phase scintillation and proxy index at high latitudes during a moderate geomagnetic storm, 2013.

Schaer, S., Beutler, G., Rothacher, M., and Springer, T. A.: Daily global ionosphere maps based on GPS carrier phase data routinely produced by the CODE Analysis Center, in: Proceedings of the IGS AC Workshop, Silver Spring, MD, USA, pp. 181–192, 1996.

Schreiner, W. S., Sokolovskiy, S. V., Rocken, C., and Hunt, D. C.: Analysis and validation of GPS/MET radio occultation data in the ionosphere, Radio Science, 34, 949–966, 1999.

Uma, G., Brahmanandam, P., and Chu, Y.: A long-term study on the deletion criterion of questionable electron density profiles caused by ionospheric irregularities–COSMIC radio occultation technique, Advances in Space Research, 57, 2452–2463, 2016.