ESA/ESTEC 4000120868/17/NL/AF/HH :

RADIO CLIMATOLOGY MODELS OF THE IONOSPHERE : STATUS AND WAY FORWARD

EXECUTIVE SUMMARY ESR°
VERSION 1.0

Name of authors:
J. LEMORTON, V. FABBRO, and A. MAINVIS (ONERA),
G. GONZALEZ, J. SANZ, and J.M. JUAN (UPC/gAGE),
C. MOLINA, and A. CAMPS (UPC/CommSensLab-RSLab),
and J. BARBOSA (RDA)

Name of ESA study manager:
R. ORUS PEREZ

VERSIONS

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ESA STUDY CONTRACT REPORT

ESA Contract N°: ESA/ESTEC 4000120868/17/NL/AF	SUBJECT: **RADIO CLIMATOLOGY MODELS OF THE IONOSPHERE : STATUS AND WAY FORWARD** **Executive Summary Report (ESR)**	CONTRACTOR: ONERA/DEMR
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ABSTRACT:

This document is the Executive Summary Report for the ESA contract ESTEC 4000120868/17/NL/AF " Radio Climatology Models of the Ionosphere: Status and Way Forward".

The objective of this study was to use the experimental observations of the ionosphere collected in the past years to assess the performance of climatological ionosphere models, with the focus on scintillation models. This analysis has been performed in order to evaluate the ability of these climatological models to properly support future ESA needs, to identify weak areas, to propose recommendations for improvements and to implement these improvements whenever possible in existing models. An additional objective was to provide feedback on the adequacy of future Earth Observation products to contribute to a better understanding and modeling of the ionosphere.

In the study four models have been selected to be analysed in more details : GISM, SCIONAV, STIPEE and WBMOD. Several scenarios (in different regions, for different ionospheric activity intensity), figures of merits (mainly scintillation parameters S_4, σ_φ, p-slope, ROTI, or some EO instrument observables), a methodology on which to compare the models, and a large datasets of GNSS and GNSS-R measurements have been defined.

The execution of the models runs resulted in a large set of figures and numbers (PDF, CDF, point clouds, mean error, RMS error …) for each model. Observations on the behaviour of each model were established. The strengths and weaknesses of each model were identified and possible improvements highlighted. Generally speaking WBMOD + STIPEE and SCIONAV can be considered as relevant models for fulfilling the requirements, or at least the main ones.

Finally it has been shown that GNSS-R and SAR missions datasets could be processed to provide relevant information and characterisation (occurrence of scintillation events, inhomogeneity and dynamics if the irregularities) to improve the understanding of the ionosphere as a propagation medium and its impact on EO mission performances.

Perspectives and recommendations for future work have been proposed.

Names of authors:

J. LEMORTON, V. FABBRO, A. MAINVIS (ONERA), G. GONZALEZ, J. SANZ, J.M. JUAN (UPC/gAGE), C. MOLINA, A. CAMPS (UPC/CommSensLab-RSLab), J. BARBOSA (RDA)

NAME OF ESA STUDY MANAGER: Raul ORUS PEREZ DIV: EE DIRECTORATE: D TEC	ESA BUDGET HEADING:

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1. INTRODUCTION

This document is the Final Report (FR) for the ESA contract ESTEC 4000120868/17/NL/AF **"Radio Climatology Models of the Ionosphere: Status and Way Forward" [AD1]**.

For this contract, ONERA was leading a team of experienced researchers and engineers from the French Aerospace Lab ONERA in France, from Universitat Politècnica de Catalunya (UPC) in Spain and from the company Research and Development in Aerospace GmbH in Switzerland.

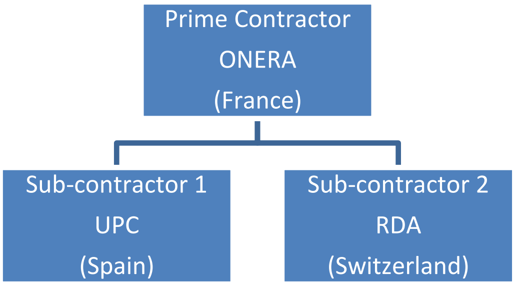

Figure 1-1 : Consortium structure

1.1. Context of the study

The interest on the characterisation of the ionosphere and its impact on Radiowave signals has been increasing in the last ten years, at least in three main areas:

- GNSS applications, where ionosphere delay corrections are necessary to improve positioning, and ionosphere scintillation effect on GNSS receivers is a major limitation, especially at high latitudes and in equatorial regions,
- EO observations, especially low frequency SAR missions (such as BIOMASS) and GNSS-R are very much sensitive to the ionosphere effects, requiring a better characterisation of these layers and their variability in time and space,
- Space Weather concerns impacting numerous facets of everyday life, as a large variety of phenomena are driven by the variability of the Sun over periods ranging from hours to years, which also interacts with the ionosphere layers to modify radiowave propagation characteristics and therefore a large set of applications (navigation, communications …).

Existing climatological ionospheric models such as WBMOD or GISM were developed a long time ago and could probably be improved from recent datasets being available, for example from GNSS ground receivers network (MONITOR, SAGAIE, SIRGAS, RBMC …). This would enable to better characterize the spatio-temporal fluctuations of the ionosphere and therefore to better predict the performance of future EO missions that are impacted by the ionosphere.

So the <u>objective of the study</u> was to use the experimental observations of the ionosphere collected in the past years to assess the performance of climatological ionosphere models, with the focus on scintillation models.

This analysis was to be performed in order to evaluate the ability of these climatological models to properly support future ESA needs, to identify weak areas if any, to propose recommendations for improvements and to implement these improvements whenever possible in existing models.

An additional objective was to provide feedback on the adequacy of future Earth Observation products to contribute to a better understanding and modelling of the ionosphere.

The study was divided into four tasks.

Task 1 was devoted to the review of the state-of-the-art on ionospheric models and the identification of relevant datasets to assess the performance of ionospheric models. It also includes the definition of scenarios (test cases) and figures of merit for assessment of future missions' performances taking into account the climatology of the ionosphere.

Task 2 was mainly focused on the execution of the different tests on the ionosphere models and the generation of the necessary figures of merits. These figures shall allow identifying the strengths and weaknesses of the different models depending on the type of application addressed. It is divided into elementary tasks referring to different EO missions.

Task 3, was devoted to the analysis of the adequacy of the performance obtained with the existing ionosphere models with future needs of EO missions. It includes activity to improve the existing models to better fulfil these requirements.

Finally Task 4 dealt with the potentials of Earth observation data to contribute to the ionosphere observing system, ie how the available and upcoming Earth observation capabilities might contribute to improving the understanding of the ionosphere as a propagation medium.

