ROM SAF Report 25
Ref: SAF/ROM/METO/REP/RSR/025
Web: www.romsaf.org
Date: 13 March 2017

ROM SAF Report 25

Survey on user requirements for potential ionospheric products from EPS-SG radio occultation measurements

Estel Cardellach,[(1)] Kent B. Lauritsen,[(2)]
Riccardo Notarpietro,[(3)] Axel von Engeln[(3)]

[(1)]IEEC, Barcelona, Spain
[(2)]DMI, Copenhagen, Denmark
[(3)]EUMETSAT, Darmstadt, Germany

DOCUMENT AUTHOR TABLE

	Name	*Function*	*Date*	*Comments*
Prepared by:	E. Cardellach	ROM SAF Local Manager	07/12/2016	
Prepared by:	R. Notarpietro	EPS-SG Consultant (EU-METSAT)	20/02/2017	
Prepared by:	A. von Engeln	Remote Sensing Scientist (EUMETSAT)	20/02/2017	
Approved by:	K. B. Lauritsen	ROM SAF Project Manager	20/02/2017	

DOCUMENT CHANGE RECORD

Issue/Revision	*Date*	*By*	*Description*
1.0	10/08/2016	EC	First version of RSR on Ionospheric users' requirements, based on an internal ROM SAF report (8 March 2016)
1.1	20/02/2017	EC KBL RN AvE	Distinction between EPS-SG focus on neutral atmosphere and the ionosphere survey made more clearly, executive summary and references added, several editorial up-dates.
1.2	13/03/2017	KBL	Typo on page 8 corrected

ROM SAF

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralized centre under EUMETSAT, responsible for operational processing of GRAS radio occultation data from the Metop satellites as well as RO data from other missions. The ROM SAF delivers bending angle, refractivity, temperature, pressure, and humidity profiles in near-real time and offline for Numerical Weather Prediction (NWP) and climate users. The offline profiles are further processed into climate products consisting of gridded monthly zonal means of bending angle, refractivity, temperature, humidity, and geopotential heights together with error descriptions.

The ROM SAF also maintains the Radio Occultation Processing Package (ROPP) which contains software modules that aid users wishing to process, quality-control and assimilate radio occultation data from any radio occultation mission into NWP and other models.

The ROM SAF Leading Entity is the Danish Meteorological Institute (DMI), with Cooperating Entities: i) European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, United Kingdom, ii) Institut D'Estudis Espacials de Catalunya (IEEC) in Barcelona, Spain, and iii) Met Office in Exeter, United Kingdom. To get access to our products or to read more about the project please go to http://www.romsaf.org.

Intellectual Property Rights

ROM SAF Reports

This report is part of the ROM SAF report series; please find at Appendix B a list of the already published ones.

List of Contents

Executive Summary

This document presents the outcome of a survey that was conducted by the ROM SAF in cooperation with EUMETSAT to determine user requirements for ionospheric Radio Occultation (RO) products; thus establishing a general guideline for the potential delivery of GNSS RO observables and products at ionospheric altitudes. The main focus is on possible EUMETSAT Polar System-Second Generation (EPS-SG) RO products, but the outcome is also relevant for other RO instruments. The document compiles the answers of the users and their concerns. It is however clearly noted that the RO instruments on EPS-SG focus on the neutral atmosphere, and ionospheric sounding capabilities are an add-on that do not drive the instrument or programme. Nor should suggested requirements be seen as a commitment by EUMETSAT or the ROM SAF to meet these requirements.

The main findings are:

- ionospheric products have potential applications for other EUMETSAT SAFs (OSI SAF and H SAF users);
- about half of the received answers indicated that products would be used in assimilation;
- more than half of the users are interested in RO, about half in POD antenna data (or interested in both);
- although most identified products are at higher level, e.g. electron density, TEC or scintillation indexes, about half of the received answers were also interested in low-level observables; no bending angles needs were identified, however some considered assimilation possible (ionospheric users are not familiar with bending angle);
- timeliness requirements are very demanding, often 15 minutes to 30 minutes are desired (some even down to < 5 minutes). Generally, about 55% of the user responses can be met by the EPS-SG global service; the regional one could meet more user needs (albeit within a limited Area of Interest);
- responses expressed concerns on the RO limitations to sound only up to 500 km instead of to orbit altitude;
- the sampling frequencies of the EPS-SG RO instrument easily fulfil suggested requirements, in particular on the occultation antenna;
- suggested accuracy requirements on SNR, phase, amplitude are also met by the RO instrument.

1. Introduction

EUMETSAT is preparing for the EUMETSAT Polar System (EPS) Second Generation (EPS-SG), follow-on to the current Metop satellites (EPS). EPS-SG will provide continuity of observations obtained from polar orbiting satellites during the 2021-2040 timeframe. The two Metop satellites operating at the moment and the one to be launched in 2018 all include GNSS radio occultation (RO) payloads (the GRAS instrument) providing vertical atmospheric sounding of the lower atmosphere, up to 80 km altitude, and are mostly used in weather forecast applications up to 40 to 50 km.

EPS-SG (2021 onwards) extends these capabilities by operating GNSS radio occultation instruments up to 500 km, which includes the sounding of ionospheric layers. It has been widely proven with other RO missions (e.g. CHAMP [see e.g. Jakowski et al. 2002], PICOSat [Strauss et al., 2003], COSMIC/Formosat-3 [e.g. Schreiner et al., 2007, Carter et al., 2013]) that GNSS RO sounding of the ionospheric layers provides valuable information about its electron content distribution and scintillation phenomena. Moreover, ionospheric and space weather models started to assimilate radio occultation observations [e.g. Bust et al., 2004, Angling et al., 2008, Komjathy et al., 2010, Lee et al., 2012] and this will be one of the main applications also for the future. Although neutral atmospheric sounding products are the main driver of the EPS-SG RO system, EUMETSAT plans to generate and disseminate the observables (Level 1) of the uppermost EPS-SG RO profiles, whereas EUMETSAT's Radio Occultation Meteorology Satellite Application Facility (ROM SAF) plans to extract the geophysical products (Level 2). In order to maximize the outcome of the EPS-SG ionospheric sounding and products, EUMETSAT and the ROM-SAF wanted gather information on potential requirements of ionospheric application and products of GNSS RO data.

Therefore, a survey among potential users was organized to identify and quantify their needs and determine their requirements on ionospheric data. The survey questionnaire was accompanied with a brief description of the EPS-SG mission and its RO payload. Even if it was highlighted that EUMETSAT would not commit to fulfil the requirements provided by ionospheric users (as the main driver for the RO system aboard EPS-SG is the tropospheric to stratospheric sounding) the users were also asked to evaluate any weaknesses in the system (e.g. maximum Ionospheric height, ground-segment timeliness) with respect to their needs.

This document presents the outcome of the conducted survey, compiling the answers and concerns of the potential users of ionospheric data.

The questionnaire was prepared in agreement with EUMETSAT, and distributed to 52 individuals and institutions during December 2015:

- 5 messages could not be delivered (problems sending message out);

- Some of the individuals replied that they belong to the same consortium or co-operative groups, and they would merge their requirements into a single questionnaire form. Some others forwarded the request to third centers or colleagues;
- 11 questionnaires were returned from 15 institutions and consortiums, as some organizations coordinated their answers.

In addition, 5 other institutions replied and provided some valuable information about the field of application or potential interest of these data sets for them. However, they did neither return the forms filled nor the requirements quantified.

2. The Questionnaire

The questionnaire that was sent out is included in Appendix A . The form was accompanied with a brief justification of the survey, and relevant information about EPS-SG and its RO capabilities and limitations.

The users were explicitly asked about the sampling, precision and latency requirements, their preferred formats and dissemination channels, or the application they target, among other things. In addition, they were invited to read the information about the EPS-SG RO mission provided with the questionnaire and comment on potential limitations identified and their impact on the user's application or operations.

