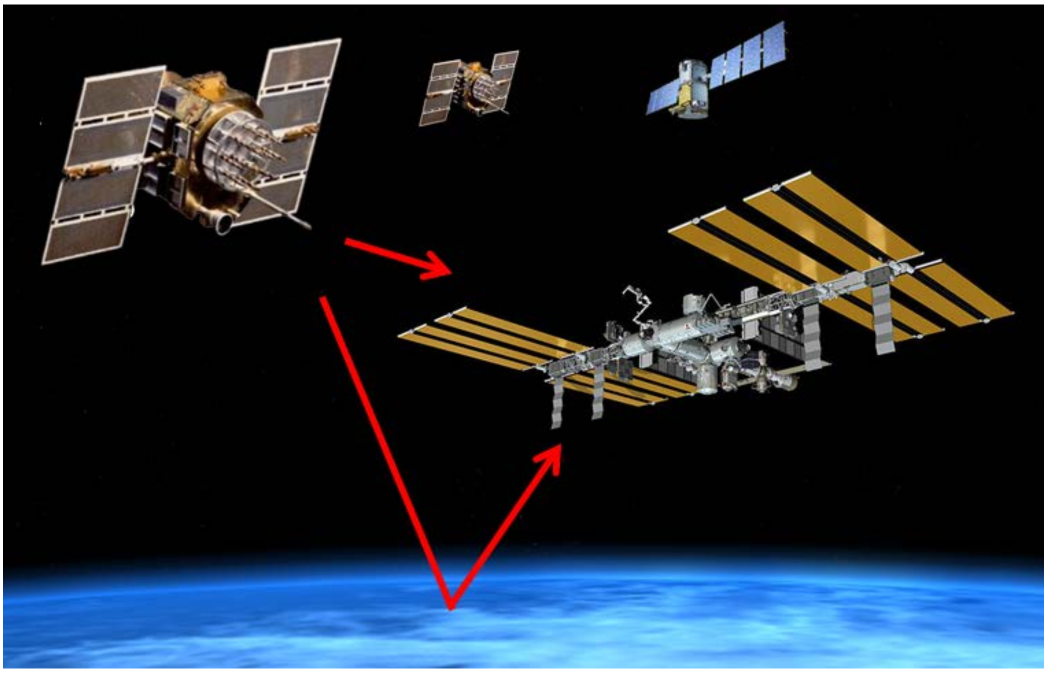
Executive Summary Report

ESA-AO1-7850/14-GARCA-ESR

GNSS-R – Assessment of Requirements and Consolidation of Retrieval Algorithms

GARCA



Report date: November 4 2016

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Acronyms and abbreviations

3PLE	3 Points in the Leading Edge (algorithm)
AGSP	Antenna Gain at the Specular Point
ATBD	Algorithm Theoretical Baseline Document
BeiDou	Chinese satellite navigation system
C/A	Coarse Acquisition and Civil Available GPS code
CYGNSS	CYclone Global Navigation Satellite System (U.S. GNSS-R mission)
DDM	Delay Doppler Map
ECMWF	European Centre for Medium-Range Weather Forecasts
ESA	European Space Agency
FDI	Fast Delivery Inversion (algorithm)
FOV	Field of View
GALILEO	European satellite navigation system
GARCA	GNSS-R Assessment of Requirements and Consolidation of the retrieval Algorithms
GEROS	GNSS rEflectometry, Radio Occultation and Scatterometry
GFZ	German Research Centre for Geosciences
GLONASS	Global'naya Navigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GNSS-R	GNSS Reflectometry
GPS	Global Positioning System
ID	Identifier
IEEC	Institute for Space Studies of Catalonia
iGNSS-R	interferometric GNSS-R
I/O	Input/Output
ISS	International Space Station
L1,L2, L5	GPS frequency band-1, -2, -5
LC	Ionospheric-free combination of GPS frequencies
LED	Leading Edge Derivative
M1	GEROS-SIM geometric and orbital module
M2	GEROS-SIM instrument-to-Level 1 module
M3	GEROS-SIM Level-1 to Level-2 group-delay altimetric products module
M4	GEROS-SIM Level-1 to Level-2 phase-delay altimetric products module
M5	GEROS-SIM Level-1 to Level-2 scatterometric products module
M6	GEROS-SIM systematic effects module
MSE	Mean Squared Error
PRN	Pseudo-Random Noise (modulation)
POD	Precise Orbit Determination
QZSS	Quasi-Zenith Satellite System (regional satellite navigation system)
RMS	Root Mean Square
RMSE	Root Mean Square Error
SBAS	Satellite-based augmentation systems
SNR	Signal to Noise Ratio
SP	Specular Point
SPIR	Software PARIS Interferometric Receiver
SSH	Sea Surface Height
TaG	Topography above Geoid
TDS	TechDemoSat (UK microsatellite)
Z-V	Zavorotny-Voronovich

1 Documents

1.1 Applicable documents

Ref.	Title	Number	Issue	Date
AD1	GEROS-ISS Mission Requirements	EOP-SM-2587/MK-mk	1	14/11/2013
AD2	GEROS-ISS System Requirements	TEC-ETP/2013.202/MMN	2.4	10/09/2015
AD3	Statement of Work GNSS-R – Assessment of Requirements and Consolidation of Retrieval Algorithms (GARCA). Appendix 1 to AO/1-7850/14/NL/MV	EOP-SM/2614/MK-mk	1	24/02/2014
AD4	Draft contract, Appendix 2 to AO/1-7850/14/NL/MV			
AD5	GARCA proposal AO/1-7850/14/NL/MV: Volume II: Technical Proposal	GARCA-TP	1.0	13/05/2014
AD6	GARCA proposal AO/1-7850/14/NL/MV: Volume III: Management and Implementation Proposal	GARCA-MIP	1.0	13/05/2015
AD7	Special conditions of Tender, Appendix 3 to AO/1-7850/14/NL/MV			
AD8	GARCA TN-1, Review of the state of the art and consolidation of the requirements	ESA-AO1-7850/14-GARCA-TN-1	1.1	19/03/2015
AD9	GARCA TN-2, Algorithm Theoretical Baseline Document (ATBD) for the GEROS-SIM internal algorithms	ESA-AO1-7850/14-GARCA-TN-2	1.1	31/08/2015
AD10	GARCA TN-3, Validation and Test Plan	ESA-AO1-7850/14-GARCA-TN-3	1.3	28/12/2015
AD11	GARCA TN-4, Data Acquisition and Analysis Report	ESA-AO1-7850/14-GARCA-TN-4	3.0	20/10/2016
AD12	GARCA TN-5, Impacts of SLA observations derived from GEROS-ISS into the current oceanographic system	ESA-AO1-7850/14-GARCA-TN-5	1.0	22/09/2016
AD13	GARCA TN-6, OSSE Synthetic observations	ESA-AO1-7850/14-GARCA-TN-6	1.0	17/05/2016