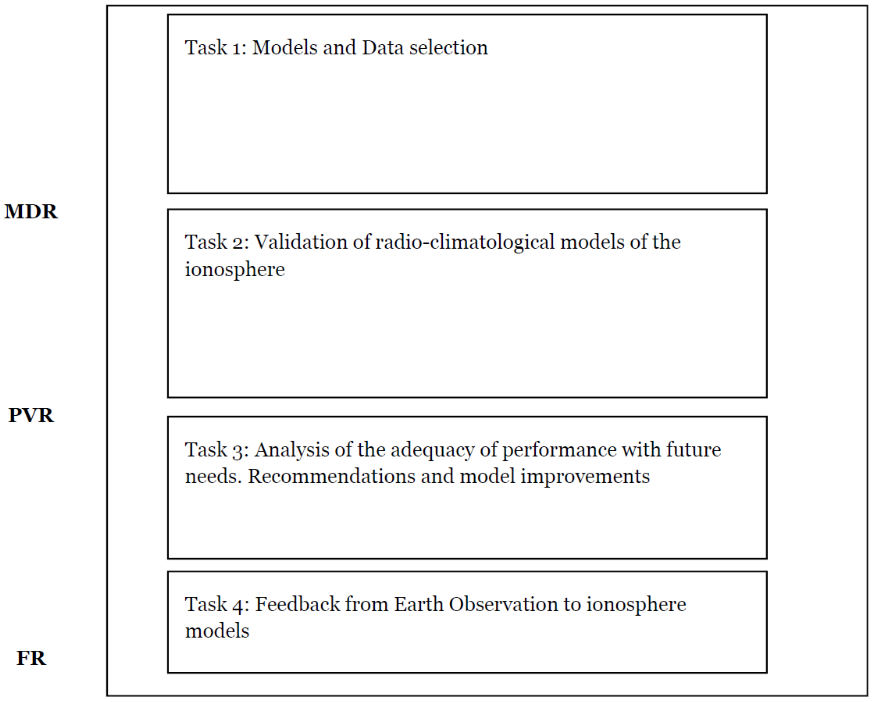

Figure 1-2 : Study logic proposed in the SOW [AD2] and followed in the study

The global Work Breakdown Structure is given on the figure below.

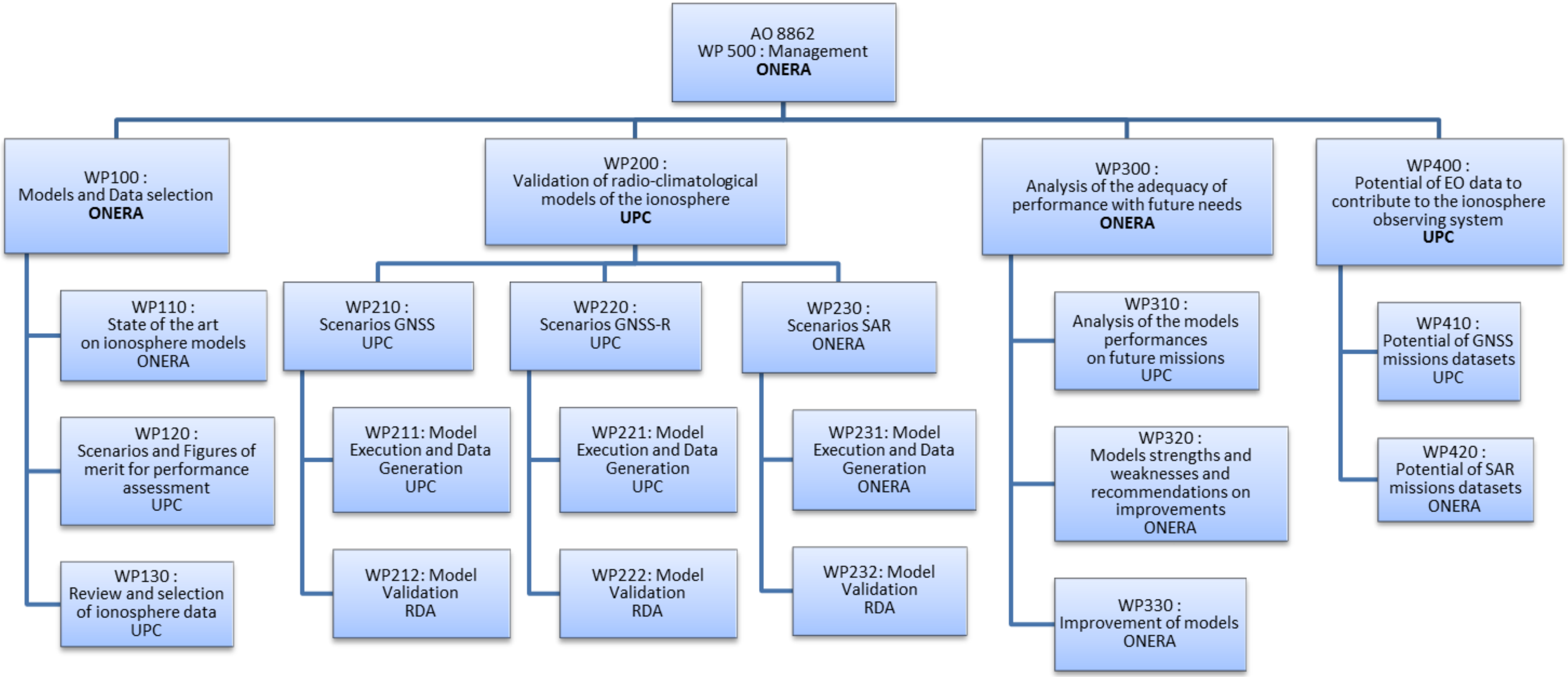

Figure 1-3 : Detailed Work Breakdown Structure with all Work Packages

1.2. Applicable and Reference documents

1.2.1. Applicable Documents

[AD1]	ESA contract "Radio Climatology Models of the Ionosphere : Status and Way Forward"	ESTEC 4000120868/17/NL/AF
[AD2]	ESA Statement of Work	Ref ESA TEC-EEP-SOW-004116, Issue 0 revision 2 January 25th 2017
[AD3]	Minutes of the Negotiation Meeting ..	June 12th 2017, reference 20170612_DEMR-27542_ESTEC_ClimIono_MoNegoM signed
[AD4]	General Clauses and Conditions for ESA Contracts	ESA REG 002
[AD5]	ONERA Proposal	DEMR-T/110/17 March 24th 2017
[AD6]	AO 8862 : Answers to Negotiation points	ONERA document, June 7th 2017

1.2.2. Reference Documents

[RD1] Technical Note TN1 v2d0, ESTEC 4000120868/17/NL/AF CLIM IONO, February 2018.

[RD2] Technical Note TN2 v2d0, ESTEC 4000120868/17/NL/AF CLIM IONO, May 2020.

[RD3] Technical Note TN3 v1d0, ESTEC 4000120868/17/NL/AF CLIM IONO, April 2020

[RD4] Technical Note TN4 v1d0, ESTEC 4000120868/17/NL/AF CLIM IONO, April 2020

[RD5] Final Report v1d0, ESTEC 4000120868/17/NL/AF CLIM IONO, May 2020

[RD6] NorthWest Research Associates (NWRA). “WBMOD (for WideBand MODel) ionospheric scintillation model”. http://www.nwra.com/ionoscint/wbmod.html

[RD7] [Beniguel 2002] Béniguel Y, “Global Ionospheric Propagation Model (GIM): a propagation model for scintillations of transmitted signals”, Radio Sci., Vol 37, N° 3, May 2002.

