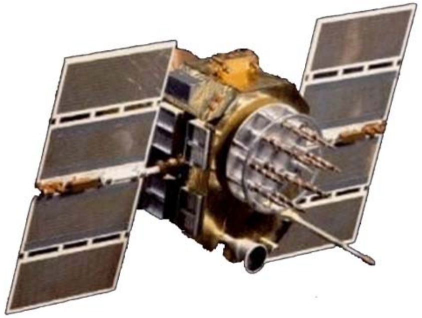
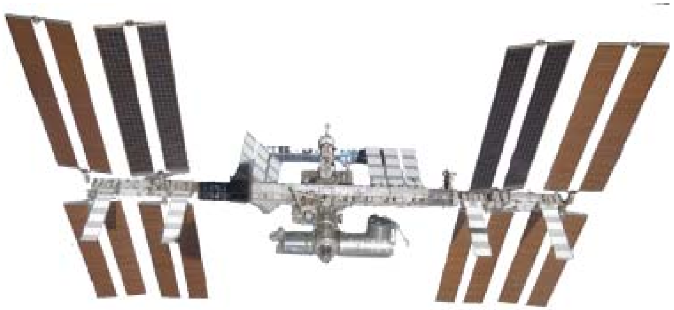
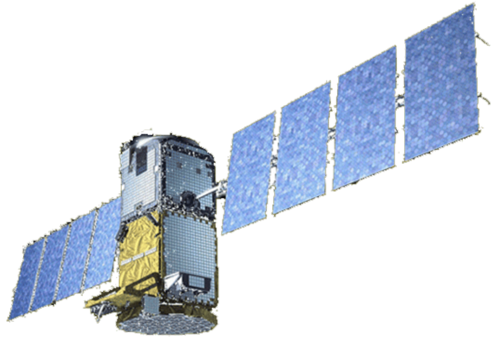
  

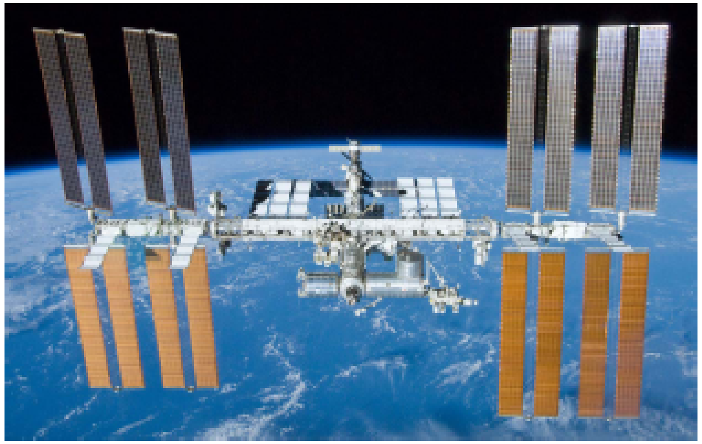
Innovative Sea Surface Monitoring with GNSS-Reflectometry aboard ISS: Overview and Recent Results from GEROS-ISS

J. Wickert, O. Andersen, L. Bertoni, B. Chapron, E. Cardellach, N. Catarinho,
C. Gommenginger, G. Foti, J. Hatton, P. Høeg, A. Jäggi, M. Kern, T. Lee,
M. Martin-Neira, N. Pierdicca, J. Rosello, C.K. Shum,
M. Semmling, A. Sousa, J. Xie, C. Zuffada

IAG-C4, Wroclaw
Sept. 6, 2016

ESA call 2011:
Climate change related research aboard ISS

European Space Agency
Research Announcement for International Space Station Experiments relevant to study of Global Climate Change



Letters of Intent due:

9th September 2011

* * * * *

Proposal due:

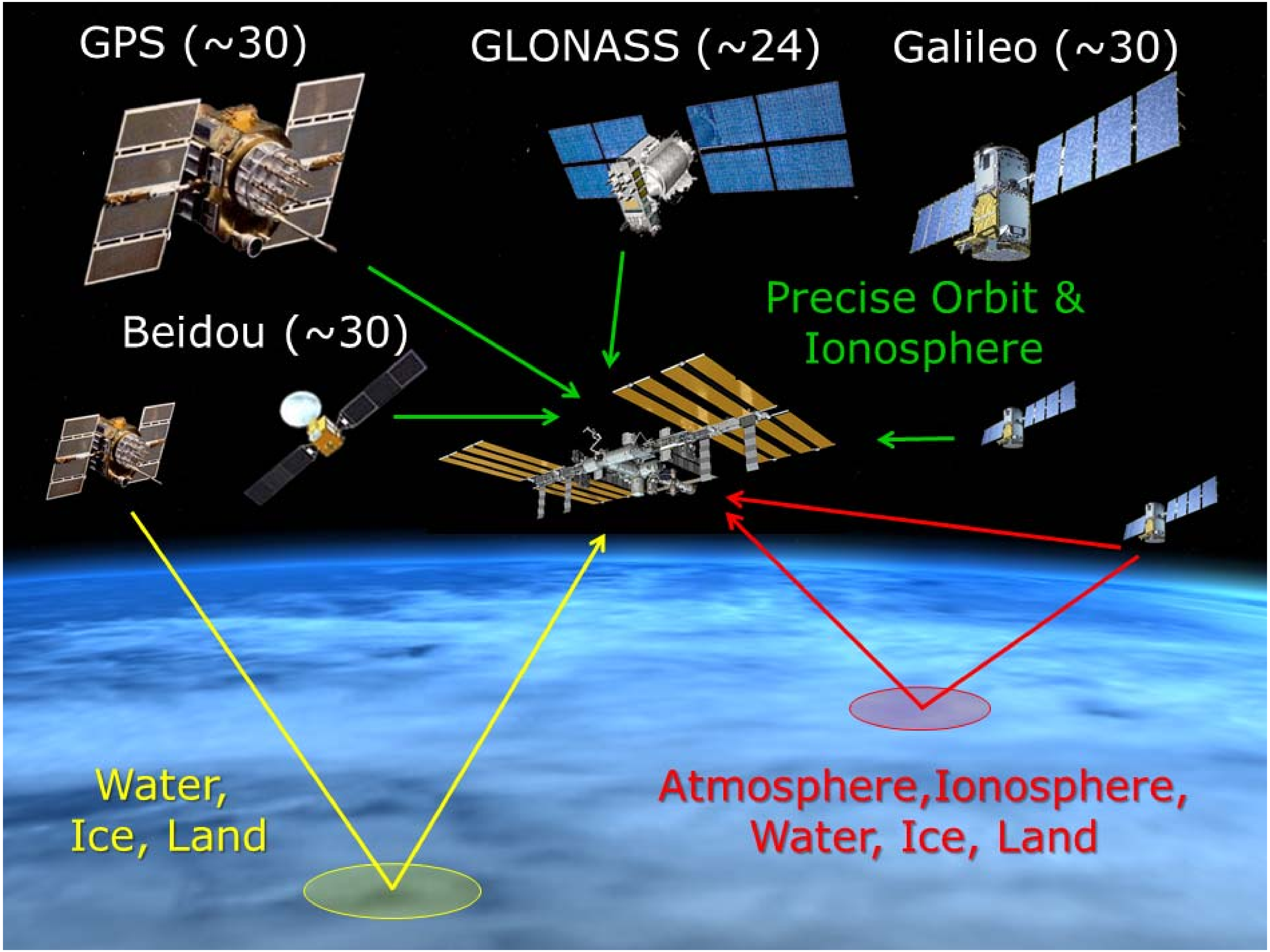
4th November 2011

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



GPS (~30)
GLONASS (~24)
Galileo (~30)
Beidou (~30)
Precise Orbit &
Ionosphere
Water,
Ice, Land
Atmosphere,Ionosphere,
Water, Ice, Land

Advantages of GNSS vs. Radar Altimetry

* Signals are „free of charge“

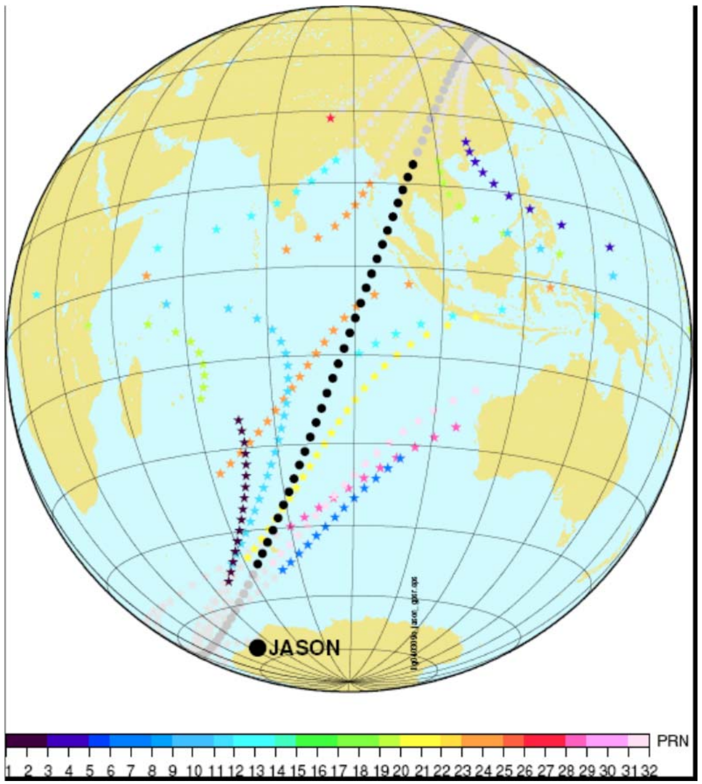
* Many reflection points

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)