Below we list the institutions that answered the survey (filled out or just providing some general comments). In some cases several organizations sent a shared answer to our request (coordinated answer):

- Coordinated answer from: **Instituto Nazionale di Geofisica e Vulcanologia** (INGV), **Italian Air Force - Operational Centre for Meteorology**, **Osservatorio Astronomico di Trieste – Istituto Nazionale di Astrofisica** (OAT-INAF), Italy;
- **GeoForschungsZentrum** (GFZ), Germany;
- **University of Birmingham**, SERENE group, United Kingdom;
- **European Space Agency, ESOC Navigation Support Office**, EU;
- **European Space Agency, ESTEC TEC-EES**, EU;
- **GMV** company, Spain;
- **Politechnical University of Catalonia** (UPC), IonSAT group, Spain;
- **Jet Propulsion Laboratory** (JPL), USA;
- **NOAA Space Weather Prediction Center**, USA;
- **Royal Observatory of Belgium**, Belgium;
- **UK Met Office**, United Kingdom;
- **Institut Français de Recherche pour l'Exploitation de la Mer** (IFREMER), France;
- **National Space Science Center** (NSSC)**,** Chinese Academy of Sciences (CAS), China;
- **Royal Netherlands Meteorological Institute** (KNMI), The Netherlands;
- Coordinated answer from **Institute of Atmospheric Sciences and Climate** (ISAC-CNR) and **Servizio Metereologico Aeronautica Millitare**, Italy
- **CLS** company, France;
- **Technical University of Wien**, Dept. Geodesy, Austria.

3. Summary of the answers

The questionnaire did not constraint the list of products, but left it as an empty list to be filled by the users. Therefore, each user who answered the questionnaire listed their required products. The list of products derived from the list includes level 1 (observables) and level 2 (geophysical) products. Some of the users provided distinctive and precise information about the products, for instance, separating vertical Total Electron Content from slant or along-the-line-of-sight one. Some others did not. In these cases, the un-specified one is added as a third product (e.g. vTEC, sTEC, TEC). They were asked to provide all fields of the questionnaire for each of the listed product, although some were left unanswered. For this reason, the number of answers compiled for different fields may differ.

3.1 Target Applications

The users provided lists of observables or products of their interest and had the chance to associate each of them to a given application. This was an open field (without a close list of options) and could be left undetermined. We compiled 57 inputs to the question on the application that the products would target.

The range of applications identified by the users is shown in Figure 1. Most of the ionospheric products target ionospheric monitoring or modelling and space weather applications, but a significant number of users need this sort of data for other purposes, such as precise navigation, radio propagation, or as corrections for other remote sensing techniques (ocean altimetery, scatterometry and radiometry). It is relevant to highlight that in this sense **the products have potential applications for other EUMETSAT SAFs** (OSI SAF and H SAF users).

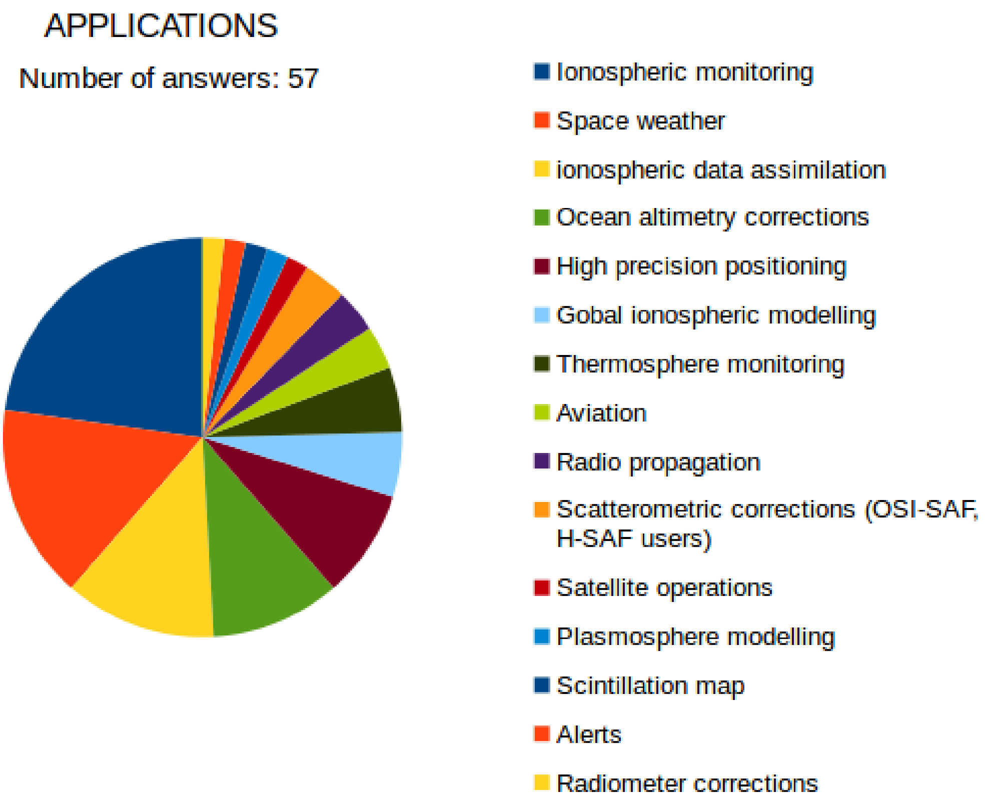

Figure 1 Variety of applications the users identified for RO ionospheric products. The pie-chart represents the amount of times that users or products are identified to a given application, sorted from most populated to less populated.

In 32 of the answers the users indicated that the products would be used in assimilation models. The models listed were:

- AENeAS [e.g. SERENE],
- CTIPe [Millward et al., 2001],
- GAIM [e.g. Thompson et al., 2006],
- GIM [e.g. Hernandez-Pajares et al., 1999],
- G-TEC [SWPC],
- IDA4D [e.g. Bust et al., 2007],
- MIDAS [University of Bath],
- NA-TEC [SWPC],
- TIE-GCM [HAO],
- WAM-IPE [e.g. ESRL].

Other users did not provide the name of the model to which data would be assimilated but only that the model is:

- either TEC and scintillation short-term forecasting model;
- or Ionosphere-Plasmasphere assimilation model.

3.2 Required products

Figure 2 summarizes the list of products required by the users and their occurrence (number of times each product is specified in the questionnaires). We received a total number of 61 inputs to this question which we could group into 19 different products. As mentioned in the introduction, we have preserved as much as possible the original description of the product. For this reason, several products may be considered nearly the same (e.g. 2-frequency phase vs. 2-frequency excess phase).

The **most required products are higher level products** as electron density, TEC or scintillation indexes (32 answers) followed by **low-level observables** as phase and amplitude or SNR (18 answers). Some products require ancillary data such as receiver clocks and orbits.

Nobody gave requirements for bending angles, it seems that this observable is not widely used in the space-weather and ionospheric communities. However, one centre did admit as additional comment that in the future they would be interested in assimilating bending angles, but they do not have requirements on these products because they are not familiar with bending angles yet.

The listed products are those derived by observations taken either by the RO antennas (thus in the limb sounding geometry) or by the Zenith antenna used for POD purposes:

- answers that required RO antenna observables/products: 42
- answers that contained Zenith antenna observables/products: 3

(note that many answers did ask for both RO+POD antenna outputs).