[RD8] [Camps & al 2017b] A. Camps, J. Barbosa, M. Juan, E. Blanch, D. Altadill, G. González, G, Vazquez, J. Riba, R. Orús, "Improved Modelling of Ionospheric Disturbances for Remote Sensing and Navigation " presentation at 2017 IEEE International Geoscience and Remote Sensing Symposium, July 2017, Fort Worth, Texas, USA.

[RD9] [Carrano & al 2012] Carrano, C. S., K. M. Groves, and R. G. Caton (2012), Simulating the impacts of ionospheric scintillation on L band SAR image formation, Radio Sci., 47, RS0L20, doi:10.1029/2011RS004956.

[RD10] [Galiegue 2013] Galiegue H. “Modélisation des effets des scintillations ionosphériques sur la propagation des ondes électromagnétiques en bande L aux latitudes polaires” PhD thesis, ONERA – CNES, University of Toulouse, 2013

[RD11] [Rogers & Cannon 2007] Rogers N. and P. Cannon, "The Impact of Ionospheric Irregularities on Wideband Satellite SAR", ACRAS Workshop, BAS Cambridge, UK, May 2007

[RD12] [Wernik & al 2007] Wernik, A.W., L. Alfonsi And M. Materassi (2007): Scintillation modelling using in situ data, Radio Science, 42 (1), RS1002, 2007

[RD13] [Zernov & al 2008b] Zernov N.N. et al, “On the effects of scintillation on the trans-ionospheric paths of propagation”, in Proceedings of IES2008, (Alexandria, Virginia, USA, 13-15 May, 2008), p. 8

[RD14] [Fabbro & al 2019a] Fabbro V., Jacobsen K.S., Rougerie S.. “HAPEE, a prediction model of ionospheric scintillation in polar region” EUCAP 2019, 31 March-5 April 2019

[RD15] [Fabbro & al 2019b] Fabbro V., Jacobsen K.S., Rougerie S.. “HAPEE, a statistical approach for ionospheric scintillation prediction in the polar region” Beacon Satellite Symposium, Aug 2019, OLSZTYN, Poland. hal-02365033

1.3. Acronyms

AATR	Along Arc TEC Rate
CDF	Cumulative Distribution Function
CNES	Centre National d’Etudes Spatiales (French Space Agency)
DEMR	Département ElectroMagnétisme et Radar de l’ONERA
DoY	Day of Year
EO	Earth Observation
FR	Faraday Rotation
GISM	Global Ionospheric Scintillation Model
GNSS	Global Navigation Satellite Systems
GNSS-R	GNSS Reflectometry
GNSS-RO	GNSS Radio Occultation
IGRF	International Geomagnetic Reference Field
IRI	International Reference Ionosphere
PDF	Probability Density Function
PLC	Polar Cap area
RDA	Universitat Politècnica de Catalunya
RF	Radio Frequency
RO	Radio Occultation
ROTI	Rate of Change of TEC Index
SAR	Synthetic Aperture Radar
SCIONAV	SCIONAV ESA project : Improved Modelling of Short and Long Term Characteristics of Ionospheric Disturbances
SOW	Statement of Work (ESA document)
SSN	Sun Spot Number
STIPEE	Software Tool for Ionospheric Propagation Effects Evaluation
TEC	Total Electron Content
UPC	Universitat Politècnica de Catalunya
WAM	Wernik-Alfonsi-Materassi model
WBMOD	WideBand MODel

2. SYNTHESIS AND PERSPECTIVES OF THE STUDY

The objective of the study was to use the experimental observations of the ionosphere collected in the past years to assess the performance of climatological ionosphere models, with the focus on scintillation models.

This analysis was to be performed in order to evaluate the ability of these climatological models to properly support future ESA needs for future Earth Observation missions, to identify weak areas if any, to propose recommendations for improvements and to implement these improvements whenever possible in existing models.

An additional objective was to provide feedback on the adequacy of future Earth Observation products to contribute to a better understanding and modelling of the ionosphere.

2.1. Ionospheric Models and Data Selection

The objectives of Task 1 were threefold:

- to identify the most relevant ionosphere models suitable for ionosphere modelling, and define their capabilities and limitations for GNSS and Earth observation missions (especially low frequency SAR)
- to define scenarios (test cases) and figures of merit for assessment of future missions performances taking into account the climatology of the ionosphere
- to review and select the datasets to assess the performance of ionospheric models

So, in a first step, a state-of-the-art review of existing climatological models of the ionosphere, and especially ionospheric scintillation models, was performed. Ionospheric scintillation models aim at predicting the indices of scintillation on a particular trans-ionospheric signal from a description of the ionospheric layers and inhomogeneities. Several of them were identified in the literature:

- The Global Ionospheric Scintillation Model (GISM) developed by IEEA (Fr) {Beniguel 2002 [RD7]},
- WBMOD (Wide Band Model) developed by NWRA in Seattle (USA) {WBMOD 2020 [RD6]},
- The STIPEE model developed at ONERA (Fr) {Galiegue 2013 [RD10]}
- The Hybrid scintillation model developed by universities of Leeds and Saint Petersburg {Zernov et al., 2008b [RD13]},
- The Trans Ionospheric Radio Propagation Simulator (TIRPS) developed by Qinetic (UK) {Rogers & Cannon 2007 [RD11]},
- The WAM Model developed by INGV Roma and the Polish Space Research Center, Warsaw {Wernick & al 2007 [RD12]}
- the SAR Scintillation Simulator (SAR-SS) developed in the US {Carrano & al 2012 [RD9]},
- SCIONAV, developed by a team from UPC, RDA and the Observatori de l'Ebre {Camps & al 2017b [RD8]}

There are in fact two different kinds of models, climatological models or physical-based models. And globally, these models can be split also in two different parts: a first part dedicated to ionospheric medium irregularities characterization, and a second part dedicated to radiowave propagation through the inhomogeneous ionospheric layer.

After a critical analysis of these models, on different criteria (validity coverage, type of inputs related to solar and geomagnetic activity, type of outputs, access to the code …), four models have been selected to be analysed in more details and to be tested in the validation exercise: GISM, SCIONAV, STIPEE and WBMOD.

Different scenarios have then been defined taken into account solar activity and singular events, like geomagnetic storms, that caused the largest ionospheric disturbances during the current and past solar cycle, and additionally, being focused in the different regions of the World. The following regions have been considered for the selection of scenarios to be used in model assessment:

- Polar cap (PLC): locations with a magnetic dip angle (D) greater than 80° in the two hemispheres. In general, this region is enclosed within the aurora oval.
- High latitudes (HLT): locations with D>73° or D<-65°, excluding the PLC region. In general, under high solar or ionospheric activity, they can be reached by the aurora oval.
- Europe (EUR): locations with geographic longitude and latitude in the intervals [-15°, 35°] and [33°, 60°], respectively. This includes the continental region, Great Britain islands, South of Scandinavia peninsula and Northern Africa.
- Low/equatorial latitudes (LEQ): locations with modified dip angle (modip) under 36° in both hemispheres. According to {Juan et al., 2018}, this region concentrates the effects of the ionospheric activity related with phenomena taking place around the geomagnetic equator.

Then various figures of merit have been identified for comparing the capacity of the models to represent the quantities that can be measured by EO missions. It ends up with mainly scintillation parameters S_4, σ_φ, p-slope, ROTI, and some EO instrument observables.