AD14	GAT Software User Manual	E-GEM-DME-GAT-SUM	84	18/11/2015
AD15	Products Definition for the GEROS-SIM	GARCA-DME-TEC-PRD01	149	29/10/2015

1.2 Reference Documents

Ref.	Document
SSW+15	Saynisch, J., M. Semmling, J. Wickert, and M. Thomas, Potential of space-borne GNSS reflectometry to constrain simulations of the ocean circulation, Ocean Dyn., vol. 65, no. 11, pp. 1441–1460, 2015.
LLL+13	Lee, T., Z. Li, S. Lowe, and C. Zuffada, Observing energetic eddies with GNSS reflections from the ISS, Communication to the ESA Science Advisory Group of the GEROS mission, 2013.
WCM+16	Wickert, J., E. Cardellach, M. Martin-Neira, J. Bandeiras, L. Bertino, O.B. Andersen, A. Camps, N. Catarino, B. Chapron, F. Fabra, N. Floury, G. Foti, C. Gommenginger, J. Hatton, P. Høeg, A. Jäggi, M. Kern, T. Lee, Z. Li, H. Park, N. Pierdicca, G. Ressler, A. Rius, J. Rosello, J. Saynisch, F. Soulat, C. K. Shum, M. Semmling, A. Sousa, J. Xie, and C. Zuffada, GEROS-ISS: GNSS REflectometry, Radio Occultation, and Scatterometry Onboard the International Space Station, IEEE Journal of selected topics in applied Earth observations and Remote Sensing, Volume: 9 Issue: 10, 1-30, doi: 10.1109/JSTARS.2016.2614428, 2016.
ZV00	Zavorotny, V. U. & Voronovich, A. G. Scattering of GPS Signals from the Ocean with Wind Remote Sensing Application. IEEE Transactions on Geosciences and Remote Sensing, 2000, 38, 951-964

2 Introduction and Background

This document provides a short summary on the background, goals, the course and brief overview on selected results of the international GARCA project (GNSS-Reflectometry – Assessment of Requirements and Consolidation of Retrieval Algorithms), which was performed between 2014 and 2016 by an international consortium of research institutions. GARCA is a supporting activity for the geoscience GEROS-ISS mission (GNSS REflectometry, Radio Occultation and Scatterometry onboard the International Space Station).

2.1 The GEROS-ISS mission

GEROS-ISS is a scientific experiment, successfully proposed to the European Space Agency (ESA) in 2011. The experiment as the name indicates will be conducted on the ISS. The main focus of GEROS-ISS (GEROS hereafter) is the dedicated use of signals from the currently available Global Navigation Satellite Systems (GNSS) in L-Band for remote sensing of the Earth with a focus to study climate change. Prime mission objectives are the determination of the altimetric sea surface height of the oceans and of the ocean surface mean square slope (MSS), which is related to sea roughness and wind speed. These geophysical parameters are derived using reflected GNSS signals (GNSS reflectometry, GNSS-R). Secondary mission goals are atmosphere/ionosphere sounding using refracted GNSS signals (Radio Occultation, GNSS-RO) and remote sensing of land surfaces using GNSS-R [WCM+16].

2.2 The GARCA project

GARCA is a scientific study, funded by ESA. GARCA is part of the Phase A activities of the GEROS mission and supports the assessment and consolidation of scientific requirements and the consolidation of retrieval algorithms for a spaceborne GNSS-R experiment, focusing in particular on the GEROS concept and its main data products (sea surface height and ocean surface roughness). The ITT AO/1-7850/14/NL/MV (Invitation To Tender) for GARCA was released March 21, 2014. The study is performed by an European consortium under main contract between ESA and GFZ (German Research Centre for Geosciences). The GARCA team consists of seven partners from six countries and is supported by 12 external experts from nine countries (see Sect. 2.1). The external experts are involved in the GARCA study as beta-testers of the developments and also contribute to the sustainable formation of an interdisciplinary GEROS user community.

2.3 GARCA project goals

The main goals of the GARCA project are:

(1) To develop a tool capable to simulate GNSS-R data products for various instrument implementations using state-of-the-art techniques, including GEROS phase-A candidates, up to Level-1 observables and Level-2 geophysical data products, which will be freely and easily accessible to the interdisciplinary scientific GEROS community.

(2) To study the compliance of different GEROS implementations with respect to the Mission Requirements, and study the optimization of its geophysical data products.

(3) To study the impact of the GEROS-ISS data products on the current Global Ocean observation system and its synergies with existing satellite missions.

(4) To foster a broad GEROS-ISS scientific community, as a way to promote and advertise the concept and its potential, and as a way to promote feed-back from possible future interdisciplinary data users with different levels of expertise and interests.

2.4 GARCA project partners and external experts

2.4.1 Partners

Company	Prime/Contractor	Address and contact details
GFZ	Prime	Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ) Telegrafenberg D-14473 Potsdam, Germany
CLS	Subcontractor	Collecte Localisation Satellites Space Oceanography Division 8-10 rue Hermès 31520 Ramonville St-Agne, France
DEIMOS	Subcontractor	DEIMOS Engenharia Av. D. Joao II, Lt 1.17.01, 10 1998-023 Lisboa, Portugal
IEEC	Subcontractor	Institut de Ciencies de l'Espai (IEEC) Campus UPC Nord, Ed. Nexus H201, C/ Gran Capita 2-4, 08034 Barcelona, Spain.
Ifremer	Subcontractor	Institute français de recherche pour l'exploitation de la mer Laboratoire d'Océanographie Spatiale (Bât. 815) Urbain Le Verrier

		IFREMER - Centre de Brest Pointe du diable, BP 70 29280 Plouzane, France
NERSC	Subcontractor	Nansen Environmental and Remote Sensing Centre Thormøhlensgate 47 5006 Bergen, Norway
NERC (NOC)	Subcontractor	National Oceanography Centre University of Southampton Waterfront Campus European Way Southampton SO14 3ZH United Kingdom

2.4.2 External experts

Prof. Ole Andersen

Danish Technical University

Oceanography expert

Member of the GEROS-ISS Science Advisory Group

Dr. Maria Paola Clarizia

University of Michigan, U.S.