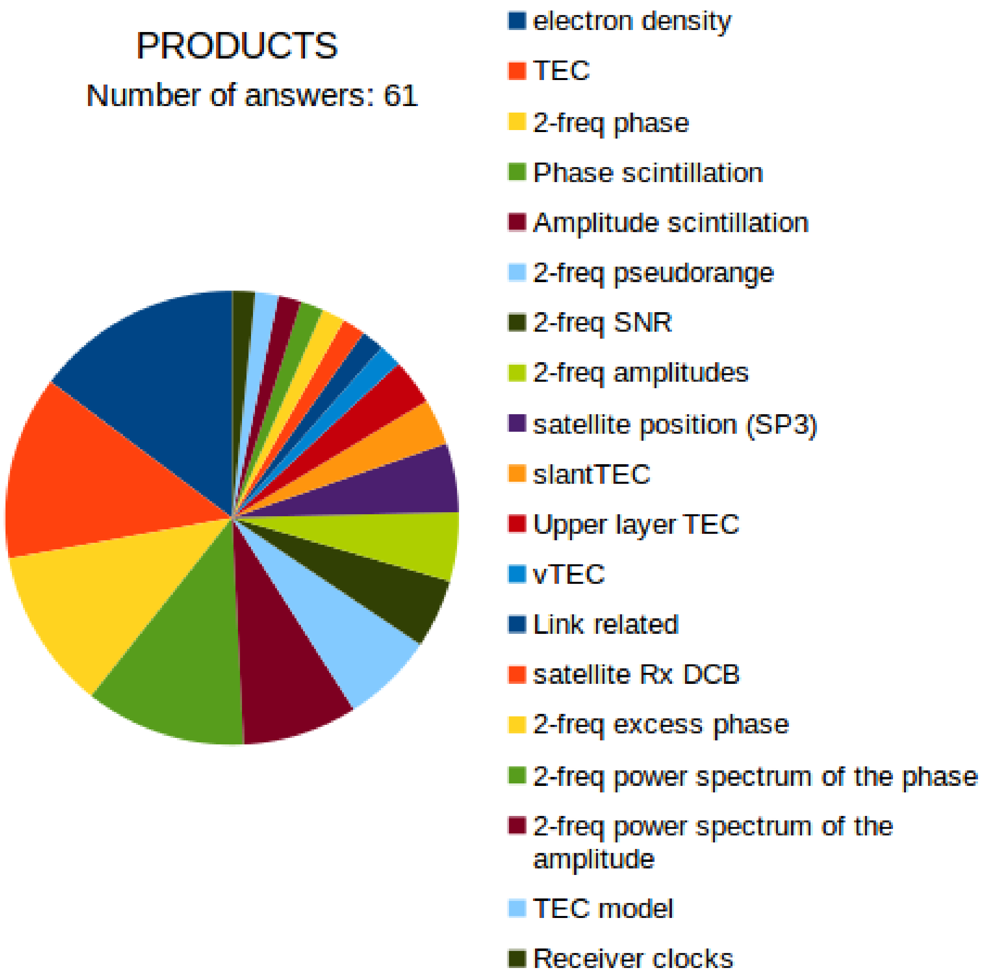

Figure 2 Variety of products required by the users in the questionnaire. The chart illustrates the relative number of times each product type is cited, sorted from most populated to less populated. The total number of inputs is 61.

3.3 Latency/Timeliness requirements

One of the most demanding aspects for the ionospheric community is the latency of the product. Thus offline products are still used by most of the users being asked since they cannot get data within their timeliness requirements. Some users indicated they could work with latencies given by once-per-orbit (~100 minute) dissemination, still easily in line with the EPS-SG global timeliness requirement at Threshold for L1B products (basic GNSS observables on RO/Zenith antenna, LEO orbits and clocks, bending angles - see Appendix A for further details). However, several users highlighted that the NRT delivery capability planned for EPS-SG might not be sufficient for some of the space weather applications they target, where 15 to 30 minutes latency is expected, and up to 45 minutes still valuable (these could be fulfilled by the EPS-SG regional service, however not providing global coverage – see Appendix A). A few other users did not specify their NRT needs (only noted “NRT”, without further details or numbers). This is shown in Figure 3. The same information is plot in Figure 4 as a histogram, where the latency is sorted by its length (we have assumed the unspecified 'NRT' answer as ~3 hours).

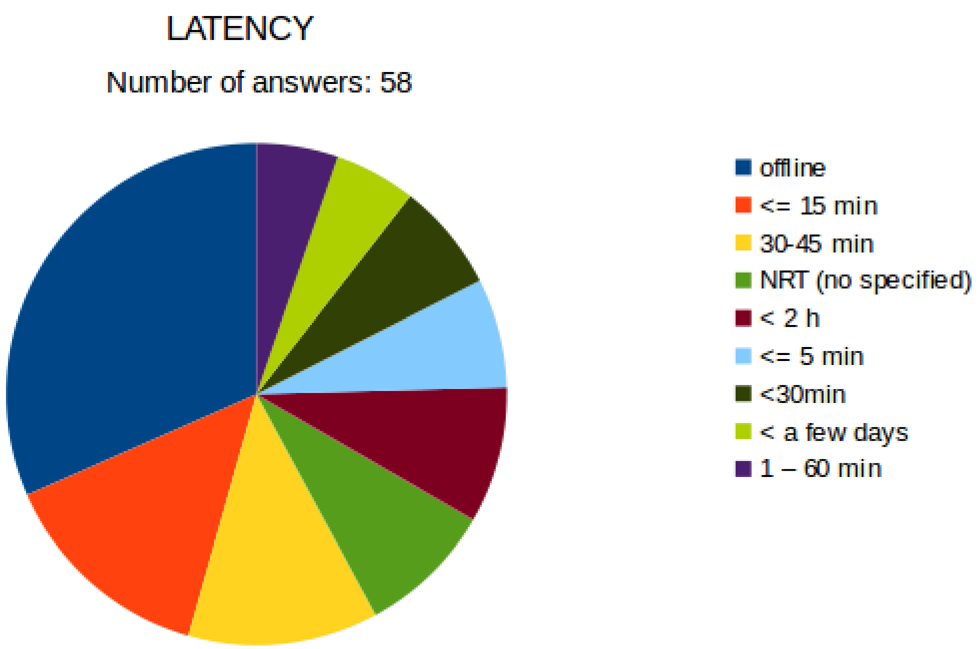

Figure 3 Latency requirements, sorted from most to least populated.

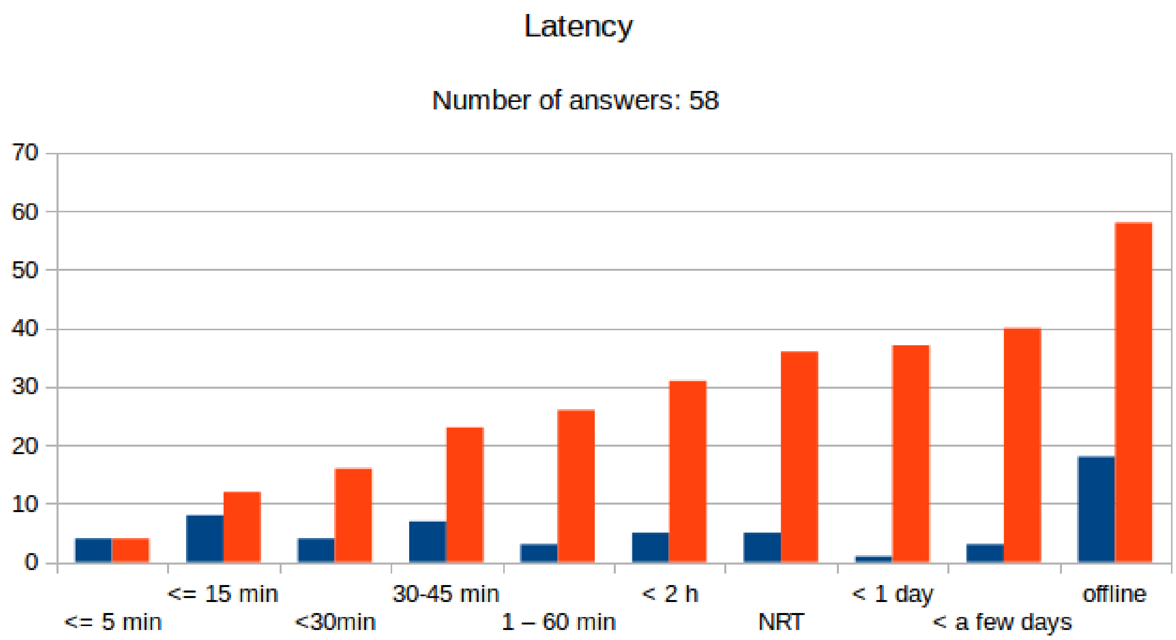

Figure 4 Histogram of the answers received regarding the latency of the data (blue bars) and its cumulative histogram (orange bars). We have assumed that near-real time to be of the order of 3 hours.