Different data sets were initially reviewed that could be used to assess the performance of climatological ionospheric models: GNSS data from ground, radio occultation (RO) from space and reflectometry, DORIS data, Beacon satellite data, EO data from SWARM and ALOS satellite and incoherent scatter radar data from EISCAT.

2.2. Validation of selected radio-climatological models of the ionosphere

The objectives of Task 2 were to plan and execute the different tests on the ionosphere models and generate the necessary figures of merits by mission scenarios.

First the Validation procedure was defined with the objective of proving that the models are representative of the physical phenomena for each of the cases, including a quantitative assessment of the level of agreement. Performing a Validation/Verification in the above sense, matching the model results with the experimental data, is a necessary proof that the models are correctly developed and implemented. However, this might still be not a sufficient proof because such experimental data may not be fully representative or suffer from systematic or random errors that would make the model not according to reality but only according to the original data.

So an in-depth look on the datasets available from GNSS, GNSS-R and SAR EO missions was performed. The datasets were selected to be as representative as possible. So considering datasets available and relevant it resulted in a large number of samples from GNSS ground receivers and GNSS-R equipment, and on a small number of case studies on SAR equipment.

As far as the validation procedure is concerned, it is important to mention here that, depending on the model characteristics (inherent principle, functionalities, input, output …) and on the mission types, the tests could be substantially different. In some cases, for example, a more or less direct comparison of the model outputs can be done with the equipment measurements, even if convenient processing of the raw data has to be performed. In the other cases, the mission data measurements have to be furtherly processed to achieve a comparison of the model outputs. It must be mentioned for example that for a given RF link and ionospheric condition (SSN, doy, hour, RF link characteristics), since scintillation is a very variable phenomenon, WBMOD provides a complete distribution of scintillation parameters from which the mean value can be extracted, but also different values for different percentiles. Other existing models give only one value, which can be regarded as the mean.

For GNSS data, in each case, several satellites are observed, and so datasets correspond to a large number of samples $(S_4, \sigma_\phi)_{meas}$. The execution of models was made in a similar way, so we obtained a large number of $(S_4, \sigma_\phi)_{simulated}$ for SCIONAV, GISM and WBMOD + STIPEE. As STIPEE is not alone a climatological model since its inputs can be either quantities proposed by WBMOD (as CkL, drift velocity, slope, anisotropy) or given by the user (electron density variance and ionospheric spectrum parameters such as drift velocity, slope, anisotropy), in the tests it has been associated to WBMOD.

A large amount of work was then devoted to the final data collection by extracting from actual data the values which could be used as a reference for assessing the test results:

- From ground receivers, classical scintillation parameters.
- From GNSS-R and GNSS-RO missions, instrument observables for given times and locations.
- From SAR missions, instrument observables for the given times and locations.

GNSS data used for comparison are for example given on Table 2-1.

Table 2-1 : List of processed GNSS test scenarios for the first campaign

Region	Stations	Year	Day of the Year	UT interval (h)	Ionospheric Activity
Periods of High Activity					
LEQ (South America)	areq, bogt, kour	2015	290, 291, 298, 299	[0, 5]	High, over 95% of AATR distribution in current solar cycle
LEQ (East Africa)	mal2	2015	115,116	[17, 22]	Idem
LEQ (South East Asia)	pimo	2015	115, 275, 299	[12, 14:30]	Idem
Europe	redu, vill	2015	291, 298	[11, 13]	Moderate to low, in 3rd quartile of AATR distribution in current solar cycle
High Latitudes and North Polar Cap	fair, kely, kiru, yell	2015	250, 252	[0, 12] [12, 23]	High, moderate and small geomagnetic storms. Over 99% of AATR distribution in current solar cycle
High Latitudes and South Polar Cap	mcm4	2015	274, 282	[17, 23]	Small geomagnetic storms. Over 99% of AATR distribution in current solar cycle

Periods of Low Activity					
LEQ (South America)	areq, bogt, kour	2015	114,115,116, 250, 251, 252	[7, 12]	Low, around the median of AATR distribution in the current solar cycle
LEQ (South East Asia)	pimo	2015	250, 251, 252	[14, 22]	Low/quiet, mostly under the median of the AATR distribution in the 1st and 2nd quartiles
High Latitudes and North Polar Cap	fair, kely, kiru, yell	2015	114, 115, 116	[13, 23]	Low, around the median of AATR distribution in current solar cycle
High Latitudes and South Polar Cap	mcm4	2015	114, 116 251 275	[14,21] [12,17] [03,11]	Low, just around the median of AATR distribution

We then followed the proposed Validation Plan. The execution of the models runs resulted in a large set of figures and numbers (PDF, CDF, point clouds, mean error, RMS error, …) for each model. Some are shown below:

2.2.1. Results for S_4

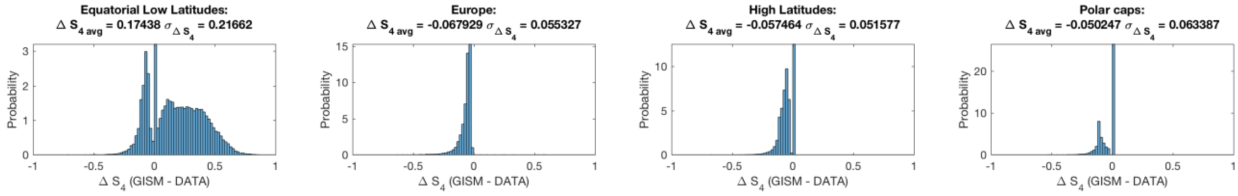

Figure 2-1 : Error distributions for S_4, from GISM model, per region (SCIONAV = GISM)

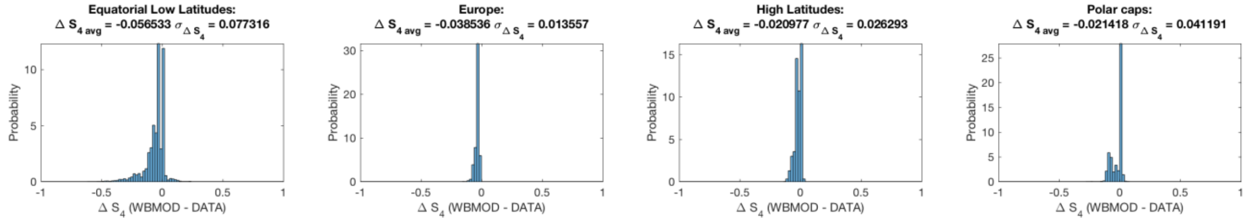

Figure 2-2 : Error distributions for S_4, from WBMOD model, per region

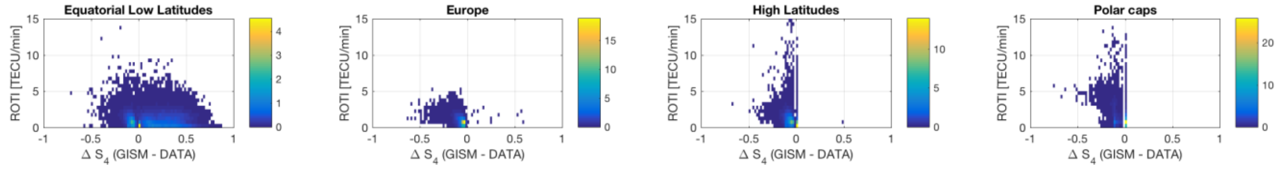

Figure 2-3 : Error distributions for S_4 vs ROTI, from the GISM model, per region (SCIONAV has the same behaviour)