CYGNSS Team member, GNSS Reflectometry specialist

Dr. Thomas Gruber

Technical University Munich, Germany

Geodesy expert (satellite orbits, gravity field, satellite altimetry)

Member of the proposing GEROS-ISS team

Prof. Rüdiger Haas

Chalmers University, Gothenburg, Sweden

Geodesy expert (VLBI, GNSS, Reflectometry)

Prof. Per Høeg

Danish Technical University, Copenhagen, Denmark

Space Sciences expert, GNSS Radio Occultation and Reflectometry

Key member of the proposing GEROS-ISS team

Dr. Thomas Hobiger,

National Institute of Communication and Information Technology, Japan

Geodesy and GNSS expert

Prof. Adrian Jäggi, University Bern, Switzerland

Director Astronomical Institute

GNSS expert, Space Geodesy, Precise Orbit Determination, Gravity field

Member of the GEROS-ISS Science Advisory Group

Prof. Nazzareno Pierdicca, University La Sapienza, Rome, Italy

Expert Microwave Remote Sensing, GNSS Reflectometry from land surfaces

Member of the GEROS-ISS Science Advisory Group

Prof. Chris Ruf, University of Michigan, U.S.

Director, Space Physics Research Laboratory

PI NASA Cyclone Global Navigation Satellite System Mission (CYGNSS)

Prof. C.K. Shum, Ohio State University, Columbus, U.S.

Professor of Geodetic Science, Oceanography, GNSS reflectometry

Key member of the proposing GEROS-ISS team

Supporting Member of the GEROS-ISS Science Advisory Group

Prof. Maik Thomas, GFZ Potsdam, Germany

Professor Earth System Research, Ocean modelling

Dr. Cinzia Zuffada, Jet Propulsion Laboratory, NASA, U.S.

Chief Scientist, GNSS Reflectometry expert

Supporting Member of the GEROS-ISS Science Advisory Group

2.5 Calendar of GARCA meetings and teleconferences

Kick-off Teleconference GARCA-Team, December 11, 2014

Requirement Review and Kick-off meeting, GFZ, Potsdam, February 6, 2015

Preliminary Design Review, ESTEC, Noordwijk, June 9, 2015

Test Acceptance Review, Webex, October 30, 2015

Splintermeeting, Errors measurements for OSSE, Webex, November 17, 2015

Splintermeeting, Initial results OSSE, Webex, February 11, 2016

Splintermeeting, OSSE results and GEROS-SIM delivery and test, April 11, 2016

Final Review, ESTEC, Noordwijk, June 9, 2016

Demonstration GEROS-SIM, Webex, June 30, 2016

2.6 List of Documents, provided by the GARCA project team

Technical notes, required according to the Statement-of-work [AD3]

Technical Note-1: ESA-AO1-7850/14-GARCA-TN-1
Review of the state-of-the-art and consolidation of the requirements
March 19, 2015, pp 62

Technical Note-2: ESA-AO1-7850/14-GARCA-TN-2
Algorithm Theoretical Baseline Document (ATBD) for the GEROS-SIM internal algorithms
August 21, 2015, pp 106

Technical Note-3: ESA-AO1-7850/14-GARCA-TN-3
Validation and Test Plan
December 28, 2015, pp 39

Technical Note-4: ESA-AO1-7850/14-GARCA-TN-4
Data Acquisition and Analysis Report
October 20, 2016, pp 174

Manuals and documentation of the GEROS-SIMulator

The manuals of the GEROS-SIM software modules and of the GEROS-SIM web are available via the GARCA FTP-Server:
ftp://ftp.gfz-potsdam.de/pub/home/kg/incoming/GARCA/SIMULATOR/DOCUMENTATION

Two technical notes were provided in addition to the required documents in [AD3]:

Technical Note-5: ESA-AO1-7850/14-GARCA-TN-5

Impacts of SLA observations derived from GEROS-ISS into the current oceanographic system, September 22, 2016, pp 35

Technical Note-6: ESA-AO1-7850/14-GARCA-TN-6
OSSE Synthetic observations
May 17, 2016, pp 46

2.7 Access to general project information

The GARCA related documents, including the proposal and the deliverables as well as the documentation of the project meetings and teleconferences are available via the GARCA FTP-server at GFZ Potsdam: ftp://ftp.gfz-potsdam.de/pub/home/kg/incoming/GARCA

A brief online description of the project can be accessed via:

https://www.gfz-potsdam.de/en/section/space-geodetic-techniques/projects/garca

It is planned to make the project deliverables (Technical Notes) available to the international scientific-technical community through this webpage.

3 GEROS-SIMulator and provided software modules

3.1 Overview on GEROS-SIM

One of the key parts of the GARCA study was to implement an end-to-end simulator (GEROS-SIM) covering from detailed instrumental aspects to higher level data products useful to assess the GEROS oceanographic impact in the current or near-future Earth Observation System. It includes the simulation of GNSS and ISS orbital propagation and the calculation of corresponding specular reflection positions over the Earth, GNSS-R observables (Product Level 1, L1), the suite of extraction algorithms to generate geophysical products (Product Level 2, L2), their time- and geo-location, and noise and systematic effects. The GEROS-SIM consists of a core of software modules which produce the GNSS-R observables from detailed geometric and instrumental parameters, plus a series of other modules with well-established Input/Output (I/O) interfaces to generate all the other steps. The overview of each modules and their I/O are sketched in Figure 1. Each of the modules runs independently of the others if the input data are provided in the correct data format, and the simulation can be executed by serial steps of each module. The submitted GEROS-SIM has been provided with implementation of proper data format input/output, i.e., the M1 outputs are properly formatted for M2 inputs; M2 outputs are properly formatted for M3/M5 output, etc. The advantage of this approach is, that the different L1-to-L2 modules can be used as retrieval algorithms also for real experimental data, if these are provided in the right format. Consequently the modules, developed within the GARCA project, provide already the initial version of the potential GEROS processor for the generation of the geophysical Level-1 and -2 data products to serve the primary mission objectives altimetry (code and phase) and scatterometry.