Taking EPS-SG timeliness requirements (see Appendix A) as a baseline, one can separate the answer to:

- about 40% of answers required less than 45 minutes latency, foreseen in EPS-SG for a small percentage of the level 1B products generated by the global mission at Threshold level but with good chance for the use of products generated by the regional mission (albeit only over/near Area of Interest, see Appendix A);
- about 60% of answers required 1 hour latency or longer, which is foreseen in EPS-SG as Breakthrough for level 1B products timeliness requirement of the global mission (> 50% of the products will be delivered within 1 hour from the observation, 95% of the products will be delivered within 70 min from the observation);
- 55% of answers required 2 hours latency or longer, which is fully compliant with EPS-SG requirement (for the level 1B products).

3.4 Sampling (time/space) and coverage requirements

The time sampling with which the data should be taken was another question of the survey. The answers (48 in total) are summarized in Figure 5. In general, most users require sampling rates of 1 to 30 seconds for some of their products, or even longer (e.g. minutes for scintillation indexes' computation). However, these indexes or the users that want to compute the indexes themselves, require higher sampling rates. The RO instrument aboard EPS-SG could fulfill these requirements (up to 250 Hz sampling rate in open loop tracking).

Only 6 answers were received regarding the spatial sampling and coverage requirements. About the vertical extension of the products, 2 answers required 90 to 150 km altitude and another one to altitudes up to the LEO orbital height. Regarding answers on spatial sampling of higher-level products, three of them required 1 deg x 1 deg optimal resolution for TEC maps, electron density and scintillation indexes, with minimum requirement of 5 deg x 5 deg.

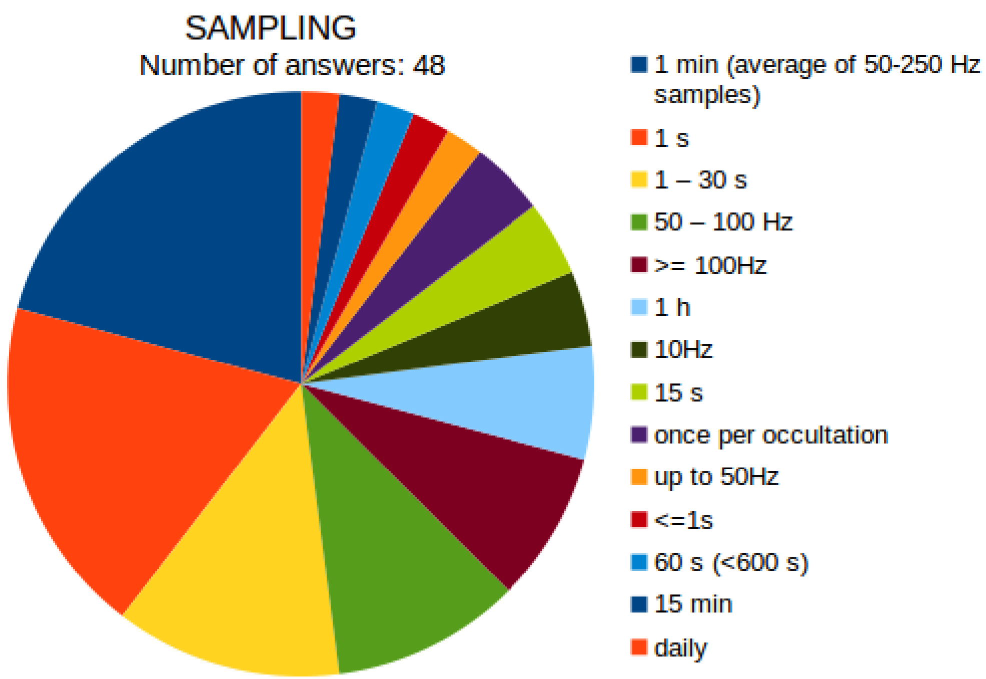

Figure 5 Sampling requirements, sorted from most to least populated.

3.5 Precision requirements

The required precision for the TEC products is depicted in Figure 6, relatively few answers were provided (15 out of 61 received inputs). Most users require precision on the order of 1 to 3 TECU.

Few users provided also accuracy figures concerning other observables or products. They are listed in Table 1. In general, amplitudes and SNR should be obtained at 5% precision, as well as electron density products.

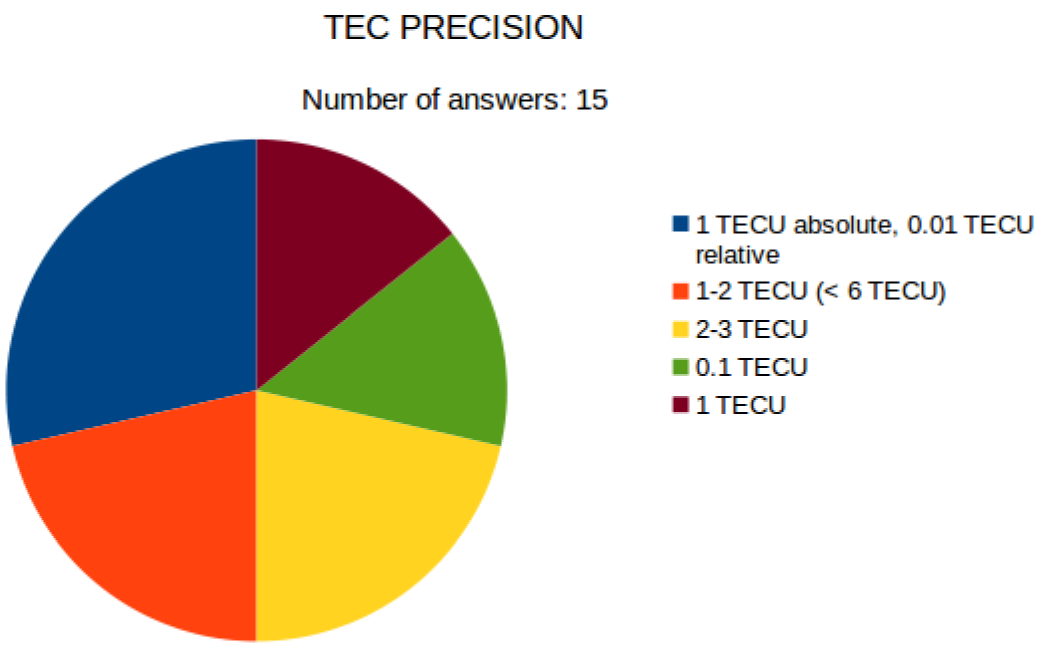

Figure 6 Requirements on the precision of the TEC products (NOTE: some of the users provided precision of electron densities in TECU units, too. These are added here too).

Phase Precision:	Occurrence:
0.01 rad	1
1 mm	1
0.1 rad	2

Amplitudes, SNR, scintillation index precision:	Occurrence:
5 %	4
10 %	1

Electron density precision (if not given in TECUs):	Occurrence:
5 %	2

Table 1: Summary of the answers received on precision of the phase, amplitude, SNR, scintillation index and electron density.

3.6 Dissemination channel and data format

The questionnaire included fields to indicate the preferred dissemination channel as well as the format of the data.

42 answers were received on dissemination channel:

- through ftp: 13
- through ftp or web: 26
- through EUMETCAST: 3

The preferred data formats are netCDF (15 answers out of 38 total) and GNSS standard files, such as RINEX, IONEX, SCINTEX, SP3 (13 answers of 38 total). Figure 7 shows the distribution of occurrence of each answer.