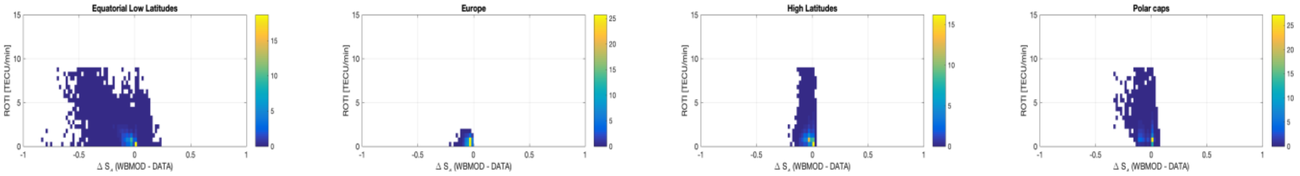

Figure 2-4 : Error distributions for S_4 vs ROTI, from the WBMOD model, per region

2.2.2. Results for σ_ϕ

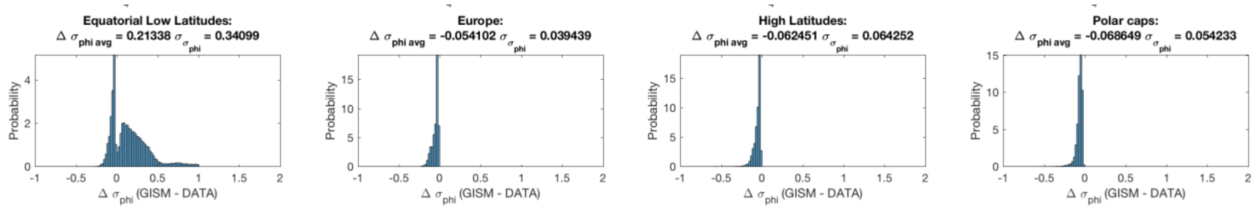

Figure 2-5 : Error distributions for σ_ϕ, from GISM model, per region

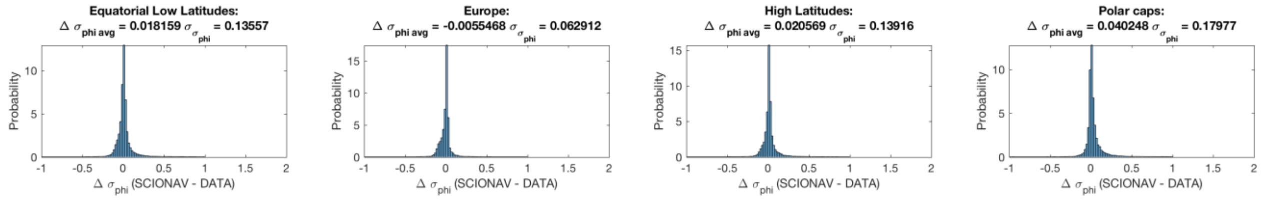

Figure 2-6 : Error distributions for σ_ϕ, from SCIONAV model, per region

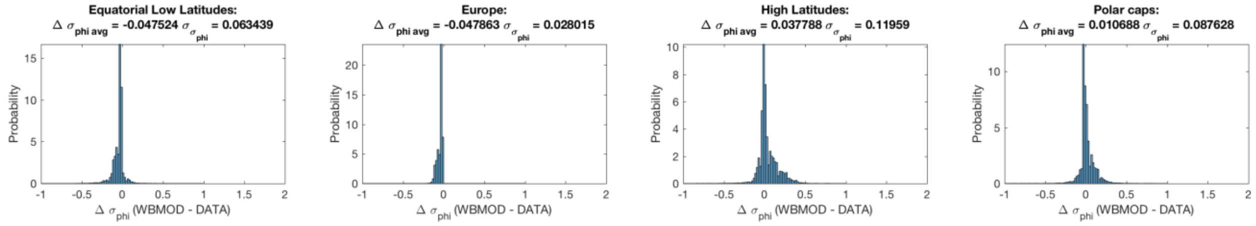

Figure 2-7 : Error distributions for σ_ϕ, from WBMOD model, per region

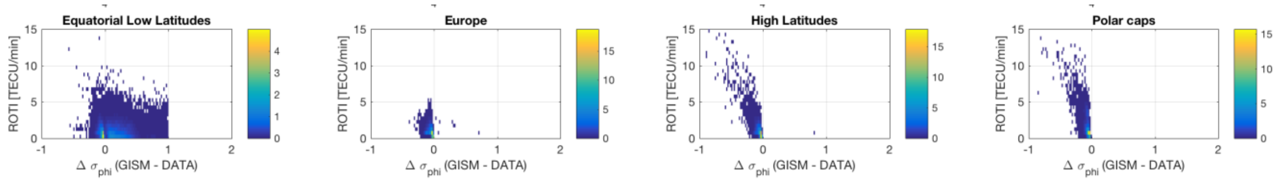

Figure 2-8 : Error distributions for σ_ϕ vs ROTI, from the GISM model, per region

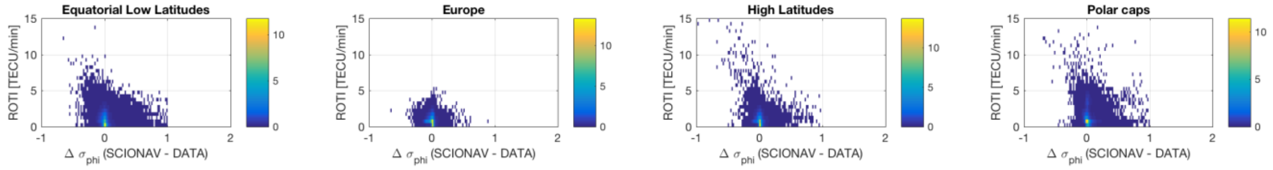

Figure 2-9 : Error distributions for σ_ϕ vs ROTI, from the SCIONAV model, per region

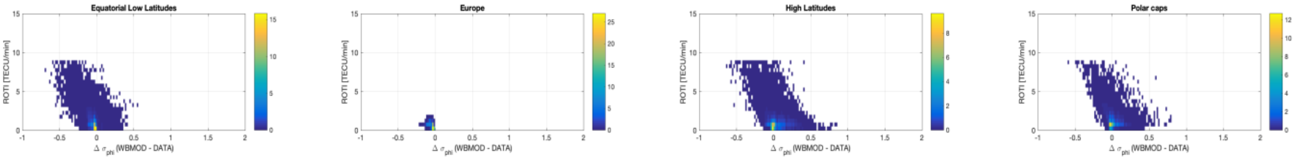

Figure 2-10 : Error distributions for σ_ϕ vs ROTI, from the WBMOD model, per region

The results of the comparison exercise are also summarized in the next tables by showing the mean error and RMS error between prediction by the models and measured values. Note that the green colour is used for the best result (lower error). Results for the p-slope comparison are also given in the Final Report [RD5].