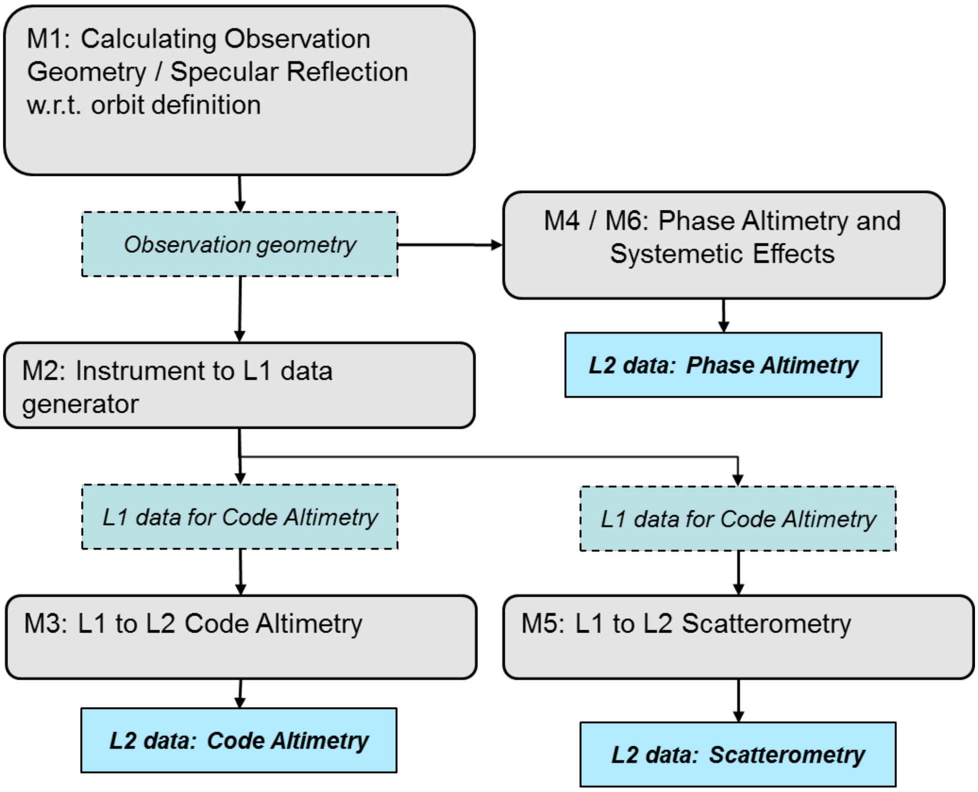

Figure 1: Schematic overview of the GEROS-SIM, consisting of 6 software modules.

3.2 List of provided GEROS-SIM software modules

The status of provided GEROS-SIM software modules is presented in Table.1. The main platform for installation and execution is Linux (64 bit), and some of the modules are provided both for Windows and Linux, or platform free. For all the modules, the installation guide and user manuals are provided as well as installation files. All files are available via the GARCA ftp site (see sec. 2.7).

Module	Platform	Manuals
M1	Linux	V
M2	Linux/Windows with Matlab Runtime	V
M3/M5PLE	Linux/Window (python files)	V
M4/M6	Windows/Linux with Matlab Runtime	V

M5	Linux/Windows with installed Matlab (Matlab p files)	V

Table 1: List of provided GEROS-SIM software modules with provided manuals (V).

M1 is the orbit/specular reflection module. With input epoch time, M1 calculates the state (position and velocity) of ISS (receiver) and GNSS satellites (transmitter) with orbital propagation. M1 also finds specular reflection points over the Earth surface according to the position/velocity of ISS and GNSS satellites.

M2 is the instrument to L1 data module. M2 finally generates the L1 data, i.e., GNSS-R observable DDM/Waveforms with auxiliary data. M2 receives as inputs the output of M1 observation geometry. It has also instrument related inputs, e.g., antenna beam pointing, RF bandwidth, noise figure, etc. The geophysical conditions of the Field Of View (FOV), e.g. see height, wind speed, ionospheric conditions are included in the M2.

M3/M5/M4/M6 are the modules, which implement the geophysical parameter retrieval to generate the geophysical Level 2 (L2) data products. M3 includes code altimetry algorithms, and M5 scatterometry algorithms. M4/M6 include the phase altimetry and systematic effects. Validation and assessment of each module are described in the later part of this document and in much detail in the GARCA TN-4 [AD11].

Additionally, the M2 module is tailored to the web service form, and provided to the public as web version, GEROS-SIM web (http://www.tsc.upc.edu/rslab/gerrossim), see Fig. 2/3.

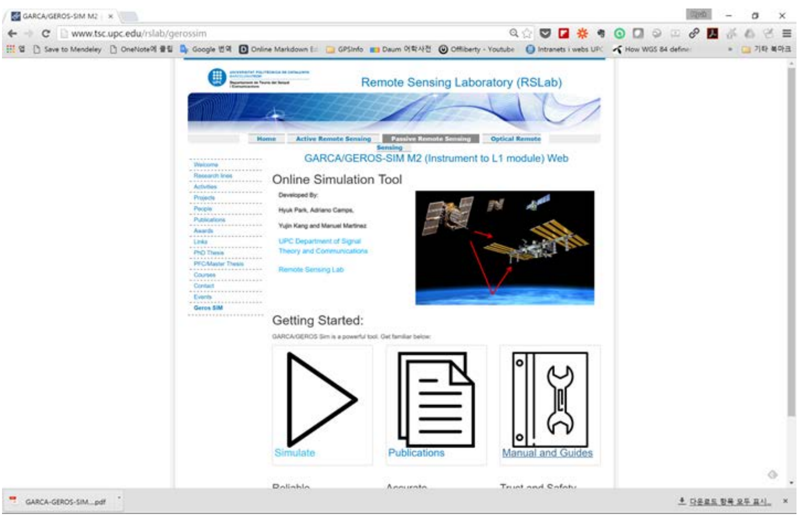

Figure 2: Screenshot of the main page of the GEROS-SIM Web.