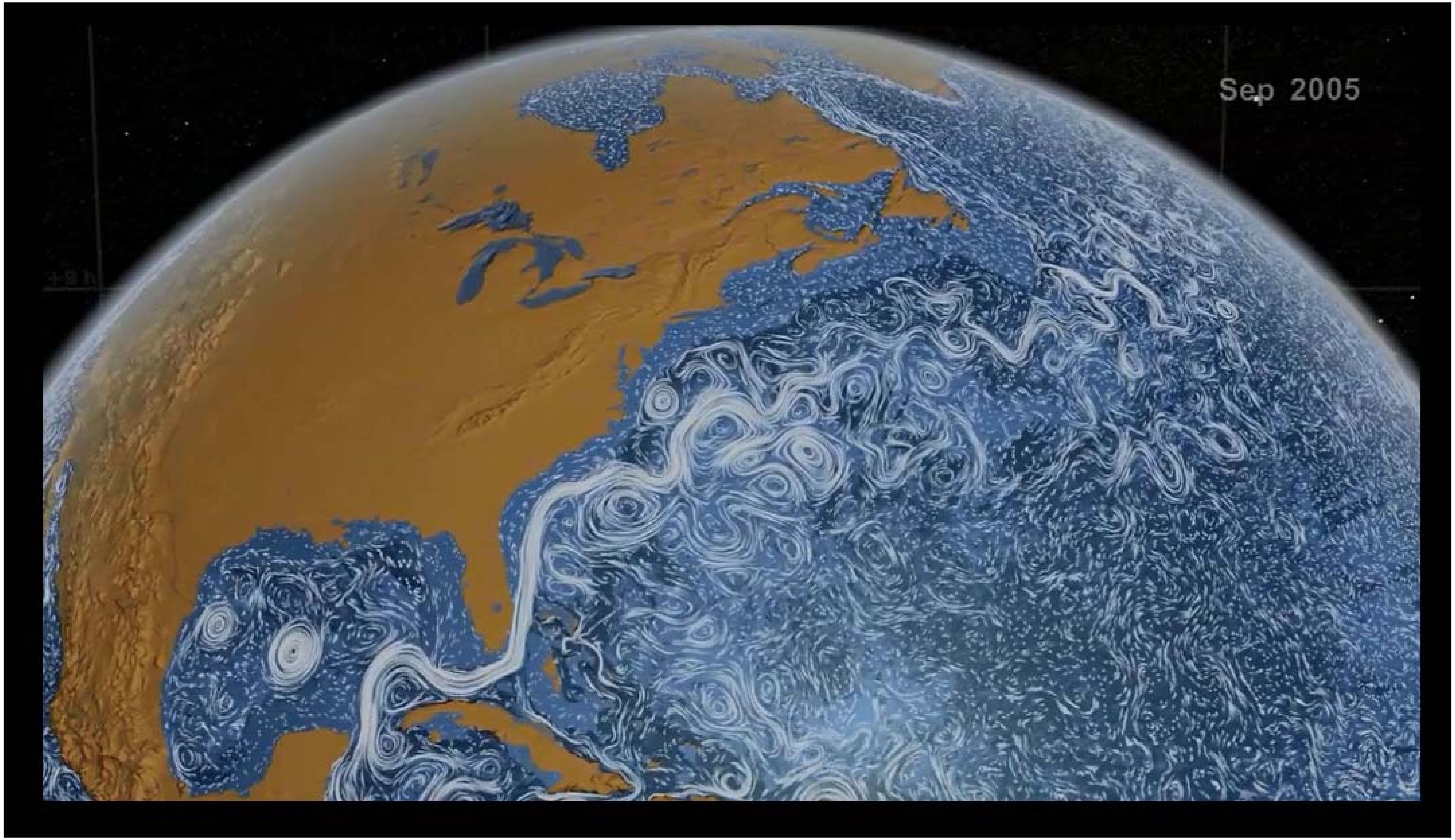
Primary:

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 cm^3),
upper balcony, power <500 W, downlink <1 Mbps

Dragon C3-1 launcher (SpaceX, from KSC)

Launch (late) 2020

Mission duration at least 1 year,
possible extension up to 5 years

Recent status

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, June 9, 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)

Official decision on Phase B expected within the next months

GEROS-ISS: Programmatic Context

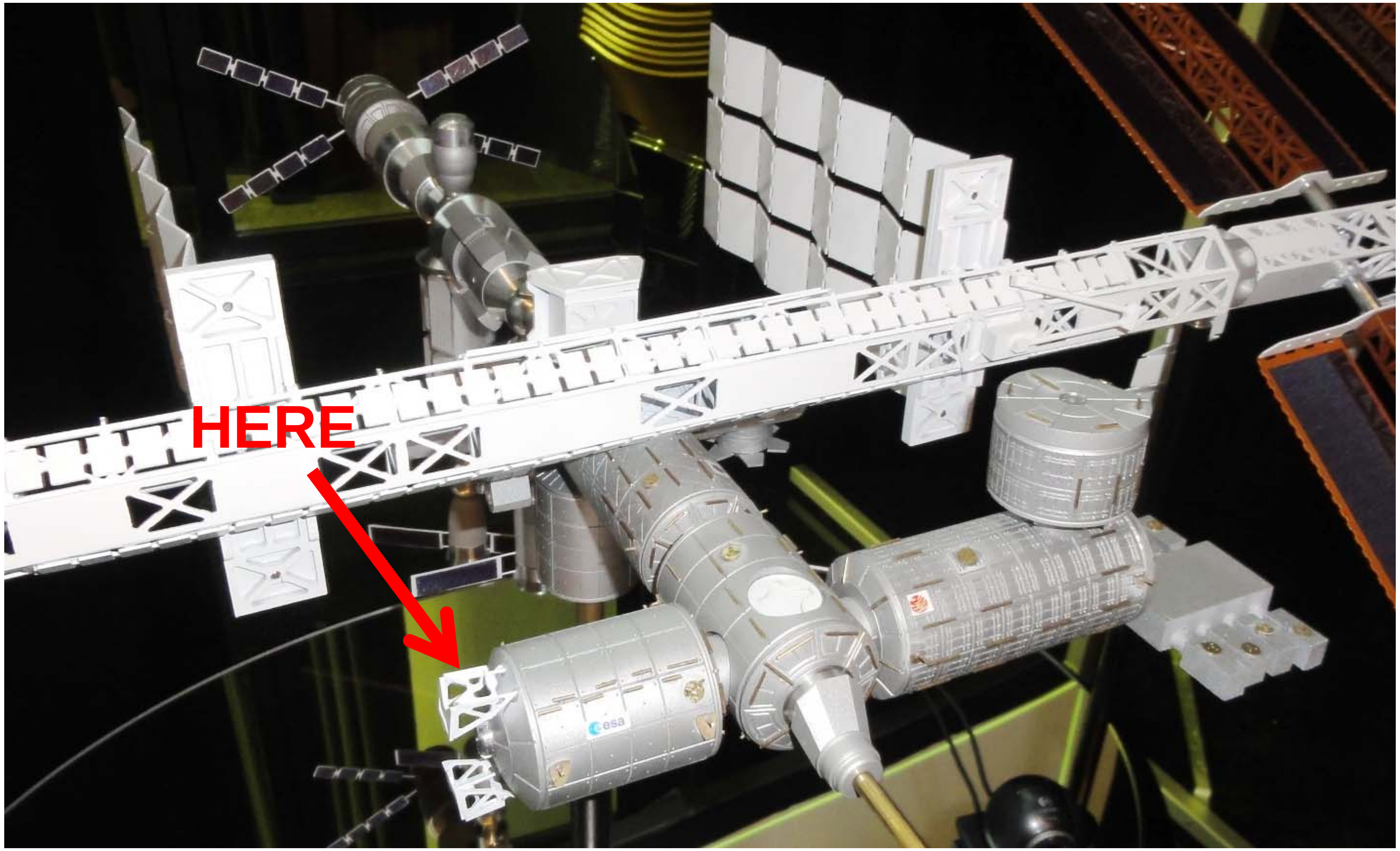
GEROS-ISS phase A, Science studies GARCA and SAG are currently the only funded activities by ESA

Implementation of subsequent steps is contingent on the following:

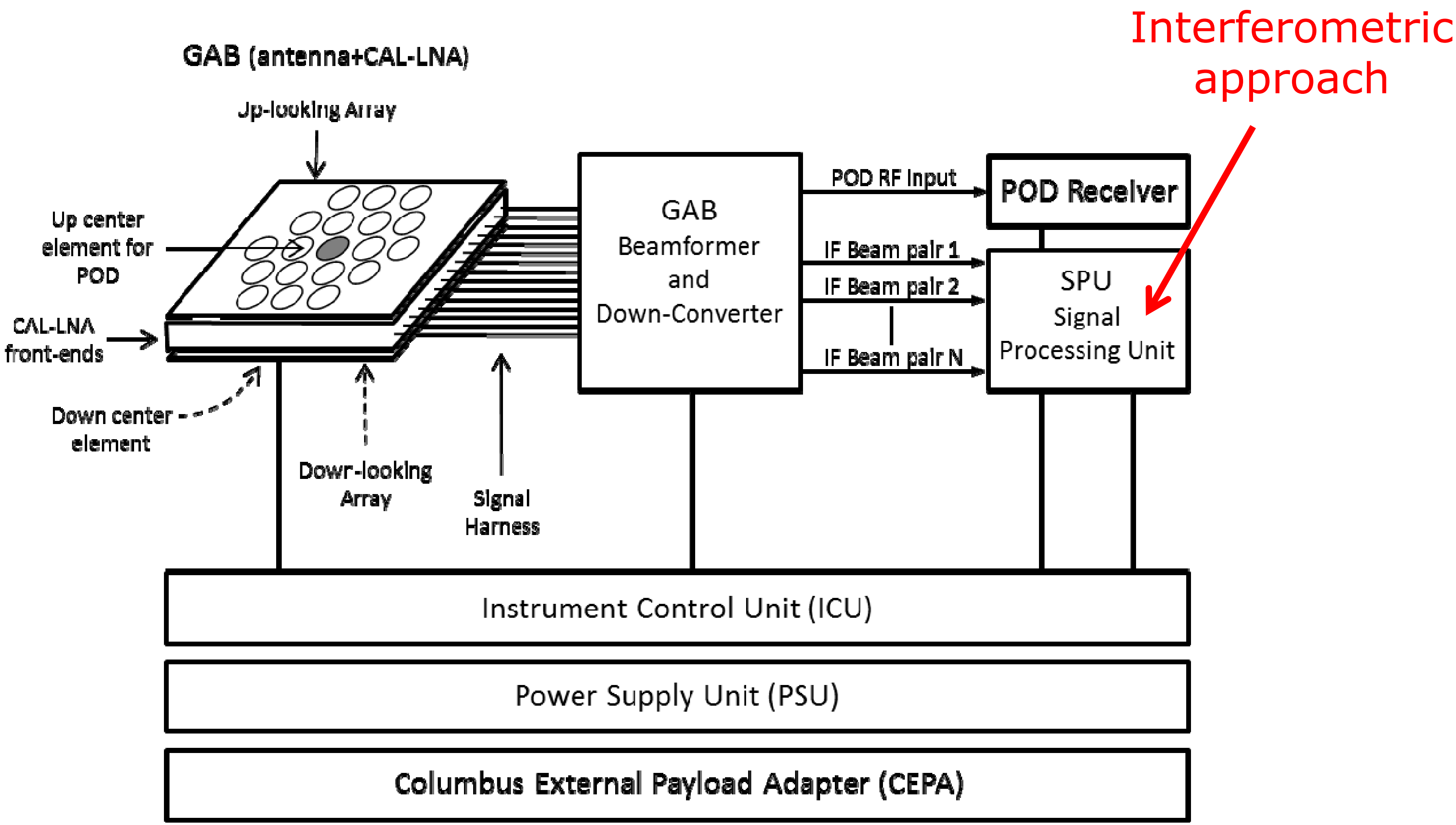
- Successful outcome of phase A, demonstrating feasibility within a realistic budget / resource envelope
- Budget for phase B/C/D development activities – TBD via GSTP programme
- ISS resources (upmass, installation, basic operation) – via ISS exploitation programme

Payload

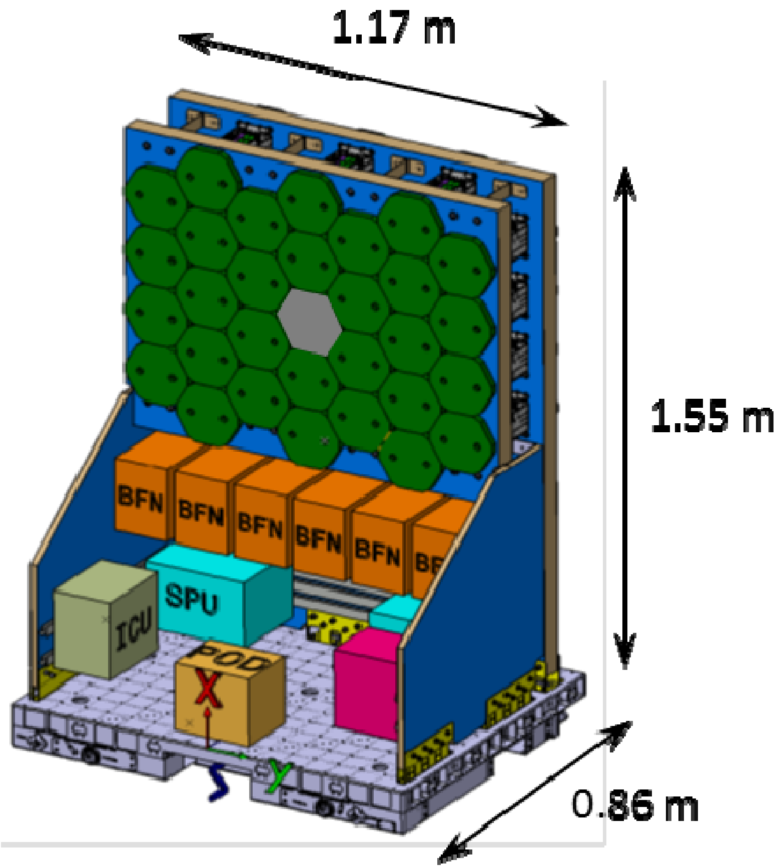
GEROS: Where to mount?