Table 2-2: Mean error for S_4

		SCIONAV	GISM	WBMOD + STIPEE
Polar Caps (PLC)	All Types	**-0.0502**	**-0.0502**	**-0.0215**
	Type 1	-0.0687	-0.0687	-0.0246
	Type 2	-0.0623	-0.0623	-0.0006
	Type 3	-0.0529	-0.0529	-0.0283
High Latitudes (HLT)	All Types	**-0.0575**	**-0.0575**	**-0.0210**
	Type 1	-0.0563	-0.0563	-0.0193
	Type 2	-	-	-
	Type 3	-0.0557	-0.0557	-0.0234
Europe (EUR)	All Types	**-0.0679**	**-0.0679**	**-0.0385**
	Type 1	-	-	-
	Type 2	-0.0681	-0.0681	-0.0385
	Type 3	-	-	-
Low/Equatorial Latitudes (LEQ)	All Types	**0.1744**	**0.1744**	**-0.0565**
	Type 1	0.1510	0.1510	-0.0691
	Type 2	0.2207	0.2207	-0.1567
	Type 3	0.241	0.241	-0.0321

Table 2-3: RMS error for S_4

		SCIONAV	GISM	WBMOD + STIPEE
Polar Caps (PLC)	All Types	**0.0634**	**0.0634**	**0.0412**
	Type 1	0.0691	0.0691	0.0446
	Type 2	0.0652	0.0652	0.0224
	Type 3	0.0660	0.0660	0.0402
High Latitudes (HLT)	All Types	**0.0516**	**0.0516**	**0.0263**
	Type 1	0.0514	0.0514	0.0269
	Type 2	-	-	-
	Type 3	0.0507	0.0507	0.0251
Europe (EUR)	All Types	**0.0553**	**0.0553**	**0.0136**
	Type 1	-	-	-
	Type 2	0.0557	0.0557	0.0136
	Type 3	-	-	-
Low/Equatorial Latitudes (LEQ)	All Types	**0.2166**	**0.2166**	**0.0783**
	Type 1	0.2023	0.2023	0.0983
	Type 2	0.2171	0.2171	0.0969
	Type 3	0.2149	0.2149	0.0298

Table 2-4: Mean error for σ_ϕ

		SCIONAV	GISM	WBMOD + STIPEE
Polar Caps (PLC)	All Types	**0.0402**	**-0.0686**	**0.0107**
	Type 1	0.0505	-0.0725	0.0458
	Type 2	0.0537	-0.0670	-0.0378
	Type 3	0.0329	-0.0692	-0.0244
High Latitudes (HLT)	All Types	**0.0206**	**-0.0625**	**0.0378**
	Type 1	0.0250	-0.0648	0.0730
	Type 2	-	-	-
	Type 3	0.0082	-0.0502	-0.0145
Europe (EUR)	All Types	**-0.0055**	**-0.0541**	**-0.0479**
	Type 1	-	-	-
	Type 2	-0.0033	-0.0522	-0.0479
	Type 3	-	-	-
Low/Equatorial Latitudes (LEQ)	All Types	**0.0182**	**0.2133**	**-0.0475**
	Type 1	0.0484	0.1623	-0.0434
	Type 2	0.0450	0.3638	-0.1160
	Type 3	0.0097	0.2860	-0.0338

Table 2-5: RMS error for σ_ϕ

		SCIONAV	GISM	WBMOD + STIPEE
Polar Caps (PLC)	All Types	**0.1798**	**0.0542**	**0.0876**
	Type 1	0.1914	0.0601	0.1024
	Type 2	0.2351	0.0511	0.0837
	Type 3	0.1427	0.0422	0.0201
High Latitudes (HLT)	All Types	**0.1392**	**0.0643**	**0.1196**
	Type 1	0.1425	0.0734	0.1418
	Type 2	-	-	-
	Type 3	0.0663	0.0316	0.0330
Europe (EUR)	All Types	**0.0629**	**0.0394**	**0.0280**
	Type 1	-	-	-
	Type 2	0.0610	0.0375	0.0280
	Type 3	-	-	-
Low/Equatorial Latitudes (LEQ)	All Types	**0.1416**	**0.3410**	**0.0634**
	Type 1	0.2190	0.2437	0.0862
	Type 2	0.2273	0.465	0.0870
	Type 3	0.0990	0.4012	0.0241

A specific activity was then performed to improve the S_4 modelling in SCIONAV by adapting a model (so called the "COSMIC" model) coming from FORMOSAT-3/COSMIC radio-occultation data. The validation exercise was executed again for S_4 on a larger dataset for GISM, SCIONAV+COSMIC and WBMOD+STIPEE. It appeared that COSMIC worked better than GISM (**Erreur ! Source du renvoi introuvable.**), and could then be advantageously associated to SCIONAV.

Table 2-6 : Mean and RMS error for S_4 (All types), including COSMIC model

		SCIONAV	GISM	WBMOD + STIPEE	COSMIC
Polar Caps (PLC)	Mean	**-0.0502**	**-0.0502**	**-0.0385**	**-0.0521**
	RMS	**0.0634**	**0.0634**	**0.0665**	**0.0876**
High Latitudes (HLT)	Mean	**-0.0575**	**-0.0575**	**-0.0353**	**-0.0643**
	RMS	**0.0516**	**0.0516**	**0.0331**	**0.0700**
Europe (EUR)	Mean	**-0.0679**	**-0.0679**	**-0.0469**	**0.0245**
	RMS	**0.0553**	**0.0553**	**0.0208**	**0.1110**
Low/Equatorial Latitudes (LEQ)	Mean	**0.1744**	**0.1744**	**-0.0645**	**-0.0146**
	RMS	**0.2166**	**0.2166**	**0.0765**	**0.1037**

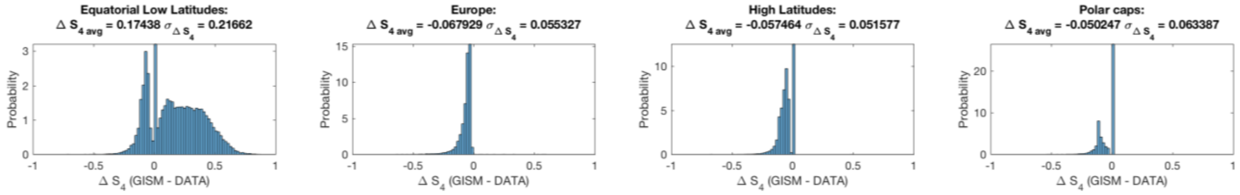

Figure 2-11 : Error distributions for S_4, from GISM model, per region

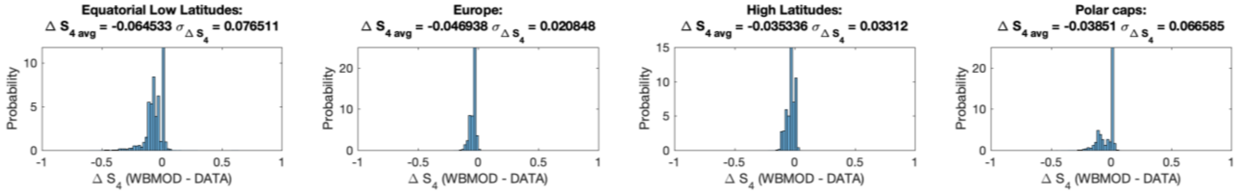

Figure 2-12 : Error distributions for S_4, from the WBMOD + STIPEE model, per region