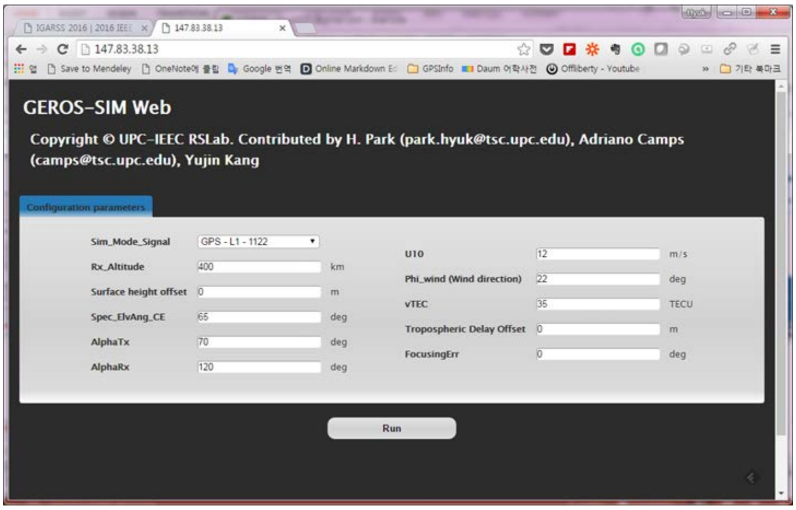

Figure 3: Screenshot of the GEROS-SIM Web interface for simulation parameter input.

3.3 Functionalities of GEROS-SIM

The provided GEROS-SIM allows an end-to-end simulation of the planned GEROS measurements, including orbital propagation and geometry (M1), instrument effect (M2/M6), and the contribution of geophysical parameters (M2), and uncertainties. Therefore, GEROS-SIM has various functionality to simulation the effect of wide range of input conditions. Corresponding to the variation of input condition, the L1 data (DDMs and auxiliary data) are generated, and therefore it is possible to see the variation of GNSS-R observable DDMs with respect of the input parameters. Also the retrieved geophysical parameters by M3, M4, M5 can be assessed, based on various L1 data. Figures 2, 3 and 4 show some examples of GEROS-SIM functionality demonstration. More detailed description of functionality of each module of GEROS-SIM is described in the provided manuals of the GEROS-SIM modules.

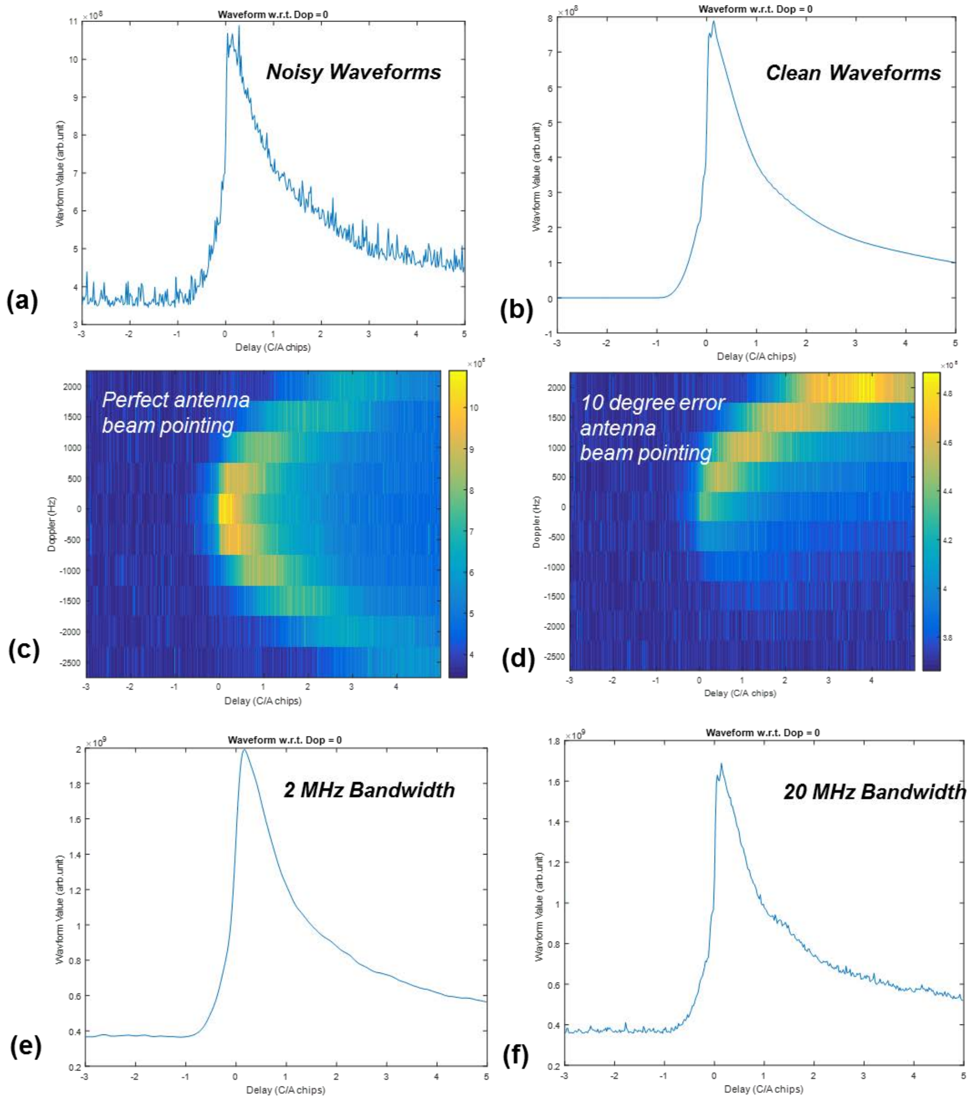

Figure 4: Examples of GEROS-SIM M2 simulation illustrating the functionality of (a), (b) noisy and clean waveforms; (c), (d) beam pointing errors; and (e) (f) bandwidths.