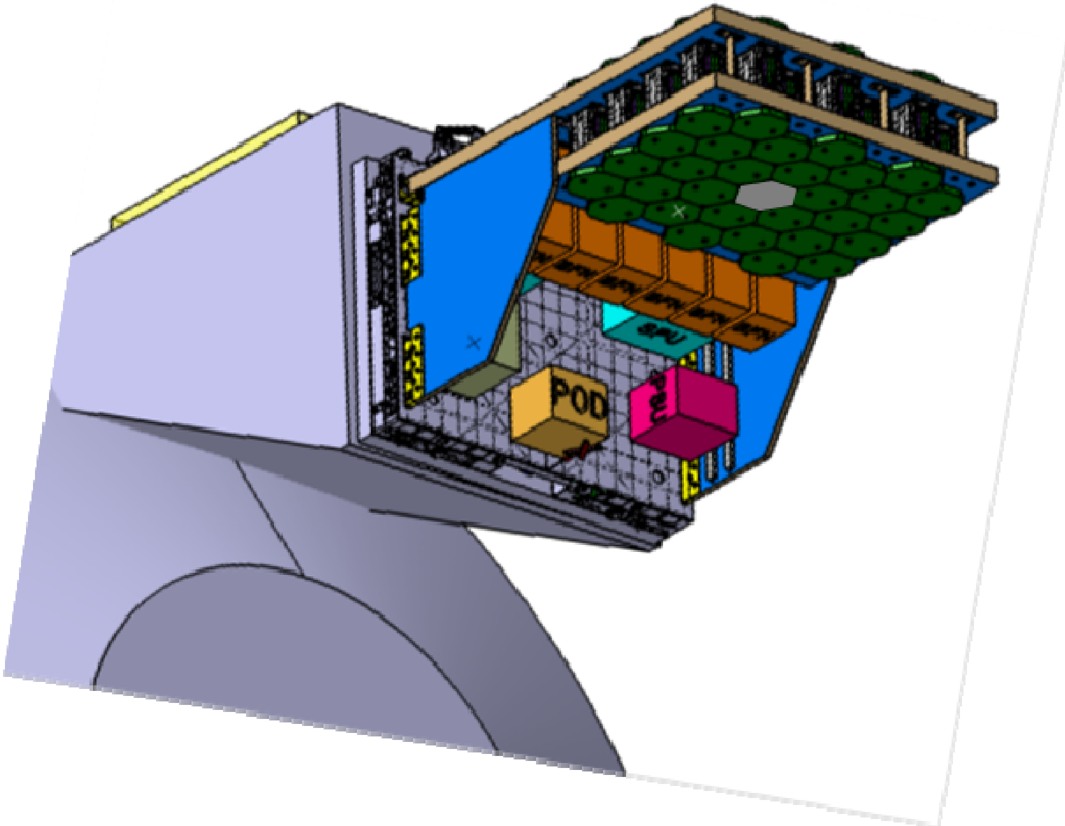


GEROS Payload Baseline Architecture



GEROS Payload on Columbus

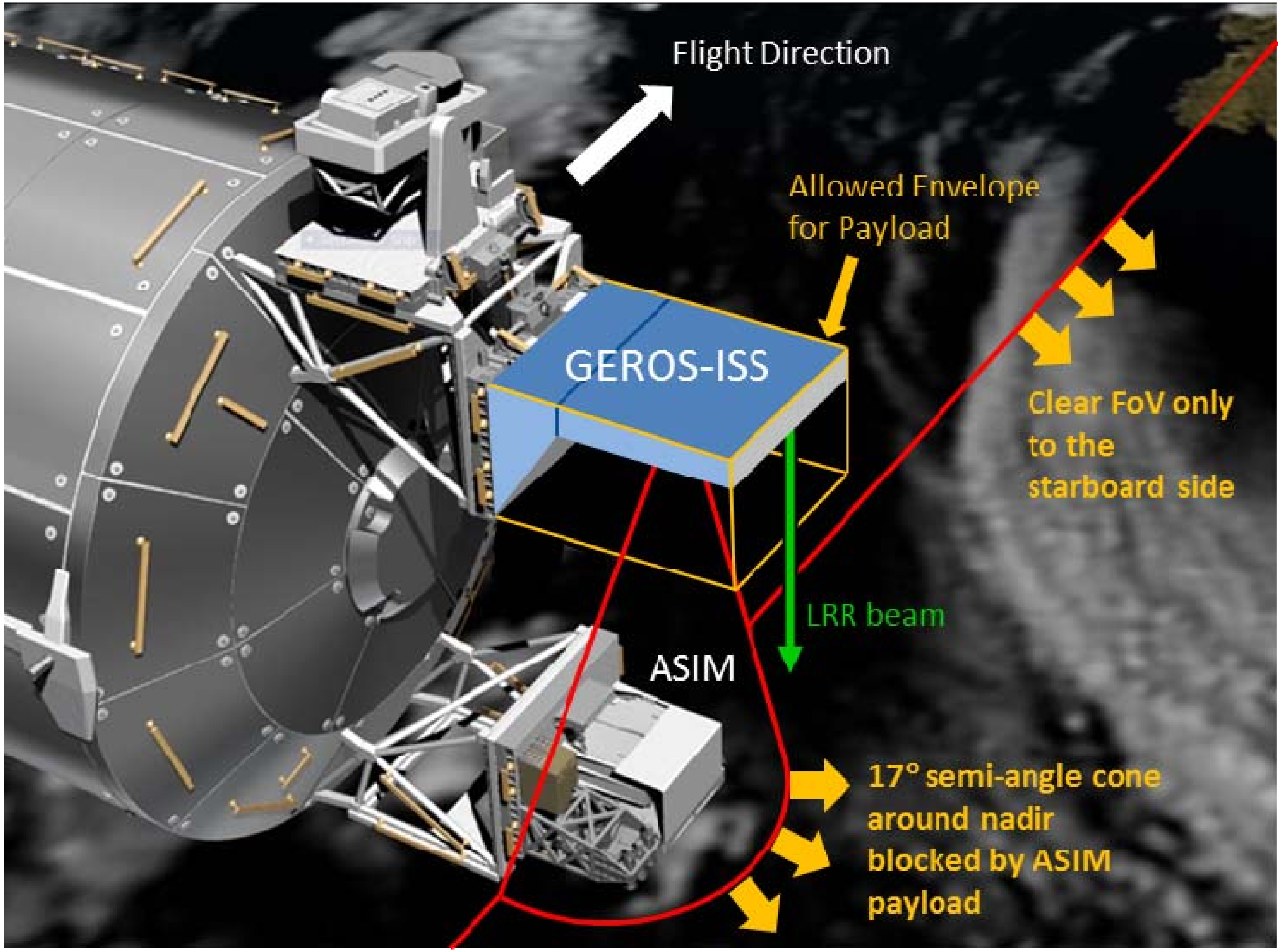




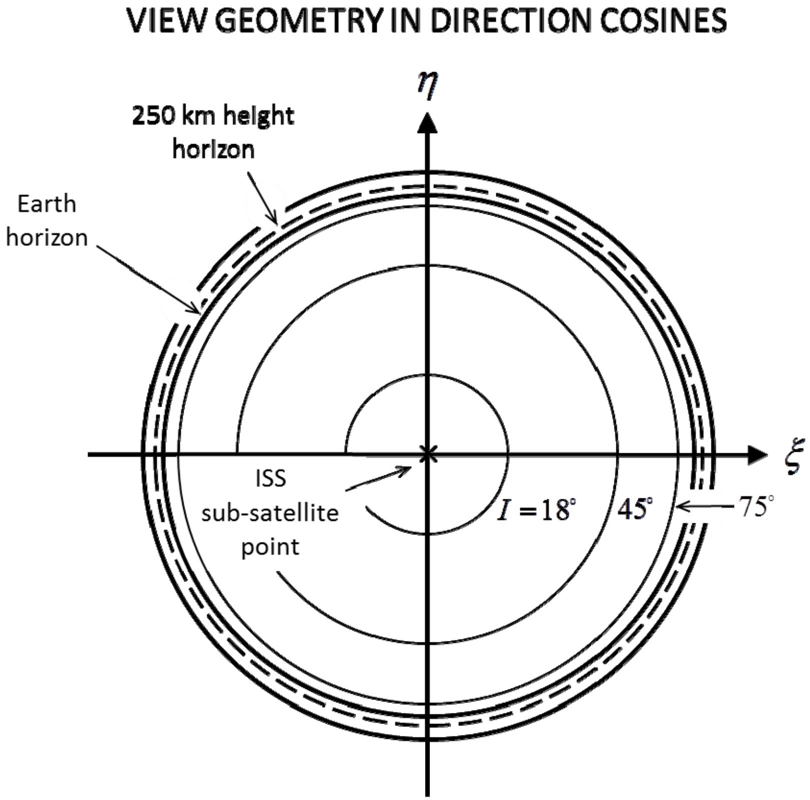
376 kg, 395 W
2 GB mass memory, 1,2 Mbps output data rate

