GNSS Reflectometry onboard the International Space Station with GEROS-ISS: Review of activities and current status

ESA call 2011: Climate change related research aboard ISS

25 letters of intent submitted, 237 science team members

Unique cooperation between 3 ESA directorates: HSO, EOP, TEC

GEROS-ISS, combined GNSS Reflectometry/Occultation mission, only mission selected for further studies

Proposing Team from: Germany, Spain, U.S., Denmark, Switzerland, Sweden
Advantages of GNSS vs. Radar Altimetry

* Signals are „free of charge“
* Many reflection points
  2018: ~100 GNSS satellites, high spatial resolution (surface mapping)
* High transmissivity at high rain rates (100 mm/hour and more)
* Low-cost sensors aboard small satellites feasible (make future constellations feasible, sustainability of measurements)

2004 sumatra tsunami detected by JASON and simulated GNSS-R (GPS)
Mission objectives of GEROS (1/2)

**Primary:**

Measure and map altimetric sea surface height of the ocean using reflected GNSS signals to allow methodology demonstration, establishment of error budget and resolutions and comparison/synergy with results of satellite based nadir-pointing altimeters. This includes Precise Orbit Determination of the GEROS payload.

**Secondary:**

To retrieve scalar ocean surface mean square slope (MSS), which is related to sea roughness, wind speed, with a GNSS spaceborne receiver to allow methodology testing, establishment of error budget and resolutions. In addition, 2D MSS (directional MSS, related to wind direction) would be desirable.
One focus: Mesoscale Ocean Currents (Eddies)
Mission objectives of GEROS (2/2)

**Additional:**

To assess the potential of GNSS scatterometry for land applications and in particular to develop products such as soil moisture, vegetation biomass, and mid-latitudes snow/ice properties and to further explore the potential of GNSS radio occultation data (vertical profiles of atmospheric bending angle, refractivity, temperature, pressure, humidity and electron density), particularly in the Tropics, to detect changes in atmospheric temperature and climate relevant parameters (e.g., tropopause height) and to provide additional information for the analysis of the reflectometry data from GEROS (Several new aspects: Precipitation, low inclination, Multi-GNSS)
Potential GEROS data products

**Sea Surface Height**
L1: Time collocated waveforms of the reflected signals  
L2: Sea surface height

**Mean Square Slope**
L1: Waveforms or Doppler Delay Maps of the reflected signal  
L2: Surface roughness, wind speed

**Precise Orbit Determination**
L1: 2F GNSS data for determination of GNSS-R phase center  
L2: Phase center GNSS-R, inter-constellation bias data

**Scatterometry over land**
L1: Waveforms or Doppler Delay Maps of the reflected signals (L1)

**GNSS Radio Occultation**
L1: 2F Excess phases, bending angles
Some numbers: Mission requirements

- **SSH** with precision of 50 cm (goal 20 cm)
- SSH scale 10 km across track, 100 km along track
- Mean Square Slope with wind accuracy 10% or 2 m/s, whichever is greater
- Temporal revisit: 4 days or less
- **POD**: 5 cm or better
- Controllable payload
- At least **L1 and L5 from GPS and Galileo**, preferably also GLONASS, Beidou and others (e.g., QZSS)
- Left hand circular minimum, preferably in addition right hand circular
- No requirements regarding latency
GEROS-ISS: Planned mission specification

Orbit altitude and inclination: 375-435 km, 51,6°

Orbit period: ~92 min

Columbus external payload facility (box ~117x86x155 cm³), upper balcony, power <500 W, downlink <1 Mbps

Dragon C3-1 launcher (SpaceX, from KSC)

Launch (late) 2021

Mission duration at least 1 year, possible extension up to 5 years
GEROS-ISS: Status

Interdisciplinary Science Advisory Group (SAG) active since 2013
J. Wickert (Chair), E. Cardellach (Co-Chair), O. Andersen,
B. Chapron, C. Gommenginger, N. Pierdicca, A. Jäggi, M. Martin-Neira, C.K. Shum, C. Zuffada

Initial Mission and system requirements in 2013

Two industrial Phase A study finished, ADS (Airbus Defense and Space, Madrid, Spain), TAS (Thales Alenia Space, Rome, Italy).

Science Study GARCA (GNSS-R – Assessment of Requirements and Consolidation of Retrieval Algorithms, Final Nov 8, 2016)

Flight campaigns May/Dec 2015 (Paris IT, Proof of, Atimetry)

Link to other missions/projects (CYGNSS, TDS-1, E-GEM)

Three OSSE ocean observations (JPL, GFZ, NERSC)

Currently cost reduction exercise (Manuel) and EE-9 proposal with strong GEROS heritage in process of submission (G-TERN)
GEROS-ISS: Programmatic Context

GEROS-ISS phase A, Science studies GARCA and SAG are currently the only funded activities by ESA.