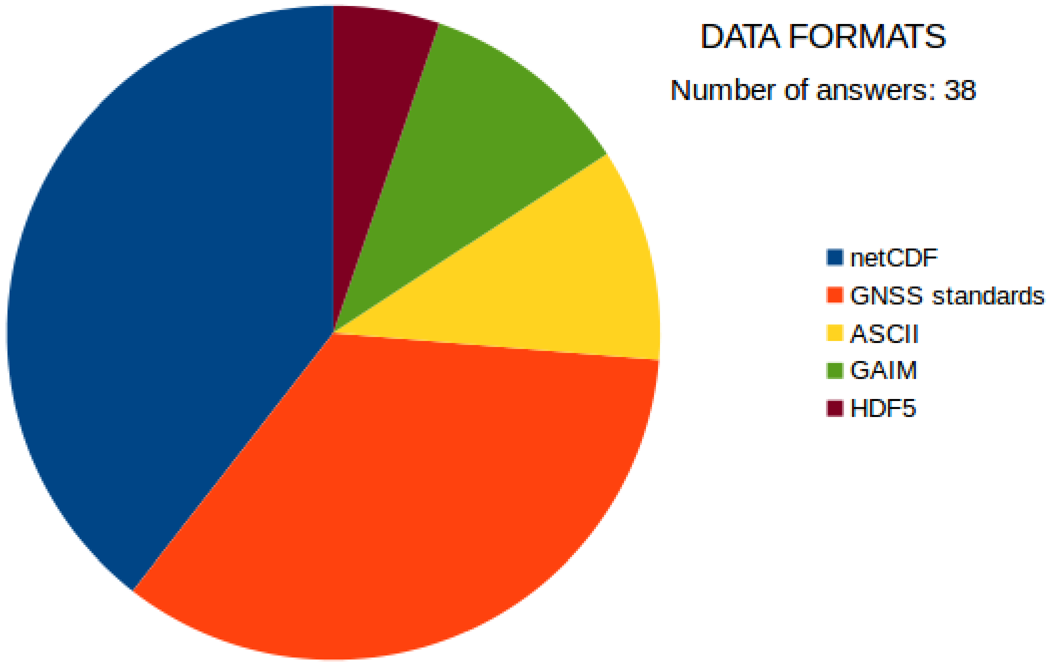

Figure 7 Preferred data formats for ionospheric products. The list is sorted by number of occurrence. GNSS standards refer to ASCII files with a defined structure for GNSS products (RINEX, IONEX, SCINTEX, SP3...). GAIM is a 4D grid format for electron density products.

4. Users' comments about EPS-SG ionospheric sounding characteristics

Several users provided comments on the EPS-SG particular characteristics, expressing their concerns (albeit noting that EPS-SG targets neutral atmospheric observations). These concerns listed two main aspects: height of the maximum observation (STLA) and the latency of the dissemination. Some other comments were encouraging and described the relevance of this sort of data, or suggesting possible mitigation options for ionospheric products derived from EPS-SG RO instrument observations.

The comments are copied below:

- ***Timeliness a little too long*** *for ionosphere, want to target 30 min with 45 min latency being acceptable. 110-120 minutes it's a bit too long;*
- *Ionospheric occultations may be significantly* ***hindered by the antenna configuration****. It will be challenging to acquire ionospheric electron density profiles due to the lack of data* ***starting at zero and low elevation angles****. The* ***POD antenna will acquire useful TEC*** *data about the ionosphere topside. The RO antenna pattern appears to favor Earth's limb, but for ionospheric occultations, one wants high gain from 0 degrees elevation through to the negative elevations at Earth's limb. Thus, TEC data and derived electron density profile data from the RO antenna will be severely compromised relative to, e.g. COSMIC or FengYun-3 (FY-3 has separate ionosphere and atmosphere occultation antennas);*
- ***Latency may be a problem for Space Weather Data Assimilation****, for real-time applications, latency of 15 minutes;*
- *The UK Met Office has run its own space weather operations centre ('MOSWOC') since Oct 2014. The space weather research programme that supports this has two strands: Short term research based on improving nowcasts or very short range forecasts based largely on domain-specific models; and Longer term research, aimed eventually at the development of a* ***Sun-to-Earth prediction system****, based on* ***coupled solar / magnetosphere / thermosphere / ionosphere / mesosphere / stratosphere / troposphere*** *models, which could potentially lead to a significantly improved prediction of space weather events. Ionospheric (and other) measurements are clearly crucial to the development of both strands, as verifying information during model development, and, eventually, as input to data assimilation systems. For these reasons the UK Met Office strongly endorses the intention of the ROM SAF to develop a range of ionospheric products during the third Continuous Development and Operations Phase (CDOP-3) of the project;*

- ***Timeliness requirements are challenging** – a possible investigation of **developing partnerships** (e.g. with COSMIC-II) to use more ground stations and this to download more of the data in a shorter period of time may be useful. Estimates of scintillation are commonly made with observations with a sampling rate of 50 Hz – this may be an issue for some observations in the 150-500 km range (see Table 3). Note that the **observation requirements were based on those in the following WMO document: http://www.wmo-sat.info/oscar/applicationareas/view/25.** The electron density is not on the WMO list but our figures are based on this and other literature.*

5. WMO Requirements

As suggested by one of the users, we include here the requirements given by the WMO through the OSCAR pages regarding space weather. The source is:

http://www.wmo-sat.info/oscar/applicationareas/view/25

The requirements provided for the Ionospheric Vertical Total Electron Content (VTEC) and reproduced in Table 2 correspond to products derived from space-borne or ground-based GNSS receivers. The site highlights that this is an important parameter to calibrate GNSS positioning systems and that observations at multiple viewing angles may be used to generate profiles by tomography.

The requirements on ionospheric scintillation concern two indices typically observed in GPS signals operating at 1.58 and 1.23 GHz and relevant for all trans-ionospheric transmissions:

- **S4:** is the coefficient of variation of intensity [standard deviation divided by mean];
- **σφ:** is the standard deviation of the phase of the radio signal.

The WMO requirements on these two indices are also reproduced in Table 2.

Id	Variable	Layer	App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
594	Ionospheric Vertical Total Electron Content (VTEC)	Ionos	Space Weather	0.1 TECU 0.5 TECU 2 TECU		100 km 200 km 500 km		5 min 15 min 60 min	60 sec 10 min 60 min	Global	tentative	2011-05-01	ICTSW-1

Id	Variable	Layer	App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
593	Ionospheric Scintillation	Ionos	Space Weather	0.1 % 1 % 10 %		50 km 100 km 200 km		60 sec 2 min 10 min	60 sec 10 min 60 min	Global	tentative	2011-05-01	ICTSW-1

Table 2 WMO requirements on vertical TEC and ionospheric scintillation as provided in the WMO OSCAR web pages (table extracted on August 10, 2016).

6. Discussion and conclusions

A questionnaire/survey to inquire on possible requirements for ionospheric RO products was sent out to 52 individuals and institutions. This was mostly done with respect to the EPS-SG RO extended sounding capabilities. The RO instruments on EPS-SG are focused on the neutral atmosphere (where user requirements are defined up to about 80 km; similar as for the current EPS GRAS instrument), thus the factors driving the design and the development of the RO instrument and antennas are targeting this atmospheric region. However, thanks to improved instrument capabilities (in terms of antenna gain, data rate and channel availability) the instrument will be capable to observe GNSS signals crossing the densest ionospheric layers and provide valuable data also for soundings up to 500 km.

20 institutions responded to the survey, either filling out the questionnaire form (11 individual or coordinated forms received from 15 organizations) or pointing out the interest and target application of the data (5 organizations).