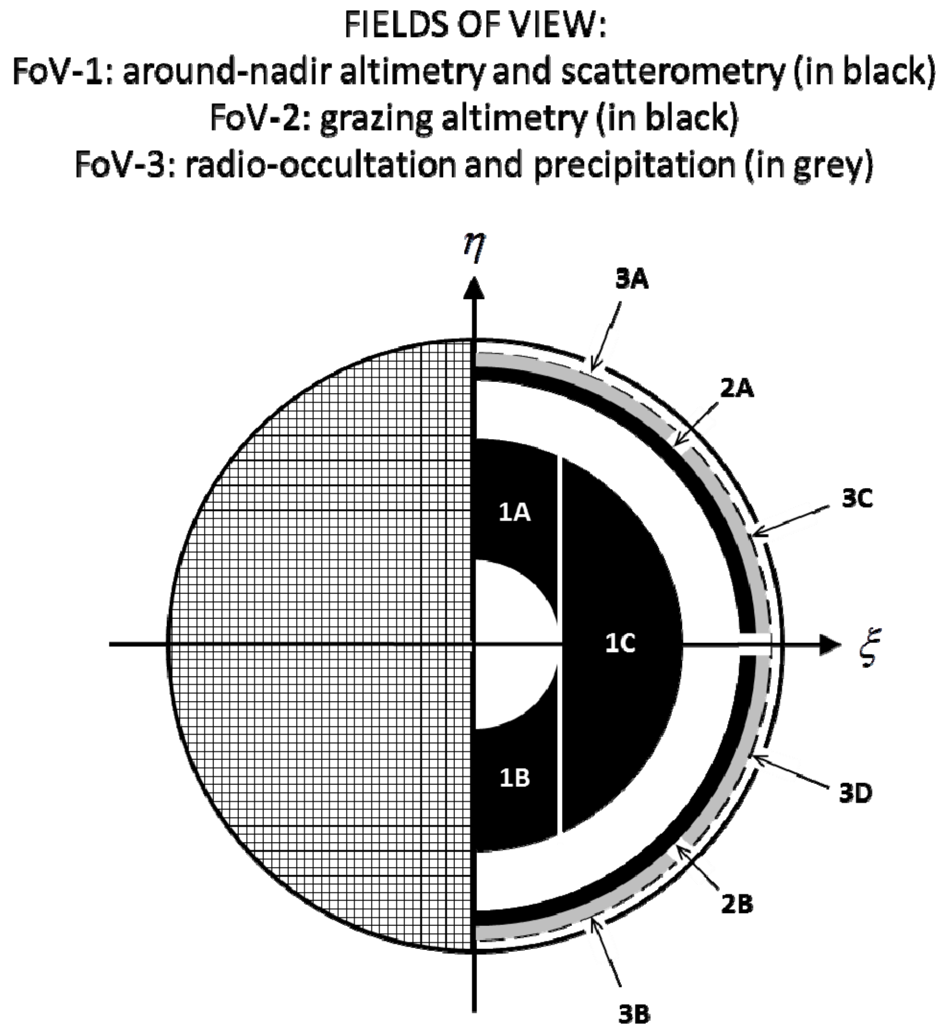
Courtesy: ADS-CASA

GEROS Field of View

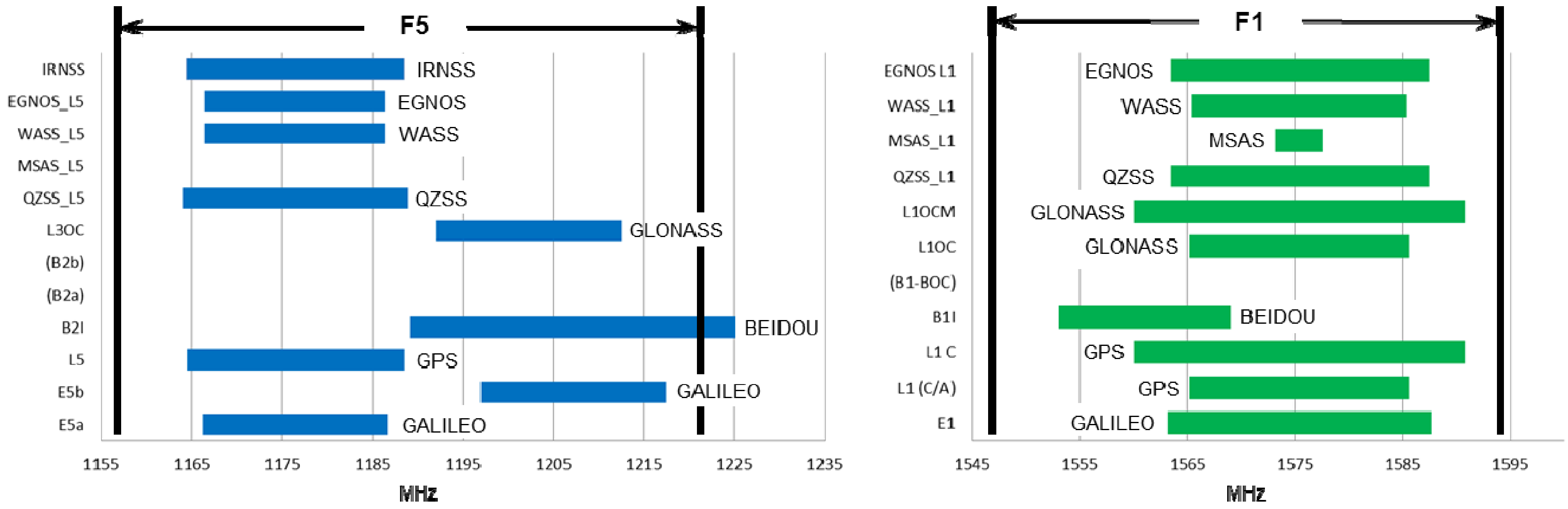


GEROS Field of View





GNSS signals which GEROS Payload can process



Courtesy: ADS-CASA

Beams and Polarization

APPLICATION	TIME SHARE	UP		DOWN				Freq.	DDM	TYPE of Waveform: Complex or Power
		DIRECT		REFLECTED		DIRECT				
		R	L	R	L	R	L			
1.- Around-nadir Altimetry	90%	X			X			F1,F5	000-111-000	P
2.- Forward Scatterometry RL	90%	X			X			F1	333-333-333	P
3.- Forward Scatterometry RR	90%	X		X				F1	333-333-333	P
4.- Forward Scatterometry LL	10%		X		X			F1	333-333-333	P
5.- Forward Scatterometry LR	10%		X	X				F1	333-333-333	P
6.- Grazing Altimetry	100%			X		X		F1,F5	000-030-000	C
7.- Radio Occultation	100%					X		F1,F5	000-030-000	C
8.- Precipitation	100%					X	X	F1	000-030-000	C
9.- Precise Orbit Determination	100%	X				X		F1,F5	N/A	N/A

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

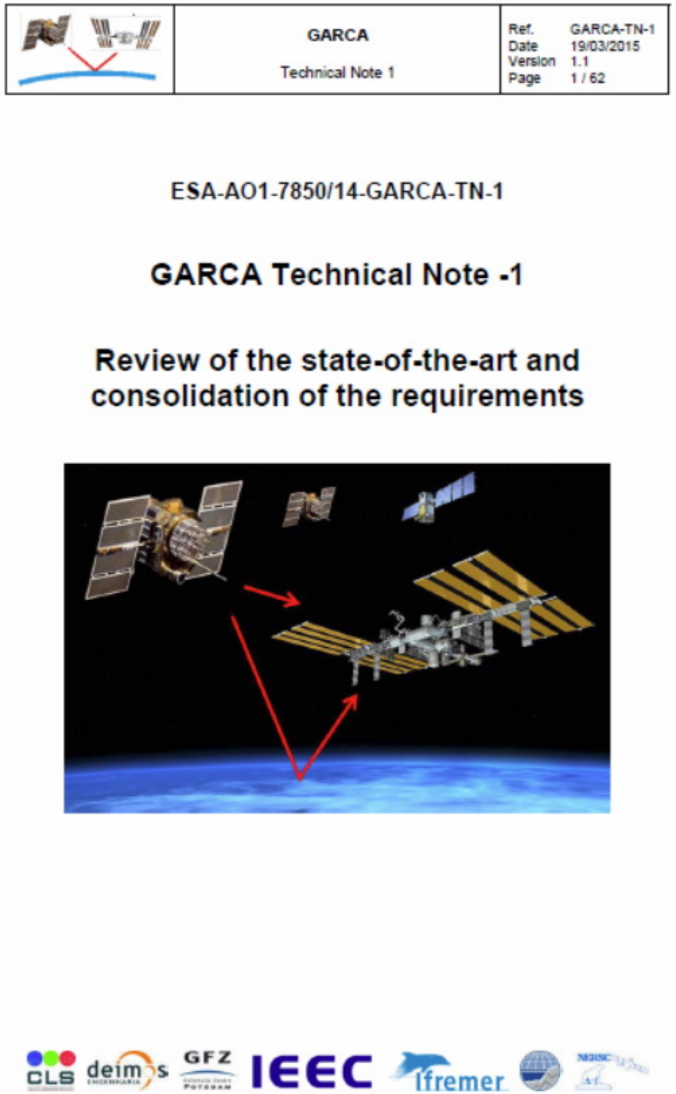
Main Objectives

- 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

- Final project presentation June 9 at ESTEC
- GEROS-SIM developed and in process of transfer to ESA/ESTEC
- Project results documented in six Technical Notes, which will be made public

GARCA – Technical Notes



GARCA Technical Note 1	Ref. GARCA-TN-1 Date 19/03/2015 Version 1.1 Page 1 / 62

ESA-AO1-7850/14-GARCA-TN-1

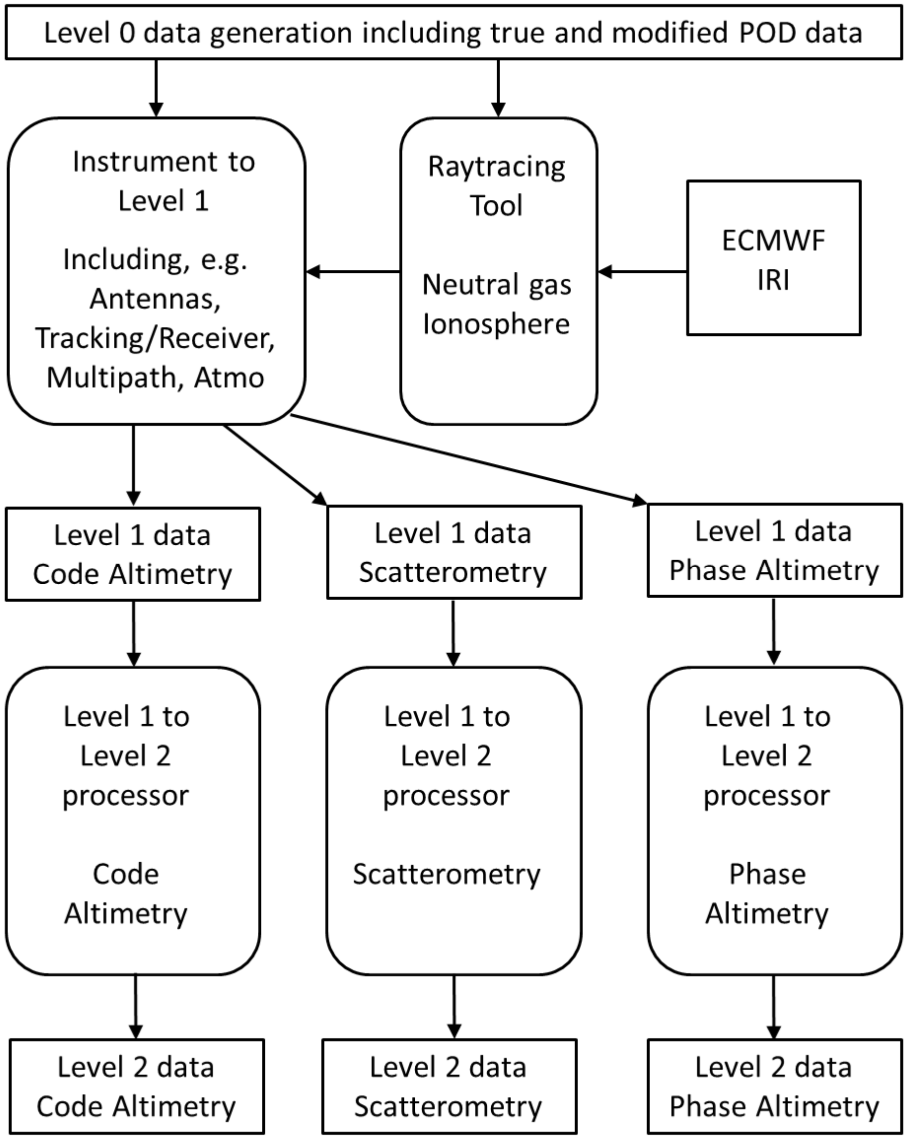
GARCA Technical Note -1

Review of the state-of-the-art and consolidation of the requirements

Technical Notes with the project results will be published

e.g., TN-1
F. Soulat et al.