3.4 Documentation of GEROS-SIM

The manuals of the GEROS-SIM software modules and of the GEROS-SIM web are available via the GARCA FTP-Server:
ftp://ftp.gfz-potsdam.de/pub/home/kg/incoming/GARCA/SIMULATOR/DOCUMENTATION

4 Validation of the GEROS-SIMulator

4.1 Module M1: Orbit and Specular Reflection

The purpose of the GAT (M1) validation is to test how accurate is the model of the involved satellite orbits, the temporal evolution of the geo-location of the reflection points and resulting multi-static geometries using the different configurations supported:

- GNSS constellations: GPS, GALILEO, GLONASS, BeiDou, QZSS and SBAS orbits.
- Receiver Platforms: Ground-based, Airborne and Space borne.
- Inclusion of uncertainties in the known trajectories either transmitters or receiver
- Signal Geometry: responsible direct and reflectometry computations sets the visibility constrains by setting incidence angle at Earth surface and as allowed by the instruments FoV.
- Allow the usage of Digital Elevation Model with mean sea height values or just using the Earth Ellipsoid.

In this way the validation of M1 is mainly functional, in the sense that it demonstrates the capabilities of the simulator to cover not only the GEROS scenario but also its applicability to other missions and scenarios.

4.2 Module M2: Instrument to Level-1 data

The M2 algorithm (Instrument 2 L1 data) has been validated using real spaceborne measurements. The M2 module generates the L1 data (DDM/Waveforms, and auxiliary), with the various input. Therefore, according to the variation of input parameters, the produced L1 data should vary (Verification) and the aspect of variation should be met with the real data (Validation). To verify the variations three main input parameters are selected: elevation angle, wind speed, antenna gain. And, to validate the algorithm, 57 set of TDS-1 DDMs are collected with variation of those three parameters.

The results showed the good agreements between M2 simulated DDM/Waveforms and those of TDS-1. For the normalized waveform comparisons, the MSE in percentage is 12.76 % in the range of tau = [0 ~ 8] C/A chips. For the DDM peak comparison test, MSE in percentage is 16 %.

The simulated DDM peaks decrease with high wind speed, similarly to the TDS-1 data. For the elevation angle, the cases of higher elevation angle show the higher DDM peaks in both cases. For the antenna gain, the cases of higher gain show the higher DDM peaks. The trend of variation and the level of values are quantitatively/qualitatively satisfactory in the validation test, which are acceptable for next retrieval algorithm modules.

4.3 Module M3: Level-1 to Level-2 altimetry products

The M3 algorithm has been validated using 24 clean waveforms generated by M2, in GEROS-ISS scenario, L1 and L5 frequency bands, and 3 different elevation angles. For validation purposes, the reference model waveform and the data waveform are the same. M3 does not present error in these circumstances.

For completeness, the absolute range of the specular point, assumed to be given by the peak of the LED, has also been used to estimate the SSH. The direct use of this observable (instead of the differential approach of M3) does introduce biases in the resulting SSH, biases between 0.77 to 3.03 meters (elevation, roughness and GNSS source and frequency dependent). Nevertheless, this is not the approach taken in GEROS-SIM M3.

The main assumptions behind the M3 LED are:

1) We are able to model the shape of the waveform in a sufficiently realistic way.

2) The a-priori knowledge of the scenario, sea surface level, etc., is accurate enough so the pre-fit residual delay error between data and model, $\Delta\rho$, is small enough to assume they can be mapped to SSH as $\Delta SSH=\Delta\rho/(2\ \sin(elevation))$.

4.4 Module 4 and 6: Phase delay altimetry and Systematic Effects

The simulation of phase altimetry (M4) and related systematic effects (M6) is demonstrated studying a GEROS-ISS test event. Phase altimetric realizations (topography above geoid – TaG) are provided comparing a reference scenario (without systematic effects) and a combined scenario (including all significant systematic effects). For the combined scenario the maximum deviation (max. dev.) from the ocean topography model (TaG) is below the 0.5 m threshold. The test event covers a range of the elevation angle between 7° and 30° at the specular point that is suitable for phase altimetry. A linear combination (LC) based realization, to mitigate the ionospheric effect, and an SNR of at least 30 dB are required. The most critical scenarios are the wet troposphere (max. dev. 18 cm) and radial perturbed receiver orbit (max. dev. 24 cm).

Main assumptions behind M4 and M6:

1) sufficient Master-Slave tracking is assumed, i.e. that the code delay τ and the Doppler freq. f of the specular reflected signal are tracked sufficiently so that residuals ($\delta\tau$ and δf) are within the support of the Woodward Ambiguity Function $\chi(\delta\tau, \delta f)$, as defined by [ZV00], and Slave correlation amplitudes (I,Q) of the tracked reflected signal are above noise level.
2) a reference scenario with 30dB SNR is possible, i.e. reflected signal coherence in the sense of specular reflection dominating over diffuse reflection is assumed
3) refraction models (based on ECMWF, IRI2007) apply for correction and a residual bias for the specific relative uncertainty persists
4) an initial track calibration, to overcome phase ambiguity, at lowest elevation is possible

4.5 Module 5 : Level-1 to Level-2 Scatterometry

For scatterometry, GEROS-SIM M5 successfully estimated Signal-to-Noise from M2 simulated delay-Doppler Maps for both the TDS-1 and the GEROS-ISS configurations. In the TDS-1 configuration, the GEROS-SIM SNR correctly reproduced the dependence of SNR on incidence angle, antenna gain at the specular point (AGSP) and wind speed as observed with real TDS-1 data. The Level 2 wind speed obtained with the M5 Fast-Delivery Inversion (FDI) algorithm in the GEROS-SIM TDS-1 setup produced similar performance to that observed with

TDS-1 data I.e. near-zero bias and RMSE around 4.5 m/s. For the GEROS-ISS setup, the FDI winds reported slightly larger bias (~1m/s) and RMSE (4.7 m/s), most likely because of the slightly different curvature of the SNR to wind speed relationship when observed from the lower altitude of the GEROS-ISS platform (current FDI optimized to TDS-1 scenario). This could be corrected with empirical adjustments.

Moreover, the IEEC complementary (not in baseline) algorithm, 3PLE has been validated under 36 scenarios, all corresponding to GEROS-ISS. For validation purposes both synthetic data and central reference model were the same, only the two remaining reference models were modified. The conclusions are that 1) exponential fits must be used to build the 3PLE functionalities; 2) the scatterometric delay observable has little informational content (formal uncertainty unacceptably high, despite providing an unbiased solution); and 3) better formal precisions are obtained when the 3 points (3 wind conditions) are relatively close to the solution (approximately at +- 25% of the actual wind speed). An iterative approach could be used.