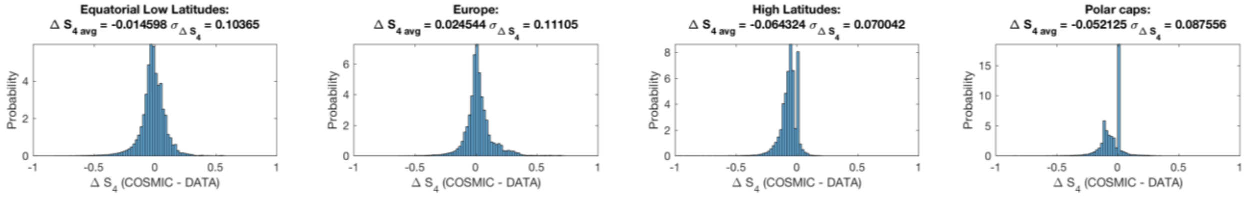

Figure 2-13 : Error distributions for S_4, from SCIONAV + COSMIC model, per region

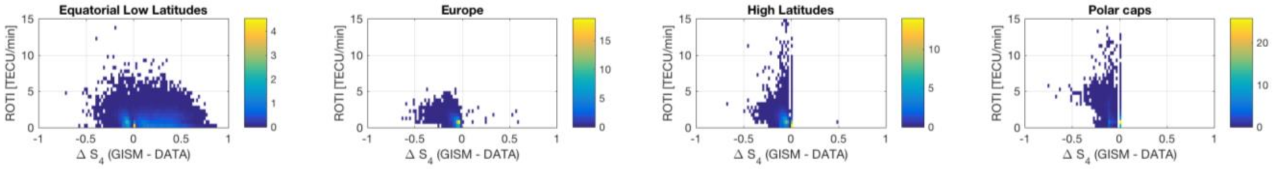

Figure 2-14 : Error distributions for S_4 vs ROTI, from the GISM model, per region

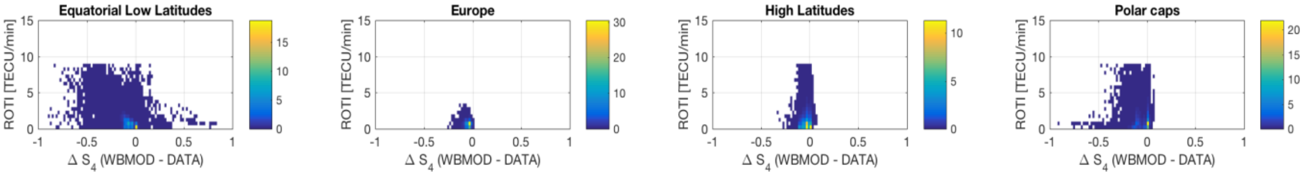

Figure 2-15 : Error distributions for S_4 vs ROTI, from the WBMOD model, per region

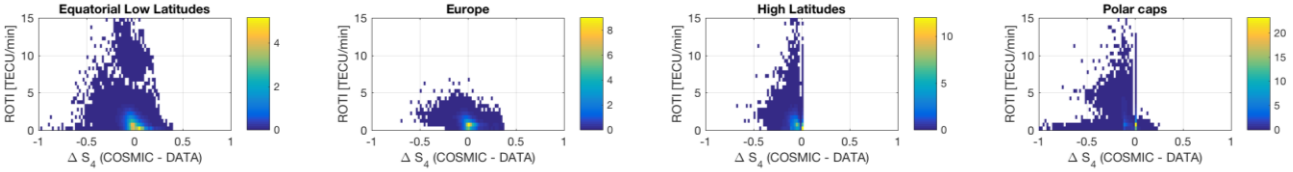

Figure 2-16 : Error distributions for S_4 vs ROTI, from the SCIONAV + COSMIC model, per region

2.3. Conclusions of the validation exercise and adequacy of the models for future EO mission needs

Then several observations on the behaviour of each model were established. The strengths and weaknesses of each model were identified and possible improvements highlighted. Generally speaking WBMOD + STIPEE for S_4 and σ_φ and SCIONAV for σ_φ can be considered as relevant models for fulfilling the requirements, or at least the main ones.

2.3.1. Main conclusions of the validation exercise

From the testing activity performed in Task 2, the following conclusions were drawn:

- S_4 modelling analysis
    - GISM models artificially high values of S_4 and is known to lack a proper model at high latitudes; it is the same for SCIONAV, which is based on GISM.
    - GISM does not have a good S_4 model, when compared against the data or against WBMOD
    - WBMOD+STIPEE has a more realistic distribution, even if it produces values slightly lower than reality,
    - While S_4 is clearly correlated with ROTI, this is not modelled by either code.
    - GISM and WBMOD model the dependency with local time
    - In SCIONAV modelling (for this study), bubbles and depletions have not been included. If they were, the S_4 values would be slightly higher

- σ_ϕ modelling analysis
    - GISM again models artificially high values of σ_ϕ
    - SCIONAV has very good agreement with the data at all levels (mean and STD for all regions, dependency with ROTI and LT)
    - WBMOD + STIPEE also has a good model, but does not reproduce so well the dispersion of values with local time for some cases.
    - SCIONAV has the best σ_ϕ model across regions and event types. However, WBMOD + STIPEE is very close, with a lower dispersion of the errors across regions.

- p-slope modelling analysis
    - data sets used for validation are contaminated by 1 Hz data, so the slopes do not exhibit a continuous variation, but a binomial one, this can be easily solved by constraining the model analysis to comparisons with 50 Hz data, only available in specific locations at low latitudes (Africa) and for some periods of time at high latitudes (North Europe).
    - PDF plots show only the lower part of SCIONAV modelled p-slope, there is another peak around 2.5 (this can be seen in the plots vs ROTI). The slopes PDF varies with σ_ϕ, and low and moderate/high scenarios have been modelled
    - WBMOD uses a fixed value depending on latitude

2.3.2. Requirements on models for upcoming Earth Observation missions, and adequacy of the existing models

Finally reviewing recent and upcoming EO missions for GNSS-R, GNSS-RO and SAR techniques, and defining the requirements on ionospheric climatological models for assessing the impact of ionosphere scintillation on these mission performances, we established the adequacy of tested models for future missions as follows:

- Positive points :
    - For the amplitude scintillation parameter S4, one model (WBMOD) predicts reasonably well the mean scintillation measured values on the testing datasets. COSMIC model seems also efficient for European and Equatorial latitudes.
    - For the phase scintillation parameter σ_ϕ, two models (SCIONAV and WBMOD) predict reasonably well the mean scintillation measured values on the testing datasets.
    - These models are global and are applicable for any areas of the World, and at any time of the Solar cycle.
    - In some cases, it could be nice for worst cases performances analysis to have the complete probability distribution of scintillation parameters, and not only mean or median values. WBMOD offers this possibility.
    - For some applications in EO performance assessment, time series of the signals affected by scintillation must be produced and used in EO instrument performance evaluation. STIPEE fed by WBMOD outputs can be used for that.
    - For some EO missions that need also global TEC maps, vertical electron density profiles or magnetic field values, although not tested and outside the scope of this study, relevant models are available for future EO performances assessment (i.e. IRI, NeQuick, Geomag, IGRF …).