GARCA: GEROS-SIM

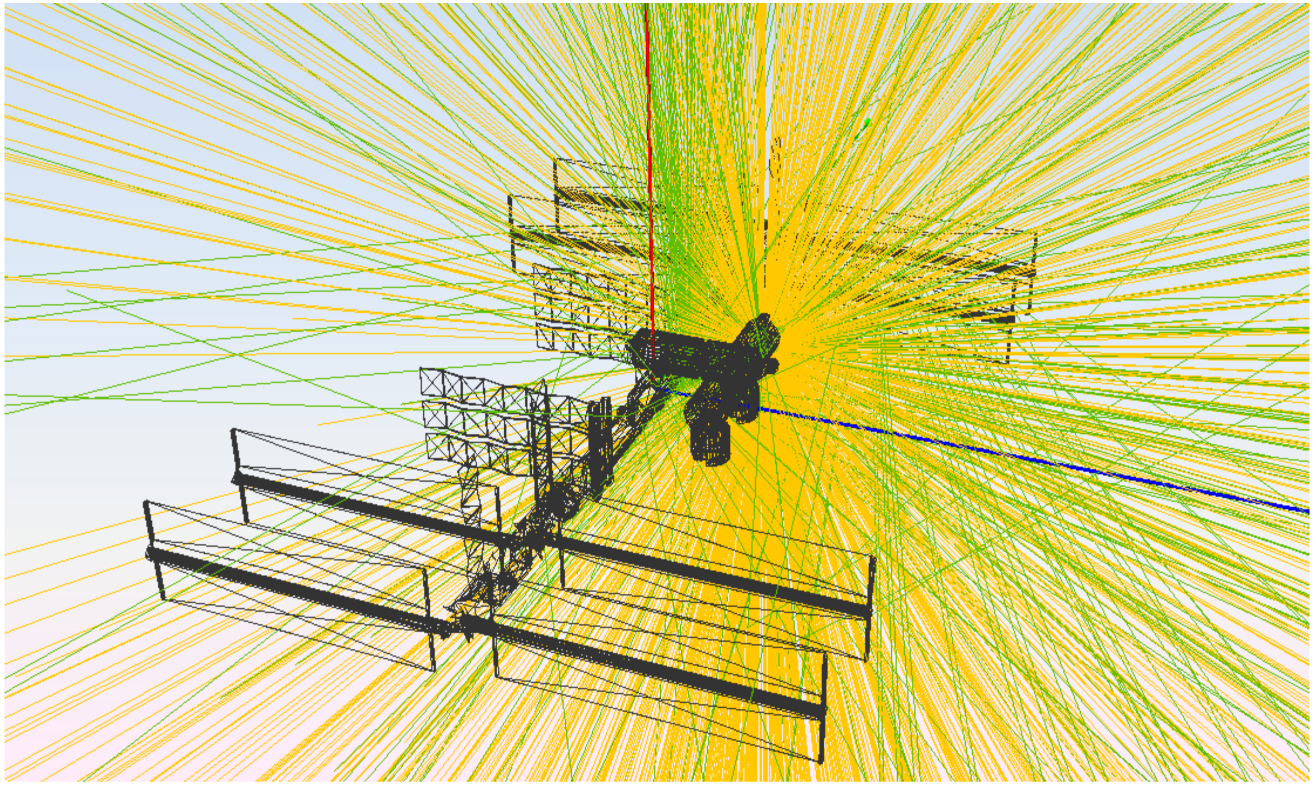


Instrument parameters, GNSS-R observables (Level 1) and geophysical observables (Level 2)

Core: PAU/PARIS
E2E Performance Simulator
IEEC

+ three Level 2 processors (Code & Phase altimetry, scatterometry)
IEEC, NOC, GFZ

Example and Challenge for GEROS: Multipath

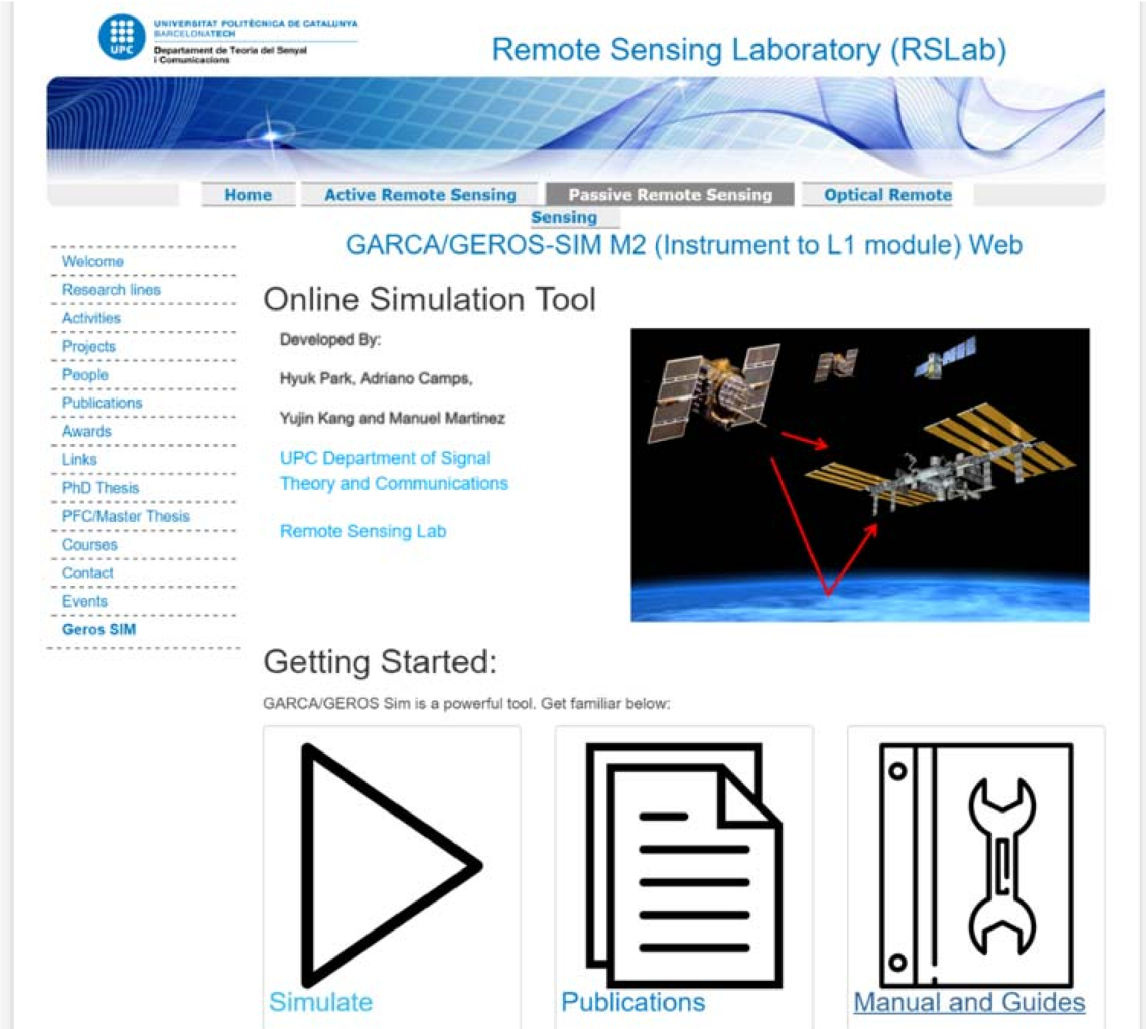


Ray tracing analysis for 1800 points in the far field

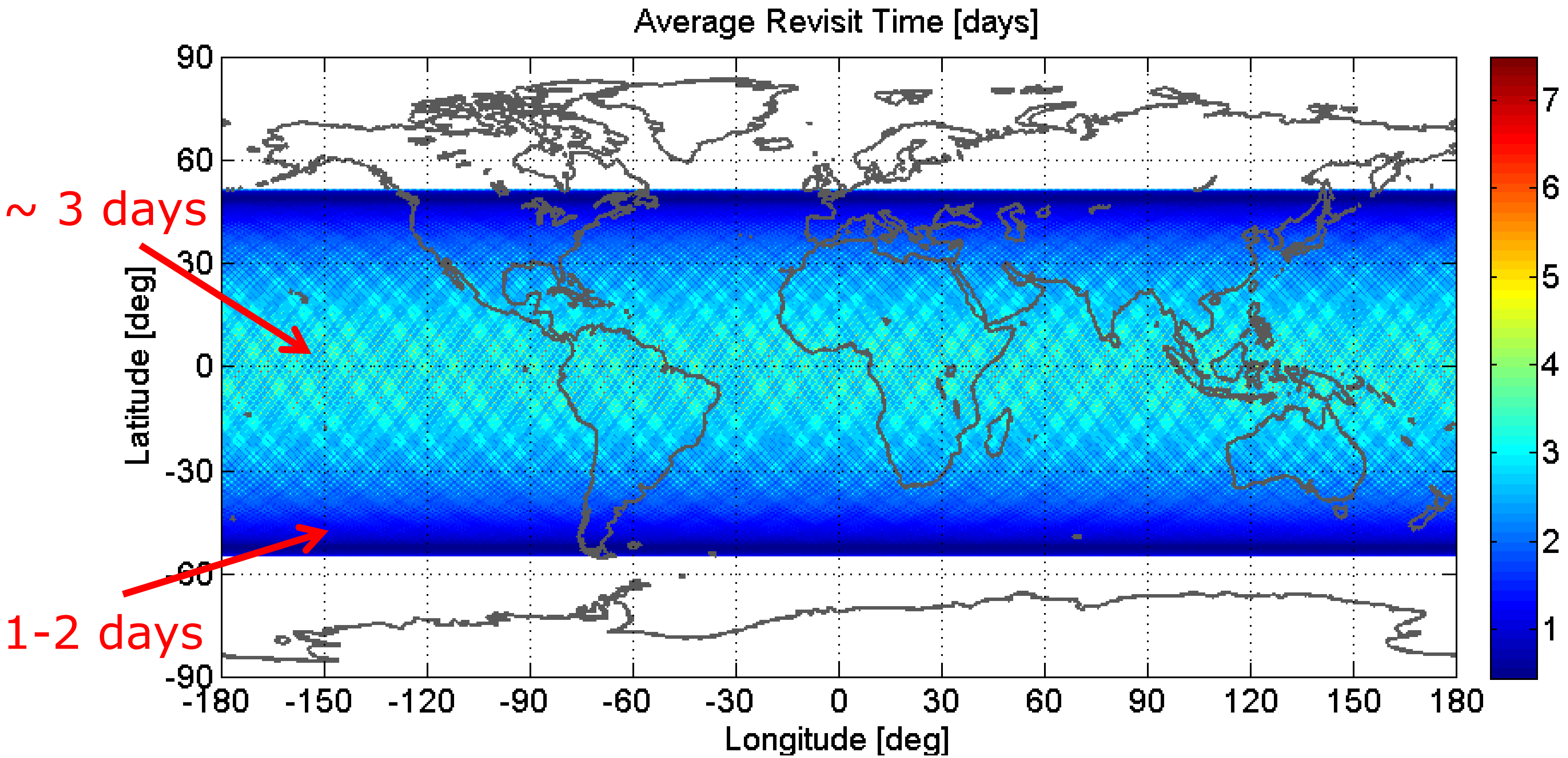
Camps/Park et al.