The identified products are mainly intended for **ionospheric monitoring** and **space weather** forecast, but also other uses emerged in the survey, including potential **interest for other SAFs** (OSI-SAF and H-SAF) for ionospheric corrections of their remote sensing techniques.

Approximately **half** of the answers indicated that the products are required for **assimilation into numerical models**.

Users are mostly interested in **level 2 products** (electron density, TEC and scintillation indexes), but many answers also required **level 1 observables** (phases, SNR or amplitudes). Nearly half of the products listed by the users required output from the **POD antenna**, too.

The latency/timeliness of the data is a key aspect for operational space weather applications. **Here, EPS-SG - with its focus on neutral atmosphere users - can meet the suggested ionospheric timeliness requirements for about 55% of the responses**, when considering the EPS-SG threshold timeliness (110 min to 120 min, see Appendix A). At Breakthrough level (60 min to 70 min, see Appendix A), more user needs could be served (noting however that a 1 min to 60 min requirement is not very precise, see Figure 4). Regional data, in particular at Breakthrough level, could reduce this to about 30%. WMO latency/timeliness requirements for coarse resolution products could be served with Global EPS-SG data at Breakthrough level. Off-line products represent 31% of the answers.

The temporal sampling of the data (i.e. the frequency at which Ionospheric products are provided) is rather diverse, from 4 milliseconds to 1 day periods, but **always within the neutral atmosphere driven sampling capabilities of the EPS-SG RO instrument** (up to 250 Hz sampling).

The precision of the total electron content is mostly between 1 and 6 TECU, whereas the observables are expected at **5 to 10% precision for SNR** and amplitude, and **mostly 1 to 3 mm phase precision**, which are **within EPS-SG RO instrumental capabilities**.

As expected, the **main concern of the users** is related to the limitation of the EPS-SG RO system of sounding the ionosphere up to 500 km. Another concern is related to the **latency of the data for operational space weather applications**. Some of the users suggested the possibility of improving the latency of these products through partnerships with other missions' ground segment facilities (this could e.g. be done by making use of the data provided by the satellite in real-time to receiving stations in visibility of the satellite (direct broadcast); this transmission will be in X-Band.).

As a conclusion, RO ionospheric sounding is of wide interest for different scientific communities, whose requirements could be mostly fulfilled except for certain operational applications. **The potential use of the RO sounding for other EUMETSAT's SAFs should also be noted**, as mentioned above. Another application of interest may be the long-term projects to develop a Sun-to-Earth prediction system which would include tropospheric models.

7. References

- Angling, M. J., First assimilations of COSMIC radio occultation data into the Electron Density Assimilative Model (EDAM), Ann. Geophys., 26(2), 353–359, 2008.
- Bust, G.S., T.W. Garner, and T.L. Gaussirian II, Ionospheric Data Assimilation Three-Dimensional (IDA3D): A global, multisensor, electron density specification algorithm, J Geophys Res, 109(A11312), doi:doi:10.1029/2003JA010234, 2004.
- Bust, G.; Crowley, G.; Curtis, N.; Reynolds, A.; Paxton, L.; Coker, C.; Bernhardt, P., "IDA4D - a new ionospheric imaging algorithm using non-linear ground-based and spaced- based data sources", American Geophysical Union, Fall Meeting 2007, abstract SA11B-06, 2007.
- Carter, B. A., Zhang, K., Norman, R., Kumar, V. V., & Kumar, S. On the occurrence of equatorial F-region irregularities during solar minimum using radio occultation measurements. Journal of Geophysical Research: Space Physics, 118(2), 892-904, 2013.
- Earth System Research Laboratory (ESRL), NOAA, http://cog-esgf.esrl.noaa.gov/projects/wam_ipe/
- Hernandez-Pajares, M., J.M. Juan, J. Sanz, "New approaches in global ionospheric determination using ground GPS data", Journal of Atmospheric and Solar-Terrestrial Physics 61, 1237-1247, 1999.
- High Altitude Observatory (HAO), National Center for Atmospheric Research, "TIEGCM V1.94 Model Description", June 16, 2016, available at: http://www.hao.ucar.edu/modeling/tgcm/doc/description/model_description.pdf
- Jakowski, N., A. Wehrenpfennig, S. Heise, Ch. Reigber, H. Lühur, L. Grunwaldt, and T. K. Meehan, "GPS radio occultation measurements of the ionosphere from CHAMP: Early results", Geophys. Res. Lett., Vol. 29, No. 10, DOI:10.1029/2001GL014364, 2002.
- Komjathy, A., B. Wilson, X. Pi, V. Akopian, M. Dumett, B. Iijima, O. Verkhoglyadova and A. J. Mannucci, JPL/USC GAIM: On the impact of using COSMIC and ground-based GPS measurements to estimate ionospheric parameters, J. Geophys. Res. Sp. Phys., 115(2), 1–10, doi:10.1029/2009JA014420, 2010.
- Lee, I.T., T. Matsuo, A.D. Richmond, J. Y. Liu, W. Wang, C. H. Lin, J. L. Anderson and M. Q. Chen, Assimilation of FORMOSAT-3/COSMIC electron density profiles into a coupled thermosphere/ionosphere model using ensemble

Kalman filtering, J. Geophys. Res., 117(A10318), doi:doi:10.1029/2012JA017700, 2012.

- Millward, G. H., I. C. F. Muller-Wodarg, A. D. Aylward, T. J. Fuller-Rowell, A. D. Richmond, and R. J. Moffett, "An investigation into the influence of tidal forcing on F region equatorial vertical ion drift using a global ionosphere-thermosphere model with coupled electrodynamics", J. Geophys. Res., 106, 24,733 – 24,744, 2001.
- Schreiner, W., C. Rocken, S. Sokolovskiy, S. Syndergaard, and D. Hunt, "Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission", Geophys. Res. Lett., 34, L04808, doi:10.1029/2006GL027557, 2007.
- SERENE group, Univ of Birmingham, http://uobserene.com/modelling.html
- Space Weather Prediction Center (SWPC), NOAA, http://www.swpc.noaa.gov/models
- Straus, P. R., Anderson, P. C., & Danaher, J. E., GPS occultation sensor observations of ionospheric scintillation, Geophysical research letters, 30(8), 2003.
- Thompson, D. C., L. Scherliess, J. J. Sojka and R. W. Schunk, "The Utah State University Gauss-Markov Kalman filter in the ionosphere: The effect of slant TEC and electron, density profile data on model fidelity", J. Atmos. Solar-Terr. Phys., 68, 947-958, 2006.
- University of Bath, Department of Electronic and Electrical Engineering, http://people.bath.ac.uk/eescnm/midas.htm

Appendix A. Questionnaire

User requirements for EUMETSAT EPS-SG GNSS-RO Ionospheric sounding

EUMETSAT is preparing for the EUMETSAT Polar System (EPS) Second Generation (EPS-SG), follow-on to the current Metop satellites (EPS). EPS-SG will provide continuity of observations obtained from polar orbiting satellites during the 2021–2040 time frame.

The two Metop satellites operating at the moment and the one to be launched in 2018, all include GNSS radio-occultation (RO) payloads, providing vertical atmospheric sounding of the lower atmosphere, up to 80 km altitude, and are mostly used in weather forecast applications up to 40 km.

EPS-SG (2021 onwards) extends these capabilities by operating GNSS radio-occultation instruments up to higher altitudes, including ionospheric layers. It has been widely proven with other missions (e.g. CHAMP, COSMIC/Formosat-3) that GNSS RO sounding of the ionospheric layers provides valuable information about its electron content distribution and scintillation phenomena. EUMETSAT plans to generate and disseminate the observables (Level-1) of the uppermost EPS-SG RO profiles, whereas EUMETSAT's Radio-Occultation Meteorology Satellite Application Facility (ROM-SAF) shall extract the geophysical products (Level-2). In order to maximize the outcome of the EPS-SG ionospheric sounding within the EPS-SG constraints, EUMETSAT and the ROM-SAF want to refine information on the requirements of ionospheric applications of GNSS RO data. We have agreed with EUMETSAT to search and compile such information.