Implementation of subsequent steps is contingent on the following:

- Successful outcome of phase A, demonstrating feasibility within a realistic budget / resource envelope.
- Budget for phase B/C/D development activities – TBD via GSTP programme.
- ISS resources (upmass, installation, basic operation) – via ISS exploitation programme.
Payload
GEROS: Where to mount?
GEROS Payload Baseline Architecture

Interferometric approach

GAB (antenna+CAL-LNA)

Up-looking Array

Up center element for POD

CAL-LNA front-ends

Down center element

Down-looking Array

Signal Harness

GAB Beamformer and Down-Converter

POD RF Input

IF Beam pair 1

IF Beam pair 2

IF Beam pair N

POD Receiver

SPU Signal Processing Unit

Instrument Control Unit (ICU)

Power Supply Unit (PSU)

Columbus External Payload Adapter (CEPA)
GEROS Payload on Columbus

376 kg, 395 W
2 GB mass memory, 1.2 Mbps output data rate

Courtesy: ADS-CASA
GEROS Field of View

- Flight Direction
- Allowed Envelope for Payload
- Clear FoV only to the starboard side
- 17° semi-angle cone around nadir blocked by ASIM payload
GEROS Field of View

FIELDS OF VIEW:
FoV-1: around-nadir altimetry and scatterometry (in black)
FoV-2: grazing altimetry (in black)
FoV-3: radio-occultation and precipitation (in grey)
GNSS signals which GEROS Payload can process

Courtesy: ADS-CASA
# Beams and Polarization

<table>
<thead>
<tr>
<th>APPLICATION</th>
<th>TIME SHARE</th>
<th>UP</th>
<th>DOWN</th>
<th>Freq.</th>
<th>DDM</th>
<th>TYPE of Waveform: Complex or Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.- Around-nadir Altimetry</td>
<td>90%</td>
<td>X</td>
<td>X</td>
<td>F1,F5</td>
<td>000-111-000</td>
<td>P</td>
</tr>
<tr>
<td>2.- Forward Scatterometry RL</td>
<td>90%</td>
<td>X</td>
<td>X</td>
<td>F1</td>
<td>333-333-333</td>
<td>P</td>
</tr>
<tr>
<td>3.- Forward Scatterometry RR</td>
<td>90%</td>
<td>X</td>
<td>X</td>
<td>F1</td>
<td>333-333-333</td>
<td>P</td>
</tr>
<tr>
<td>4.- Forward Scatterometry LL</td>
<td>10%</td>
<td>X</td>
<td>X</td>
<td>F1</td>
<td>333-333-333</td>
<td>P</td>
</tr>
<tr>
<td>5.- Forward Scatterometry LR</td>
<td>10%</td>
<td>X</td>
<td>X</td>
<td>F1</td>
<td>333-333-333</td>
<td>P</td>
</tr>
<tr>
<td>6.- Grazing Altimetry</td>
<td>100%</td>
<td>X</td>
<td>X</td>
<td>F1,F5</td>
<td>000-030-000</td>
<td>C</td>
</tr>
<tr>
<td>7.- Radio Occultation</td>
<td>100%</td>
<td>X</td>
<td>X</td>
<td>F1,F5</td>
<td>000-030-000</td>
<td>C</td>
</tr>
<tr>
<td>8.- Precipitation</td>
<td>100%</td>
<td>X</td>
<td>X</td>
<td>F1</td>
<td>000-030-000</td>
<td>C</td>
</tr>
<tr>
<td>9.- Precise Orbit Determination</td>
<td>100%</td>
<td>X</td>
<td>X</td>
<td>F1,F5</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Scientific activities
GARCA

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

- International scientific activity related to preparation of the GEROS mission
- ESA Invitation of Tender May 2014, seven partners from six European countries, complemented by 12 external experts, main contract GFZ

Main Objectives
- Development of a simulation tool for GNSS-R data (GEROS-SIM) from instrument level up to Level-1 observables and Level-2 geophysical products
- To study the impact of the GEROS-ISS data products on the current Global ocean observation system and its synergies with existing satellite missions.
- Provide an umbrella for the science activities in preparation of GEROS-ISS

Status
- Project finished November 8, 2016
- GEROS-SIM developed and in process of transfer to ESA/ESTEC
- Final project report (pp 464) contains six Technical Notes, which will be made public
GARCA Final Report

pp 464; Nov 8, 2016

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GARCA: GEROS-SIM

Instrument parameters, GNSS-R observables (Level 1) and geophysical observables (Level 2)

Core: PAU/PARIS
E2E Performance Simulator IEEC

+ three Level 2 processors (Code & Phase altimetry, scatterometry)
IEEC, NOC, GFZ
Example and Challenge for GEROS: Multipath

Ray tracing analysis for 1800 points in the far field

Camps/Park et al.
GEROS-SIM: Web-Interface

www.tsc/upc.edu/rslab/gerossim
GEROS-SIM:
Reflectometry coverage and revisit time

Average revisit time for GEROS with realistic scenario
GARCA-TN-4

~ 3 days
1-2 days
GEROS-SIM: Code Altimetry

GEROS-SIM tested with real TDS-1 data and compared with simulated GEROS interferometric approach. Different wind speeds assumed:

- Wind 8.4 m/s
- Wind 17.7 m/s

<table>
<thead>
<tr>
<th>Integration time:</th>
<th>Along-track resolution:</th>
<th>Across-track resolution:</th>
<th>Precision figure:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second</td>
<td>7.5 km</td>
<td>4 km</td>
<td>11.3 cm</td>
</tr>
<tr>
<td>14 seconds</td>
<td>100 km</td>
<td>4 km</td>
<td>3.0 cm</td>
</tr>
</tbody>
</table>

Estimated precision is well within key Mission requirement (see TN-4)
GEROS-SIM: Phase Altimetry

Ground track for the ISS example event in Agulhas region (left)
Retrieved SSH and precision estimate for different SNR (right)
Precision (1s, 7.5/0.5km along/across-track: \(0.11\) m (30 db, 5 cm POD)
GEROS-SIM: Scatterometry

GEROS-SIM with TDS-1 setup
Performance of retrieved L2 wind speed
Anti-Velocity Radio Occultation

Quite free field of view
Baltic flight experiment (1/2)

Skyvan / SPIR / Laser

TwinOtter / ASIRAS / Laser
Baltic flight experiment (2/2)

*precision of 17.8 cm for 10 seconds and 49.7 cm for 1 second for a 72 degree elevation GPS satellite*

Courtesy IEEC
OSSE study for detection of Eddies (Gulf of Mexico)

• Control run: Simulation of a “perturbed” ocean with eddy event
• Data assimilation: in 12h intervals use the simulated ISS data with error characteristics
• Free run: without data assimilation and perturbation
• Conclusion: Using the GEROS-ISS data, eddies can be detected, even with assumed 50 cm Std error randomly (by averaging ~10-20 cm), 10 km footprint

1 month after initialization

Lee (JPL) et al., 2013
OSSE study with simulated GEROS-ISS data

Two days artificial of GEROS
Observations
Ocean model ROMS,
4D Var
Realistic Forcing (ERA, ECMWF)
Saynisch et al. (Ocean Dynamics, 2015)

Assimilation improves not “only” SSH reconstruction, but also physical values as $v$, $T$, $S$ down to 4 km depth
Absolute accuracy not so important, most important spatio-temporal distribution
OSSE in South China Sea during Typhoon Rammsun

NERSC, Norway

Three months of assimilation of simulated GNSS-R data in the model and data assimilation system with HYCOM model (5 km) on top of the operationally used Radar-Satellite data (4) also during typhoon period in July 2014

Simulated observations

Three experiments:
* GEROS-ISS (limited FoV)
* Free Flyer FoV-1 (Jason like)
* Free Flyer FoV-2 (Jason like)

Assumed errors (precision):
25 cm (10 km)

Xie/Bertino et al. (NERSC, 2016)

One example: (TN-5 GARCA)
Improvement of SLA reconstruction with GNSS-R F-FoV2 compared to use of traditional altimetry satellite data only up to 50% (for GEROS up to 20%)
What is the current status of GEROS-ISS?
Cost reduction exercise (Manuel next talk)

Objective: to bring the cost of GEROS-ISS payload down to less than **20 MEuro**

Requirement: Altimetry demonstration to be fully maintained in **2 specular points simultaneously**

Simplifications at science level:

- Simultaneous measurement of the 2 polarizations (RHCP and LHCP) is not required
- Polarimetric Radio-Occultation is not required

Schedule: begin Phase B in Mid 2017, Launch late 2021

And: there is another activity …
Something new based on GEROS: G-TERN

**GNSS** – **Transpolar Earth Reflectometry exploring System**
Mission proposed in Earth Explorer 9 call from ESA
Proposal deadline June 15, 2017
Team from 10 countries (EU, USA, Canada)

Experts on:
- Polar science
- Oceanography
- Sea level
- Climate
- Meteorology
- Land applications
- Space weather
- GNSS
- Space engineering

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Planned G-TERN mission specification

Total cost limit: 150 M€ (spacecraft/payload)

One spacecraft in near-polar orbit

Orbit altitude and inclination: 500-700 km, sun-synchronous

Vega-C dual launch configuration, G-TERN satellite in Vespa adapter

Launch 2025

Mission duration at least 5 years
Polar research from ground is difficult:
Overwintering of 9 crazy germans in Antarctica

Neumayer, March 1994
Summary and outlook

• GEROS-ISS is a GNSS-Reflectometry/RO mission, which was selected from ESA as the only mission for further studies within the 2011 call for climate change related science aboard the ISS

• Main mission goal is GNSS-R based altimetry of sea surface and second main goal is GNSS-Scatterometry, Secondary mission goals are land surface monitoring and GNSS radio occultation, GEROS will also consolidated the GNSS-R technology

• GEROS-ISS finished two industrial Phase A studies and a the science activity GARCA, the technical concept (IF approach) meets mission requirements, planned launch is late 2020

• Various scientific activities related to the preparation of GEROS-ISS activities were started and briefly reviewed here, a related ISI paper is published