GEROS-SIM: Web-Interface

www.tsc/upc.edu/rslab/gerossim



GEROS-SIM:
Reflectometry coverage and revisit time

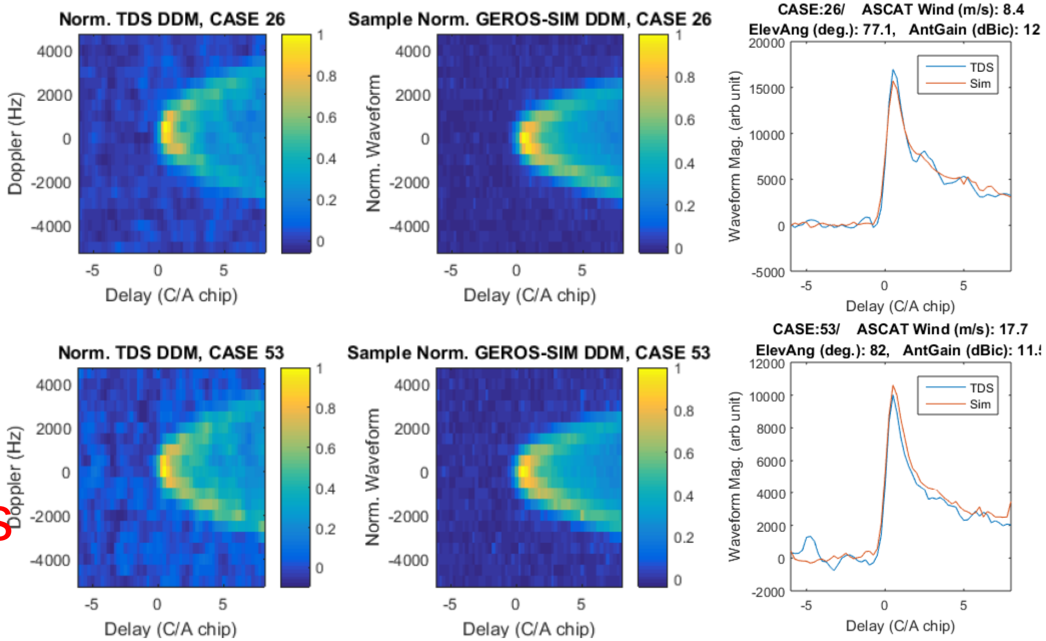


Average revisit time for GEROS with realistic scenario
GARCA-TN-4

GEROS-SIM: Code Altimetry

Wind
8.4 m/s

Wind
17.7 m/s



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

Original GEROS-SIM waveforms

Observable	1-sec precision (m)	100-km precision
GPS L1 interferometric	1.3	0.35
GPS L1 + smoothed iono correction	<1.5	< 0.40
Along-lag correlation filter applied to the noise		
GPS L1 interferometric	0.36	0.10
GPS L1 + smoothed iono correction	<0.5	< 0.13

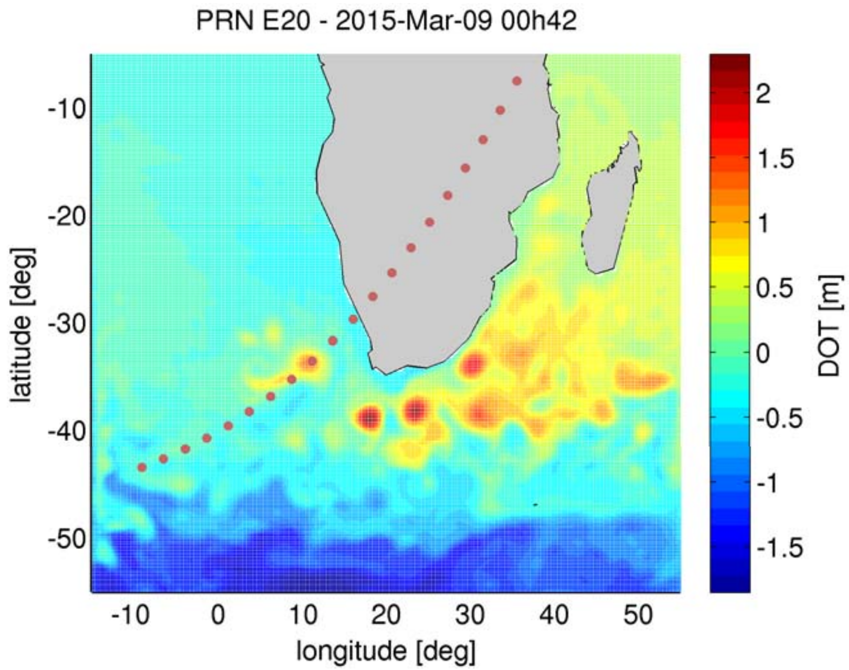
precision
0,40 m

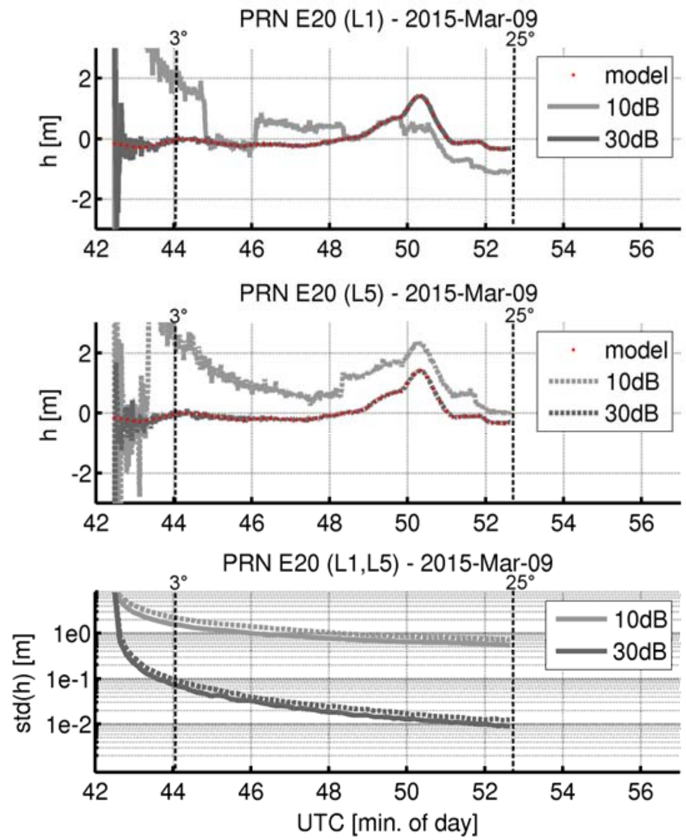
0,13 m

Estimated precision is well within key Mission requirement (see TN-4)

GEROS-SIM: Phase Altimetry

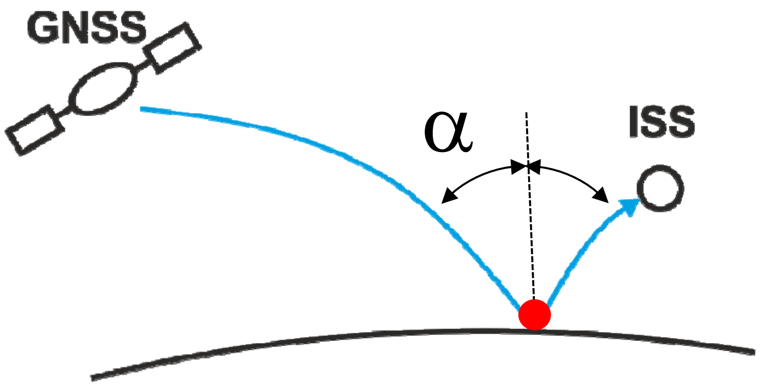
SSH reconstructions (L1,L5)

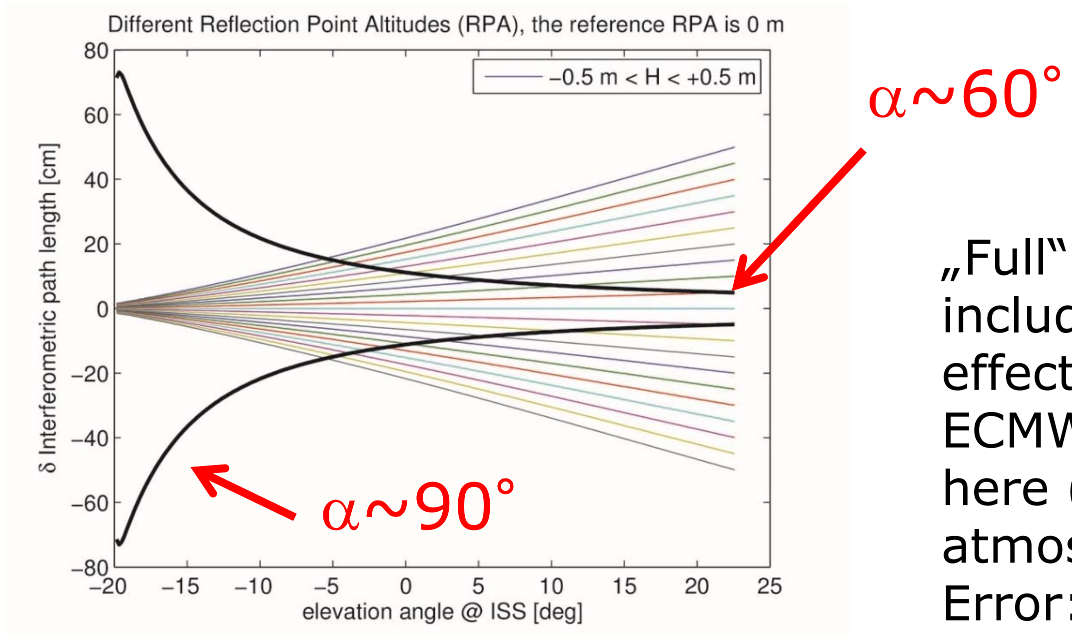




Ground track for the ISS example event in Agulhas region (left)
Retrieved SSH and precision estimate for different SNR (right)
Estimated precision: **0,07 .. 0.11 m** (30 db, LC, 5 cm POD)

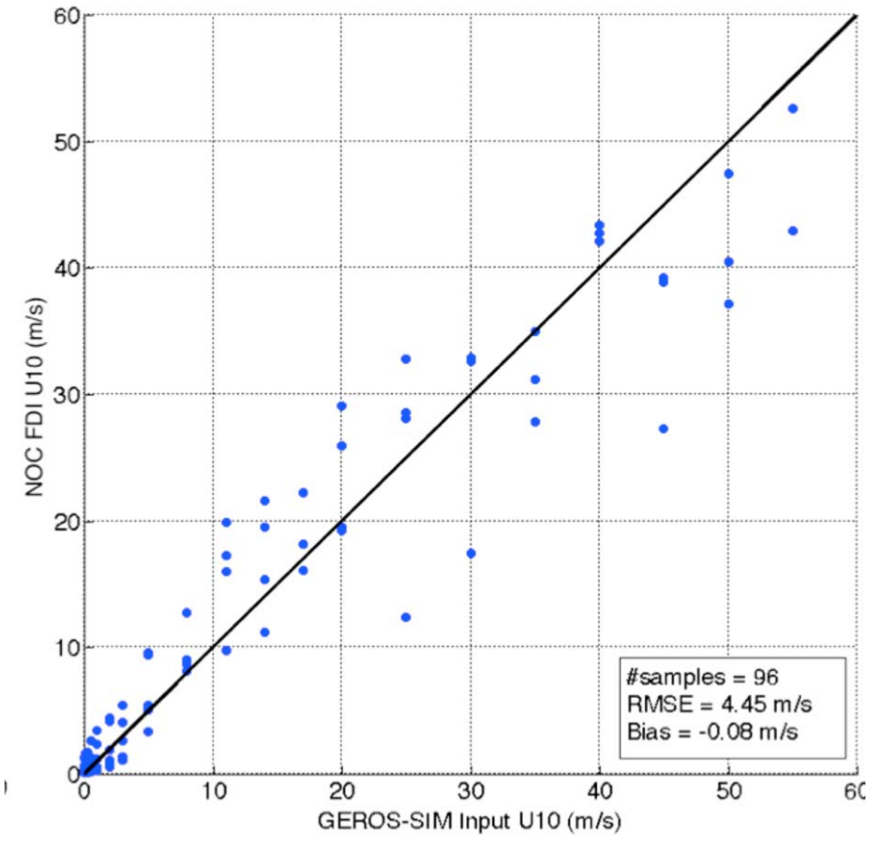
GEROS-SIM:
Atmospheric/Ionospheric propagation effects