Therefore, we ask potential users to identify and quantify their needs by filling up the information requested in the table (next page). In the context of this survey, *'ionospheric products'* refer to any GNSS RO data obtained or useful for ionospheric applications: from low level GNSS RO observables, such as excess phase and SNR, to ground-processed products, such as electron density profiles or scintillation indexes. It may also include non-RO data obtained with the satellite's GNSS receiver (e.g. using the zenith-looking antenna intended for precise orbit determination—POD). The appendix of this document contains more detailed information about the EPS-SG missions and GNSS RO instrument for the potential user to understand the capabilities and limitations of EPS-SG GNSS RO.

Two important remarks:

1) please do not limit your requirements to the limitations of EPS-SG, but indicate whether you consider certain EPS-SG limitation could affect your application or use of the data (you will find a question to address this point).
2) EUMETSAT **does not commit to fulfill the requirements** here provided by the users, but EUMETSAT does try to optimize the EPS-SG GNSS RO within its possibilities.

Please fill the fields you consider in the tables provided below (next 2 pages) and return to Dr. Estel Cardellach (estel@ieec.cat) and/or to the person who forwarded it to you before January 15, 2016.

Thank you for your cooperation!

Centre:									
Would the RO data be assimilated into iono/space-weather model?				Name of the model/s (if applicable):					
Product name[1]:	From RO or POD antenna?	For assimilation into a model?	Target Application:	Data format:	NRT/Offline:	Preferred dissemina-tion channel	Timing req.:	Sampling req. (in time and/or space):	Precision req. (at requested sampling rate):

[1] for example: excess phase, amplitude, SNR, bending angle, electron density, scintillation indexes, total electron density (vertically integrated, along-ray integrated...), Faraday Rotation measurements, zenith-looking (POD) GNSS antenna phase and amplitude, upper-layer (above LEO) TEC model... complementary data you may need (positions/velocities), or others you may consider.

Any other requirement?

After reading the appendix, have you detected any EPS-SG limitation that may hinder the use of its GNSS ionospheric sounding? Which one? Briefly explain:

Could you suggest other potential users of GNSS-RO ionospheric sounding to whom we could send this survey?	
Center/Organization:	**Contact details (if available):**

EUMETSAT

EUM/RSP/TEM/15/834151
26 November 2015

GNSS-RO on EPS-SG_summary

GNSS Radio Occultation on EPS-SG Instrument characteristics and generated products

RO Team

1 INTRODUCTION TO GNSS-RO

Global Navigation Satellite System - Radio Occultation (GNSS-RO) is an atmospheric profiling remote sensing technique based on the reception of a GNSS signal from a receiver flying on board a Low Earth Orbit (LEO) satellite, after its limb propagation through the entire Earth's atmosphere. The relative movement of the two satellites allows a complete, close to vertical, sounding of the atmosphere. Atmospheric refraction effects cause the signal to be delayed and, most important, the ray path to be bent. The main objective of the RO Instrument is the measurement of GNSS related variables (basically carrier phases and amplitudes of GNSS signals on different frequencies) for the retrieval of the "quasi" vertical profile of bending angle α and the corresponding impact parameter a. A schematic representation of the GNSS-RO geometry is given in **Fig.1**.

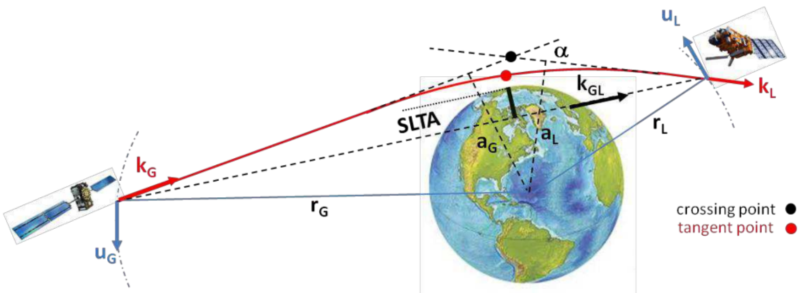

Fig. 1 - Radio Occultation geometry. Since the atmosphere is normally assumed to be locally spherical distributed, the two impact parameters in the figure (aL and aG) are equal.

Non occulting GNSS satellites are also received by the RO Instrument for measurement of its position, velocity and time vectors. Based on RO measurements and on ancillary measurements from ground stations, the Precise Orbit Determination (POD) for the RO instrument is performed by the ground segment.
The ray propagation is also affected by the electron density in the ionosphere; this effect shall be corrected for the retrieval of the bending angle component due to the neutral atmosphere only, by observing GNSS signals at two different frequencies. Contextually, ionospheric monitoring can also be exploited considering both signals acquired by the POD antenna and those observed by the occultation antenna, in case the RO Instrument is capable to provide limb measurements also above the neutral atmosphere.

2 EPS-SG MISSION

EPS-SG satellites are going to fly in the "same" sun-synchronous orbit (Equator crossing 09:30 local solar time, in descending node, yaw steering mode) as the current Metop satellites, with the following main characteristics:

- Semi-major axis: 7195.605 km (~820 km), corresponding to a 29 day repeat cycle
- Eccentricity: 0.001165
- Inclination: 98.701°
- Argument of Perigee: 90.00°

Two RO missions are foreseen on board EPS-SG:

- the Global mission, for product generation and distribution of information acquired by the on-board instrument over the full globe and downloaded at the Svalbard (full orbit dump) and McMurdo (half-orbit dump) polar ground stations;
- the Regional mission for product generation and distribution with improved timeliness of on-board measurements collected when the satellites will fly over the Area of Interest (Europe and the North Atlantic, see Fig. 2). Such measurements will be directly broadcasted in NRT to the ground based stations dislocated in the Area of Interest.

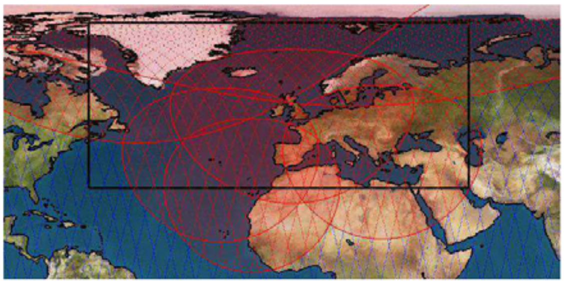

Fig. 2 – Area of Interest for Regional Mission

Global and Regional Timeliness requirements are summarized in **Tab. 1**:

Disseminated Dataset (NRT)	Threshold		Breakthrough	
Global Level 1 Products	110 min (50%)	120 min (90%)	60 min (50%)	70 min (95%)
Regional Level 1 Products	30 min (50%)	110 min (90%)	20 min (50%)	30 min (95%)

Tab. 1 – Timeliness requirements

3 CHARACTERISTIC OF THE RO INSTRUMENT ON-BOARD EPS-SG

The signals from the occulting satellites are received by the RO Instrument through two antennas, one dedicated to rising occultations and the other dedicated to setting occultations (see **Fig. 3**), both focused on the Earth's limb. The instrument also acquires and tracks GNSS signals via a third, zenith pointing antenna with a wide conical coverage which provides the associated observables for Precise Orbit Determination (POD) purposes.

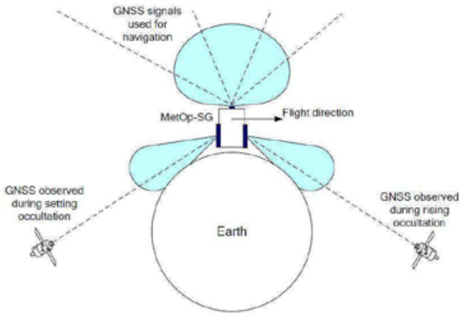

Fig. 3 – RO Instrument overview

The new RO Instrument will have the possibility to observe, acquire and track signals from the modernized GPS constellation, from Galileo and from the future CDMA (Code division multiple access) based GLONASS and COMPASS/Beidou navigation systems, handling the combinations of the dual-frequency signals listed in **Tab. 2** from the same GNSS satellite.