There are no specific assumptions behind the M5-NOC algorithm which is based on an empirical relationship derived from real TDS-1 data for winds between 3-20 m/s. M5 assumes the availability of a delay-Doppler map and of the value of the antenna gain at the specular point (AGSP). The signal is assumed to correspond to reflected signals from the rough ocean surface obtained in rain-free conditions.

The assumptions behind M5-3PLE are those of the M3 module.

5 Assessment tests for GEROS-SIM

5.1 Test scenarios to study airborne performance in combination with campaign data

10 seconds of data from two airborne GEROS-ISS experimental campaigns, conducted in May and December 2015 using IEEC's SPIR instrument have been inverted using the M3 algorithm. The data were processed using the iGNSS-R technique and corresponded to 3 and 2 different and simultaneously visible GPS sources at different elevation angles for May and December flights respectively. In addition to using the GEROS-SIM M2 synthetic data as reference model for the inversion, a second inversion has been done using the M3 algorithm but an independent waveform model as reference ('wavpy' model). The 10 seconds time evolution or topographic profile obtained for a given PRN is independent of the reference model used for the M3 algorithm and even for a model-free algorithm (absolute LED algorithm). The biases are different, but mostly cancel when the trajectory and the atmosphere are properly corrected (only done in Dec'15 flight for differential-'wavpy' and absolute-LED retrievals). Finally, the same 10 seconds of Dec'15 flight have been simulated with GEROS-SIM, including speckle and thermal noise. The resulting SSH error is unbiased and present dispersion half of the dispersion found in actual data. This could be due a combination of effects, such as under-estimation of noise in the airborne scenario, and/or data with more non-modelled noise terms (e.g. residual interference tones or residual trajectory errors).

5.2 Test scenarios to assess GEROS-ISS performance and elaborate a Level-2 product error budget for mesoscale altimetry

The altimetric retrievals are based on delay or range measurements. Different sources of delay-error can affect the measurement of the actual geometric range. Given that they are mostly fully correlated, the only way to retrieve unbiased SSH solutions is to correct for such errors using external information. In the M3 algorithm this is done through a proper model of a reference waveform. Any mismodelling of the reference is absorbed in more or less degree as an altimetric error. The impact of a suit of residual effects (not properly corrected or modelled) in the SSH solution have been assessed.

The effect which limits the most the precision is the speckle, with standard deviation of the order of 0.2 m (1 second observations) at L1, 0.1 m at L5, and up to 0.5 m (1 second observations) using the ionospheric-free combination (LC). An unexpected bias induced by speckle was also detected, of mean value around 2 cm at LC (1000 observations included in the statistics). According to M1 synthetic data and M3 algorithm, the speckle-induced precision degradation depends on the wind speed conditions: degradation of 37% in L1 and LC precision when wind conditions change from 10 m/s to 20 m/s, and 20% at L5. On the other side, mismodelling the wind speed does not alter the performance of the M3 algorithm.

The atmospheric effects also induce significant biases that must be properly corrected. The ionospheric-free combination has been shown effective for removal of this term when tested without speckle noise. Speckled tests showed the precision cost associated to the ionospheric-free combination approach. An alternative way has been assessed, to use the geometry-free combination over long data arch to estimate the ionospheric correction to be applied to L1 data. This approach improves the precision of the LC approach by a factor >2, yielding ~0.2 m precision in 1 second observations and ~0.1 m for 100 km along-track integrated solutions.

A-priori values of the SSH better than 5 meter are needed to guarantee errors below 7 cm. An iteration solution or the use of tide models would cancel this error term. Errors of the radial component of the POD map directly as errors in the SSH. Tests with combined effects show that the speckle is the main driver of the performance, whilst biases due to miscorrected delays simply sum arithmetically at L1 (not at LC).

Besides the LED observable, the MAX and HALF ones have also been tested. The performance of them all is nearly identical when thermal and speckle noise are off, while for speckled noise the LED shows significantly better results.

6 Fullfillment of the mission requirements for the main mission goal

The error budget for the code-delay altimetry is mostly driven by the speckle and thermal noise induced dispersion. This precision figure can be improved by incoherent averaging of the solutions. To constrain the spatial resolution within the Mission Requirements [AD1], no more than 14 1-second measurements can be integrated:

Integration time:	Along-track resolution:	Across-track resolution:	Precision figure:
L1 with 'clean' ionospheric correction			
1 second	7.5 km	4 km	19.1 cm
14 seconds	100 km	4 km	5.1 cm
L5 with 'clean' ionospheric correction			
1 second	7.5 km	4 km	11.3 cm
14 seconds	100 km	4 km	3.0 cm
LC			
1 second	7.5 km	4 km	36.2 cm
14 seconds	100 km	4 km	9.7 cm
L1 with 500-km geometry-free ionospheric correction			
1 second	7.5 km	4 km	16.5 cm
14 seconds	100 km	4 km	4.4 cm

Table 2: Fulfilment of the mission requirement by the group-delay altimetry technique.

The figures obtained for group-delay altimetry in this analysis (Table 2) are compliant with the objectives of the mission (50 cm at 100 km along-track resolution, 20 cm target goal). Note that it is derived from M2-synthetic data and M3 inversion approach, under the nominal conditions of this study and assuming thermal noise correlated along the delay axis as the WAF function. Note also that the along-lag properties of the noise have been shown to determine in large measure the final altimetric precision, reason for which further detailed investigations on this topic are recommended. Multi-Doppler looks or other techniques to improve the altimetric performance have not been considered.

Regarding the phase-delay altimetry, the precision figures are compliant with the requirements too, resulting in 11 cm at 1 second integration (see Table 3). This value can also be further reduced by integration of the solutions, at the cost of worsening the along-track resolution. Given that 11 cm-level is compliant with the precision requirements, there is no need of longer integration:

Integration time:	**Along-track resolution:**	**Across-track resolution:**	**Precision figure:**
1 second	7.5 km	0.5 km	11 cm

Table 3: Fulfilment of the mission requirements by the phase-delay altimetry technique.

7 Observation System Simulation experiments

The conduction of specific Observation System Simulation Experiments (OSSE) was offered by the project team in addition to the required work, described in the SoW [AD3]. The main goal of this work is to study the impact of the potential GEROS-ISS data products on the current Global ocean observation system and its synergies with existing satellite missions. Two additional OSSE were performed by the science teams of the external experts from GFZ and JPL [LLL+13, SSW+15].