„Full" 3D raytracing including bending effects and realistic ECMWF-fields here (neutral atmosphere)
Error: 0,5%

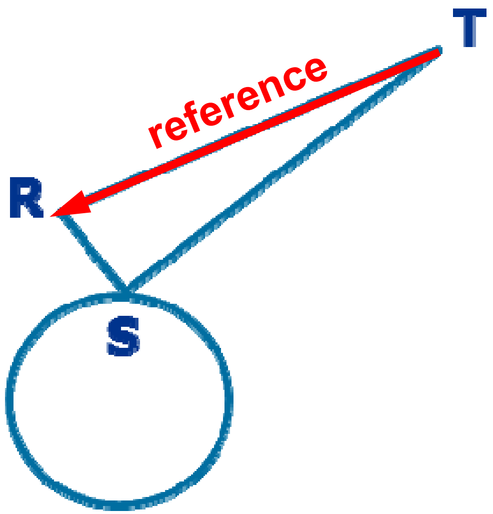
GEROS-SIM: Scatterometry



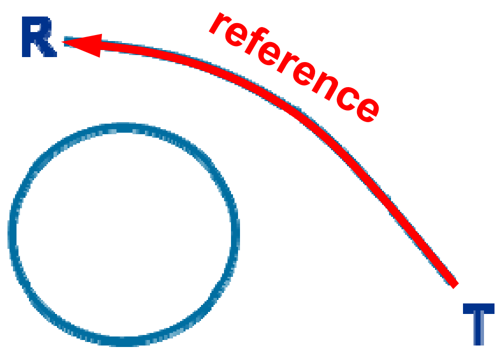
GEROS-SIM with TDS-1 setup
Performance of retrieved L2 wind speed

Interferometric radio occultation as option to classical (Code-Replica) RO
(Martin-Neira et al.)

- Use **received** signal as **reference**

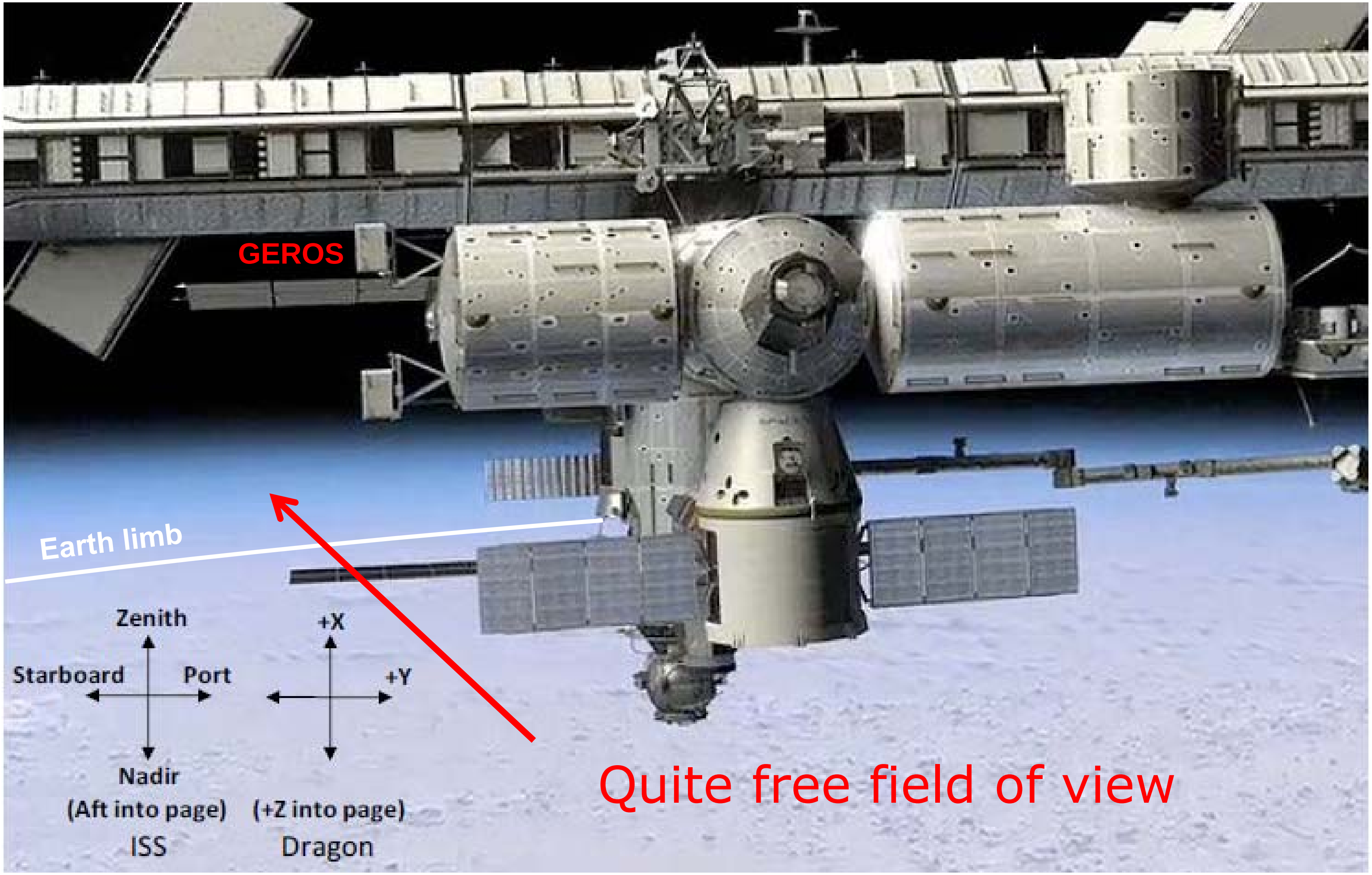


Interferometric Reflectometry

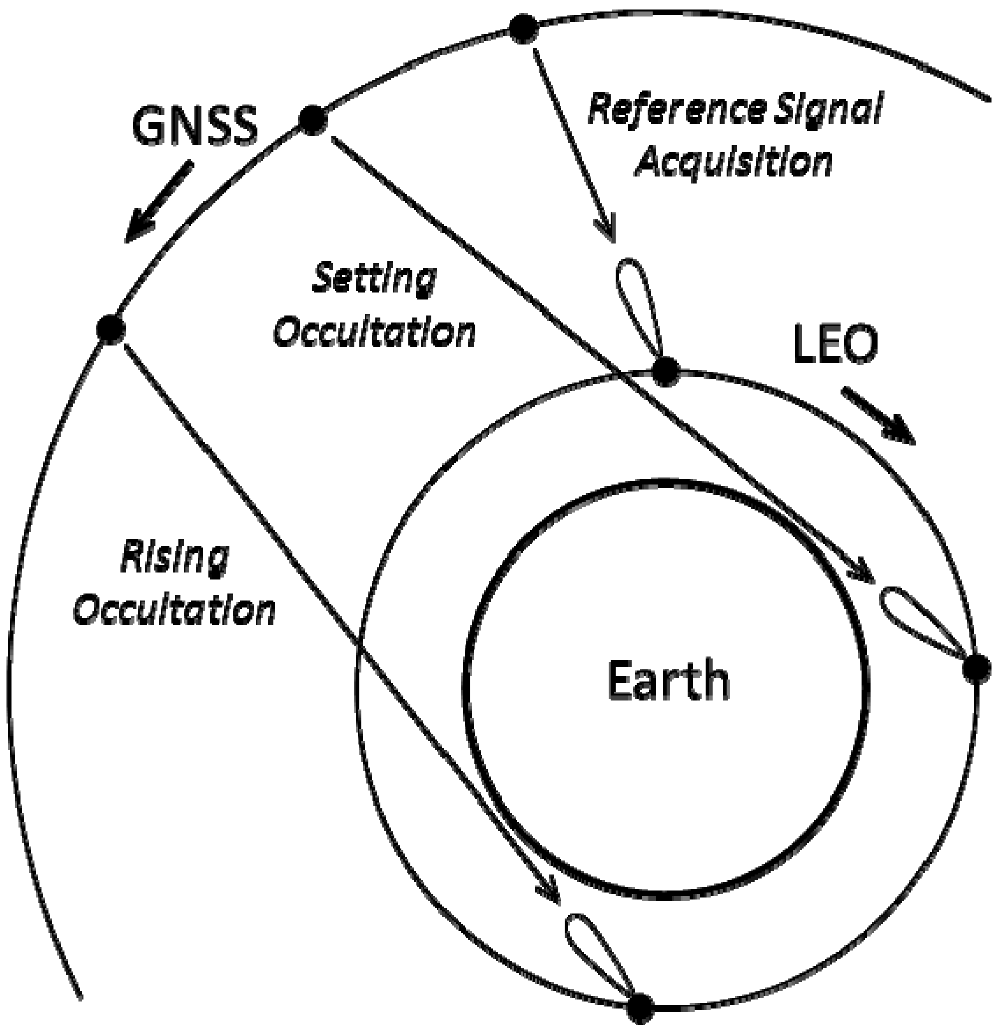


'Interferometric' *Radio Occultation*

Anti-Velocity Radio Occultation



But of course also rising RO possible



Baltic flight experiment (1/2)

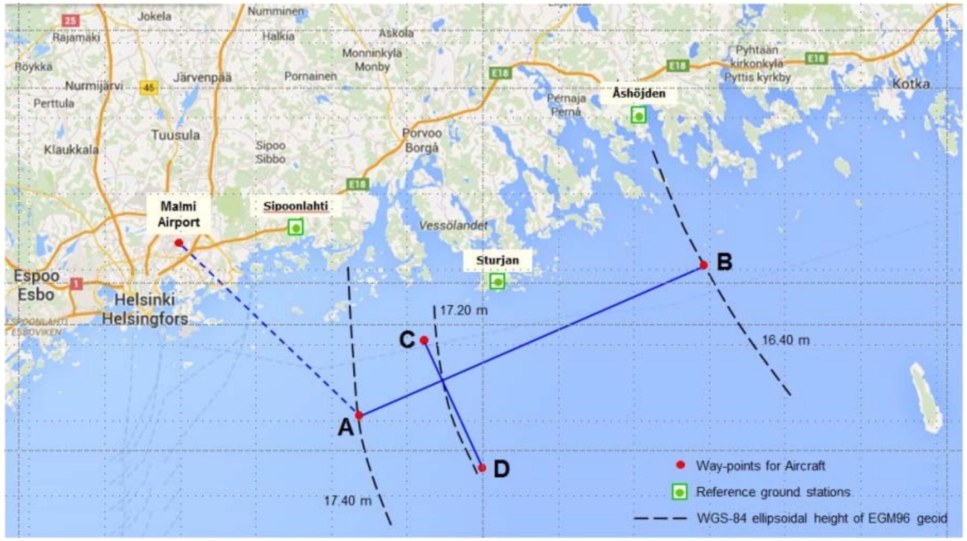
Objective:
Demonstrate sea surface height determination at several reflection points simultaneously using the GNSS-R interferometric technique