System	**Signal**	**Carrier Frequency [MHz]**
GPS	L1 C/A	1575.42
	L1 C	1575.42
	L5	1176.45
Galileo	E1-B/C	1575.42
	E5a	1176.45
GLONASS[1]	L1	1575.42
	L5	1176.45
COMPASS/ BeiDou	B1	1575.42
	B2A	1176.45

Tab. 2 - GNSS signals and frequencies that will be tracked by the EPS-SG RO Instrument.

For what concerns occultation measurements, it will try to acquire as fast as possible all the dual frequency signals exploiting a new full open-loop tracking strategy, aiding both the code phase and the carrier phase tracking through the use of a range/Doppler model. The standard closed-loop tracking is also implemented. Open-loop and closed-loop tracking will be applied to pilot and data signal components separately (for the GNSS systems which will transmit pilot and data signals). Low level observables will be available at different sampling rates, depending on the

[1] L1 refers to L1OC, the open L1 CDMA signal; L5 is L3OC, the open L3 CDMA signal, being L3 equivalent to the GPS L5 frequency.

Straight Line Tangent Altitude (SLTA – see **Fig. 1**) ranges as shown in **Tab. 3**. Since occultation measurements will be performed up to 500 km SLTA, ionospheric monitoring through the limb sounding geometry can be also performed.

SLTA range	**Sampling Rates[2] [Hz]**
-300 km – 30 km (**Closed Loop**)	10, 50, 200, 250
30 km – 150 km (**Closed Loop**)	10, 50, 200, 250
150 km – 500 km (**Closed Loop**)	1, 5, 10, 50, 200, 250
-300 km – 20 km[3] (**Open Loop**)	200, 250

Tab. 3 - RO sampling rates.

Navigation (POD) measurements will be available only for GPS and Galileo (16 dual frequency channels can be allocated contemporaneously for the closed-loop tracking of GPS and Galileo signals) and will be performed at 1 Hz sampling rate.

For both occultation and navigation measurements, low level observables available on-board (I and Q raw correlation components measured in both in open and closed-loop, Numerically Controlled Oscillator carrier and code phases, Noise power) will be processed later, on ground, into more standard GNSS observables like carrier phases, pseudo-ranges, signal amplitudes and Signal-to-Noise Ratios (SNRs) for both the frequencies received, according to Tab. 2.

Even though the instrument should be able to track signals from all GNSS constellations (GPS, Galileo, GLONASS and COMPASS/Beidou[4]), the baseline for EPS-SG Ground Segment will be the provision of occultations from GPS and Galileo only. This will allow fulfilling the requirements on the number of occultations that shall be observed per day (1100 by a single EPS-SG satellite, 2200 by two satellites, assuming 27 GNSS satellites per constellation).

Once the RO Instrument will be able to provide full multi-constellation capabilities, GLONASS and COMPASS/BeiDou provision of RO data from EPS-SG Ground Segment will be evaluated. Flexibility and support are already taken into corresponding requirements, in order to have a smooth transition once these signals are available. In this case the number of occultations that will be available per day will be likely doubled.

4 RO PRODUCTS PROVIDED IN THE FRAMEWORK OF EPS-SG

Level 1B products generated by EUMETSAT and disseminated in NRT (NetCDF-4 format, 1 file for each occultation) through the EUMETSAT's Broadcast System for Environmental Data (EUMETCast) will contain

- basic GNSS variables (dual frequency carrier-phases, pseudo-ranges, SNRs)
- LEO and GNSS satellite positions and velocities components
- LEO and GNSS satellite clock biases

[2] The sampling frequencies of 200Hz and 250Hz are not applicable to all the GNSS signals. In order to be applicable to a specific GNSS signal, the sampling rates of 200 Hz and 250Hz shall be multiple integer of the inverse of the data symbol duration of the GNSS signal under consideration.
[3] Even if the priority of the RO mission on board EPS-SG is the neutral atmosphere sounding (up to 80 km SLTA), in case channels are available Open Loop data can be further extended above.
[4] ICDs for GLONASS and COMPASS/Beidou are not available at the time of writing this document. The RO Instrument design allows some degree of flexibility, but it is not clear whether the instrument will be able to effectively track signals from those two GNSS constellations.

- High resolution and thinned bending angles and impact parameters on L1 and L5
- High resolution and thinned neutral Bending angles and impact parameters

and more other variables including quality check flags and monitoring parameters, with a vertical coverage from the surface up to 500 km.

In addiction a focused neutral atmospheric bending angle product will be disseminated in NRT to NWP users in BUFR format, via the Global Telecommunication System (GTS) and EUMETCast.

Other products will also be archived, but not disseminated. In particular, hourly Zenith GNSS data (in RINEX format) can be provided to users (currently, not in NRT). Options will be investigated for future dissemination in NRT of shorter Zenith GNSS data (covering 15 min measurements) and for the provision (not in NRT) of POD products (precise LEO orbits and clocks solutions) in sp3-c format. It is currently planned to generate daily sp3-c files (with 3 hour overlaps in the past and in the future) for reprocessing purposes.

Appendix B. ROM SAF (and GRAS SAF) Reports

SAF/GRAS/METO/REP/GSR/001	Mono-dimensional thinning for GPS Radio Occultation
SAF/GRAS/METO/REP/GSR/002	Geodesy calculations in ROPP
SAF/GRAS/METO/REP/GSR/003	ROPP minimiser – minROPP
SAF/GRAS/METO/REP/GSR/004	Error function calculation in ROPP
SAF/GRAS/METO/REP/GSR/005	Refractivity calculations in ROPP
SAF/GRAS/METO/REP/GSR/006	Levenberg-Marquardt minimisation in ROPP
SAF/GRAS/METO/REP/GSR/007	Abel integral calculations in ROPP
SAF/GRAS/METO/REP/GSR/008	ROPP thinner algorithm
SAF/GRAS/METO/REP/GSR/009	Refractivity coefficients used in the assimilation of GPS radio occultation measurements
SAF/GRAS/METO/REP/GSR/010	Latitudinal binning and area-weighted averaging of irregularly distributed radio occultation data
SAF/GRAS/METO/REP/GSR/011	ROPP 1D-Var validation
SAF/GRAS/METO/REP/GSR/012	Assimilation of Global Positioning System Radio Occultation data in the ECMWF ERA-Interim re-analysis
SAF/GRAS/METO/REP/GSR/013	ROPP PP validation
SAF/ROM/METO/REP/RSR/014	A review of the geodesy calculations in ROPP
SAF/ROM/METO/REP/RSR/015	Improvements to the ROPP refractivity and bending angle operators
SAF/ROM/METO/REP/RSR/016	Simplifying EGM96 undulation calculations in ROPP
SAF/ROM/METO/REP/RSR/017	Simulation of L1 and L2 bending angles with a model ionosphere
SAF/ROM/METO/REP/RSR/018	Single frequency radio occultation retrievals: impact on numerical weather prediction
SAF/ROM/METO/REP/RSR/019	Implementation of the ROPP two-dimensional bending angle observation operator in an NWP system
SAF/ROM/METO/REP/RSR/020	Interpolation artefact in ECMWF monthly standard deviation plots
SAF/ROM/METO/REP/RSR/021	5th ROM SAF User Workshop on Applications of GPS radio occultation measurements
SAF/ROM/METO/REP/RSR/022	The use of the GPS radio occultation reflection flag for NWP applications
SAF/ROM/METO/REP/RSR/023	Assessment of a potential reflection flag product
SAF/ROM/METO/REP/RSR/024	The calculation of planetary boundary layer heights in ROPP

ROM SAF Reports are accessible via the ROM SAF website http://www.romsaf.org