- Limitations
    - It was not possible to build a testing dataset that could consider all the possible scenarios corresponding to a complete Solar cycle or even more several Solar cycles, and that could be statistically relevant for extreme events in Polar regions (ionospheric storms). So the validation results are still partial, especially for extreme values.
    - The frequency range for which the validity of the scintillation models has been confirmed is less than the range required (because mainly based on GNSS L-band data for SCIONAV and COSMIC, and VHF to L-band data for WBMOD).
    - Vertical profiles of S_4 amplitude scintillation would be needed for GNSS-RO missions retrieving these profiles, but are not provided by any model.
    - Whereas small-scale electron content spatial and temporal fluctuations are well predicted from scintillation models, there is probably a lack of representation of median-scale TEC spatial and temporal fluctuations, which are needed for SAR missions performance assessment.

- Perspectives
    - COSMIC S4 model could be refined at high latitudes by re-analysing existing data or processing new data from upcoming RO missions. A similar model to COSMIC S4 model, but for σ_ϕ, could also be derived, particularly for equatorial regions.
    - For WBMOD, possible improvements might be obtained on climatological parameters (i.e. statistical distributions of turbulent irregularities strength for different regions and different periods of time) by using GNSS large datasets.

- At high latitudes, a new prediction model has been derived by ONERA called HAPEE (High lAtitude scintillation Positioning Error Estimator) in a French-Norwegian project that is going to be merged with STIPEE within a CNES project [RD14][RD15]. HAPEE predicts a distribution of ROTI and σ_φ (as well as mean values) depending on solar wind parameters such as solar wind pressure p and Bz the z component of the Earth magnetic field.

2.4. Potential of EO data to contribute to the ionosphere characterisation

Furthermore, a second objective of the study was:

- first to assess how the available and upcoming Earth observation capabilities (GNSS-R, GNSS-RO, SAR) might contribute to improve the understanding of the ionosphere as a propagation medium,
- secondly to elaborate a way forward to integrate this information content into ionosphere models, and thirdly, to propose corresponding recommendations.

So firstly the analysis of GNSS-R data (from CYGNSS mission) showed to be a promising tool for observing the high occurrence of scintillation events, especially related to the equatorial ionosphere anomaly. The extension, duration, position and local time of these fluctuations can be related with the known phenomena of plasma bubbles or depletions.

Therefore a continuous analysis of the data could search for them and help improving the knowledge on these events in order to improve current models on ionospheric activity and provide a statistical climatology from a systematic analysis. On future missions, it would benefit also from the fact that this method may provide results on the whole area covered by the satellite constellation, not only in regions near dedicated known ground stations.

Other phenomenon that could be studied in this phase is the occurrence of ionospheric perturbations during hurricanes and large tropical cyclones due to the coupling between the higher layers of the atmosphere with the ionosphere, and also earthquakes during the operation years of CYGNSS in order to try to find evidences on Earth-ionosphere coupling

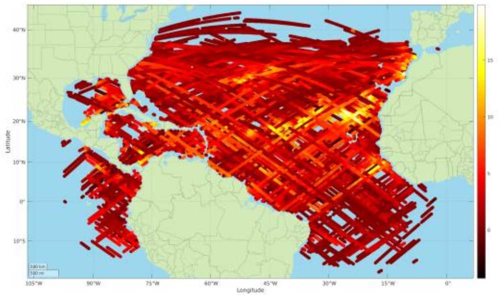

Figure 2-17 : Signal-to-Noise values measured by 4-channel, 8 CYGNSS satellites during the full day November 21st, 2017 in the Atlantic Ocean

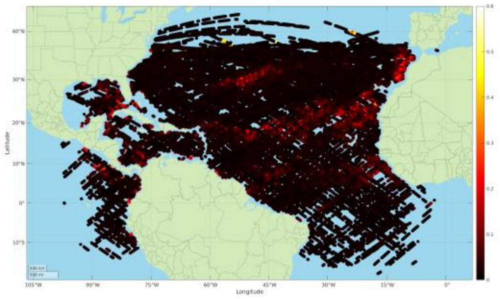

Figure 2-18 : S_4 values plotted for all points in selected region and day, showing in darker points where scintillation is close to zero

And secondly a methodology to detect and characterize the ionospheric activity from SAR measurements was looked for, developed and tested on some PALSAR data. This is based on two parameters (the mean value of the phase advance along the azimuth, and the ROTI along the azimuth in its spatial form) which manage to identify the ionospheric events (especially plasma clouds and gradients in Polar Regions, or plasma bubbles or depletions near the Equator). Also, the observation by two different means (SAR and GNSS) measuring different scales reveals that all scales of the ionosphere are impacted. Then, using several ionospheric observation tools is a relevant way to deeper study the ionosphere inhomogeneity and its dynamics.

Additional work would be needed to test the suggested parameters on more disturbed SAR acquisitions and a new approach would have to be defined to study the ionospheric activity in equatorial regions from a single SAR acquisition. Next BIOMASS and ROSE-L missions could be nice opportunities for data access.

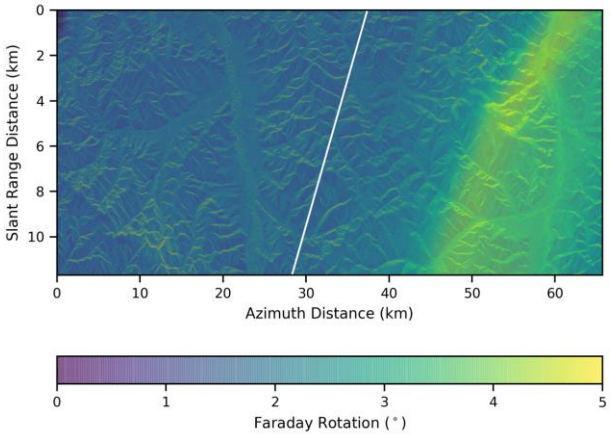

Figure 2-19 : FR map superimposed on total power image, VV polarization. The white line indicates the projected magnetic field.

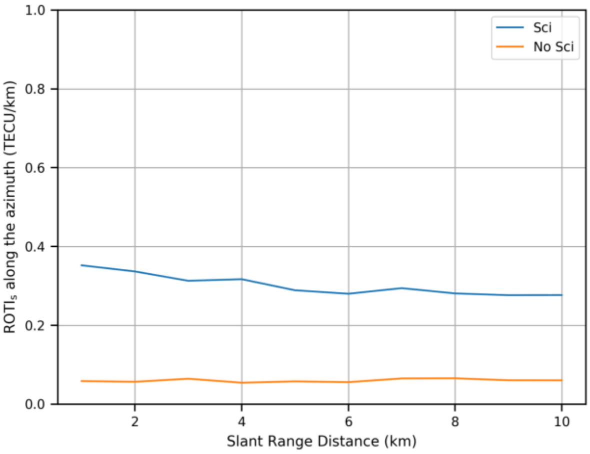

Figure 2-20 : $ROTI_s$ along the azimuth. In blue color (Sci = scintillation) during the high ionospheric activity and in orange (No Sci = no scintillation) with a calm ionosphere.