These experiments indicated in part significant impact of the potential GEROS measurements to the current oceanographic modelling and forecast systems on top of the currently assimilated radar altimetry data. We briefly refer to the results of the GARCA team, described in detail in [AD12], the investigation of the GEROS capability for the observation of highly energetic mesoscale ocean currents (eddies) with changes of <20 cm sea surface within regions of <100 km. Knowledge on these eddies is important for the characterisation of nutrients and/or pollutants with many societal and scientific applications. Presently the tracking and forecasting of eddies is limited due to the capability of the current ocean altimetry missions.

The GARCA team investigated the influence of simulated observation data from three different simulated GEROS constellations with different but realistic Field of View (FoV) configurations against the present performance of state-of-the-art eddy resolving ocean data assimilation system. GNSS-R data are expected to bring complementary observation data especially in the case of severe storms due to the high transmissivity of the GNSS L-band signals in the presence of rain. A regional HYCOM model of the South China Sea (SCS) was considered, equipped with an Ensemble optimal interpolation assimilation system for traditional along-track altimeter data and SST (Sea Surface Temperature). As period of interest July 2014 was selected, during which the SCS has been hit by the typhoon Ramasun. The investigations are described in detail in [AD12, AD13]. The simulated GEROS data were assimilated in addition to the "present day" observing system, together with their specified uncertainty properties including realistic atmospheric/ionospheric propagation effects. A "truth" run was generated by assimilation of (real) traditional altimeter and SST data. ´Then its initial conditions are perturbed by a shift of the initial date tag and two runs are integrated without GEROS (standard observing system) and with GEROS data as would have been obtained from three observing scenarios: GEROS with realistic Field of Views 1 and 2, and two scenarios for the GEROS payload aboard a potential FreeFlyer separately for FOV1 and FOV2 (not shown here, see [AD12]). The results in Fig. 5 (GEROS run) indicate that the GEROS data can improve the rendering of mesoscale features in the SCS over the satellite constellation that was active in July 2014. Statistics over the whole month of July 2014 indicate that GEROS can reduce the RMS errors of sea level anomalies by 13%, which is a significant improvement in an operational ocean forecasting system, whereas the GEROS-FoV1 and FoV2 (FreeFlyer) achieve even greater reductions by 20% and 29%, respectively.

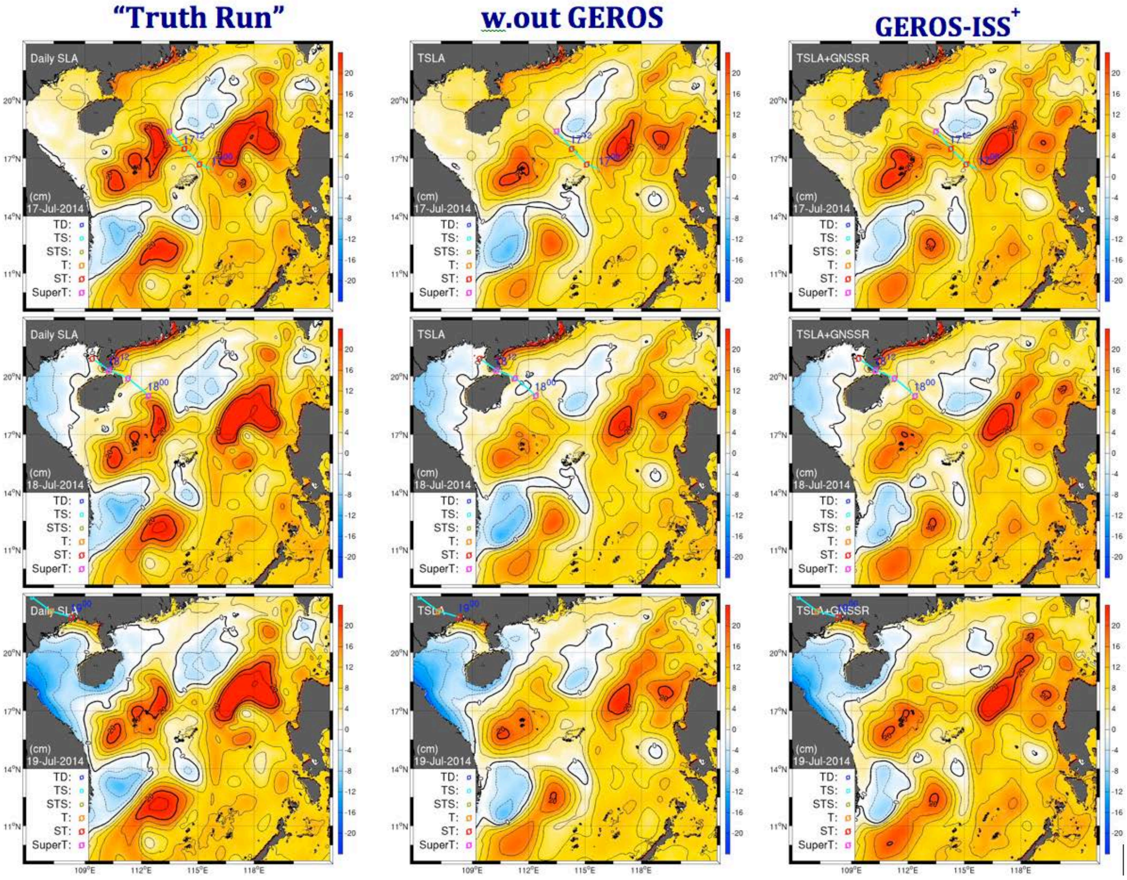

Figure 5: Daily SLA maps of "Truth" (left), standard (middle), and GEROS-ISS runs (right) from 16 to 19 July, 2014 (unit: cm). The contour interval is 4 cm, and the green line indicates the Ramasun typhoon track during the 24 h of the daily average map. The symbols of "TD, TS, STS, T, ST, SUPER T" are related with the Tropical Cyclone Classification considering the maximum wind near the centre (km/h): TD: Tropical Depression (<63); TS: Tropical Storm (63–87); STS: Severe Tropical Storm (88–117); T: Typhoon (118–149); ST: Severe Typhoon (150–184); SuperT: Super Typhoon (≥185) from [ADX, RDX].