Participants:
Institute of Space Studies (IEEC-CSIC): GNSS-R payload
Aalto University in Helsinki: Skyvan aircraft
British Antarctic Survey: TwinOtter aircraft
Technical University of Denmark: ASIRAS (airborne version of CRYOSAT payload)
Technical University of Dresden: Laser on Skyvan

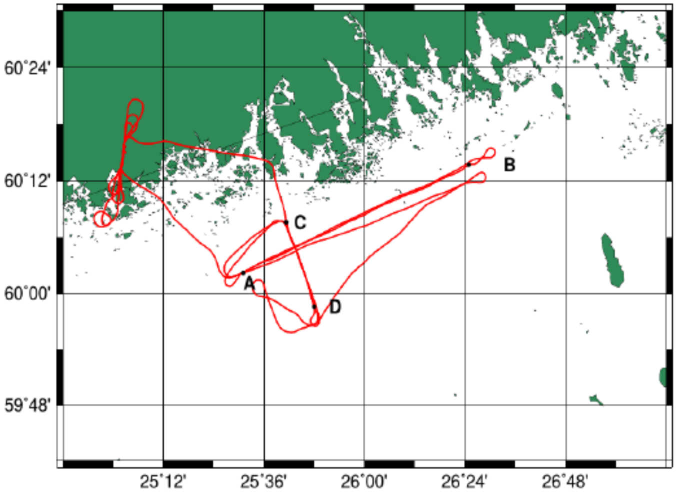
Experiment Plan:
- Fly parallel to geoid gradient (A to B) and perpendicular to it (C to D)
- GNSS-R with SPIR/Skyvan
- Conventional altimetry with ASIRAS/TwinOtter
- Lasers on both aircraft for reference/calibration
- 3 ground dual-frequency GNSS receivers along coastline for reference
- Dual-frequency GNSS receivers on both aircraft
- Skyvan and TwinOtter in loose flight formation along cross pattern

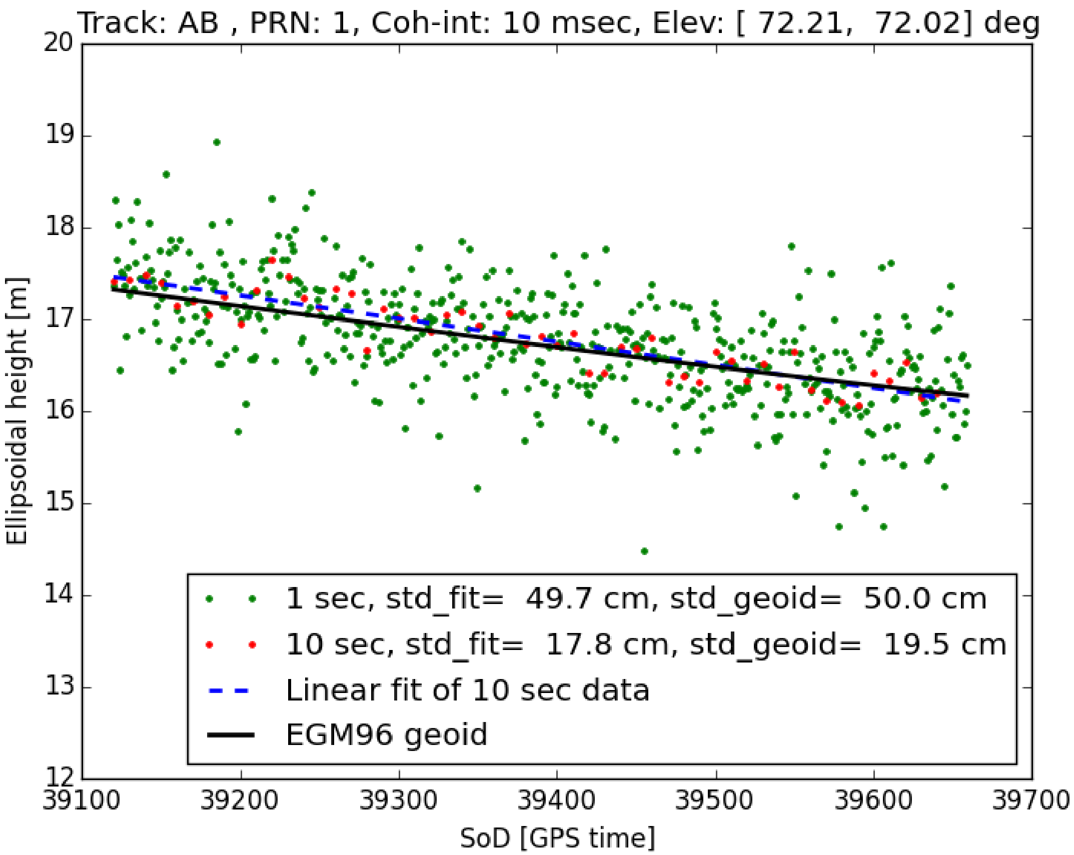
Status:
- Three flight campaigns carried out

Baltic flight experiment (2/2)



Baltic flight experiment





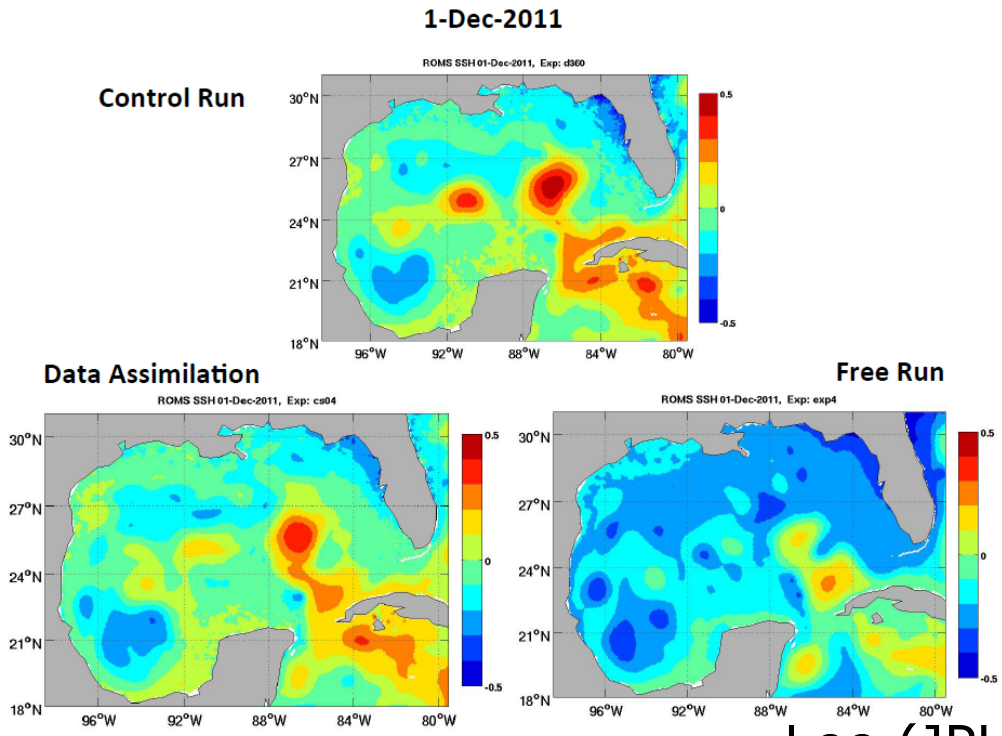
Courtesy IEEC

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

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 deteceted, even with assumed 50 cm Std error randomly (by averaging ~10-20 cm), 10 km footprint

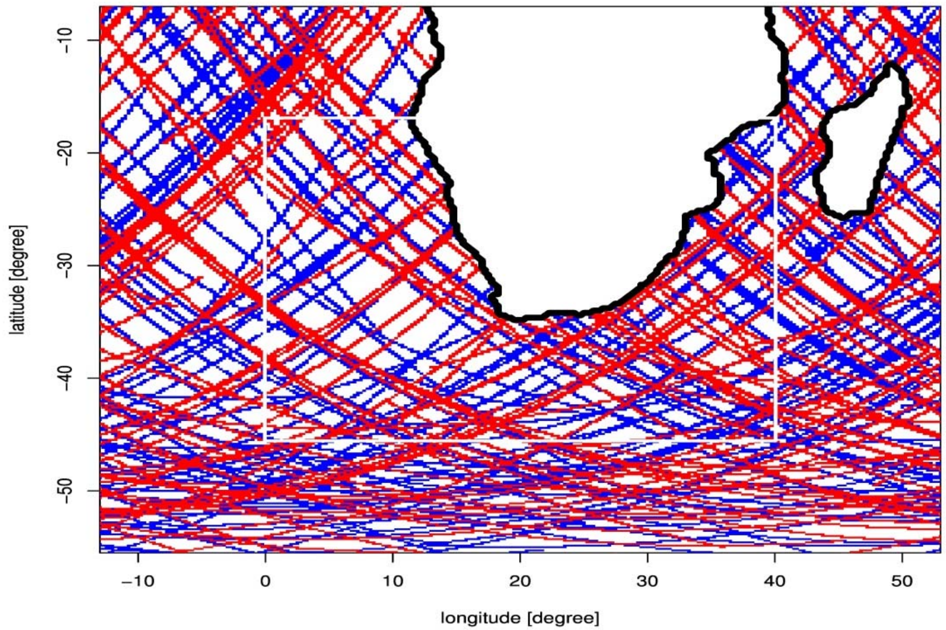
1 month after initialization



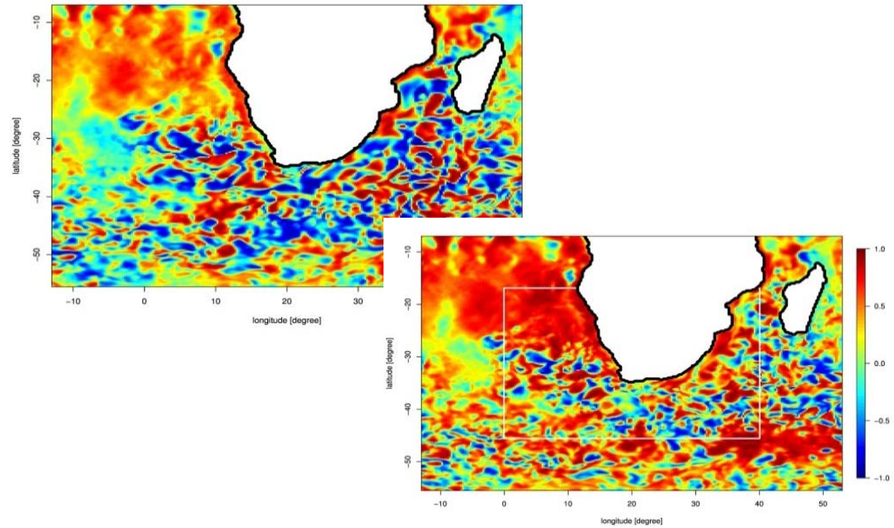
Lee (JPL) et al., 2013

OSSE study with simulated GEROS-ISS data

Observation tracks, day1 (red), 2 (blue)



Covariance SSH „truth"- reconstructed without and with GNSS-R 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

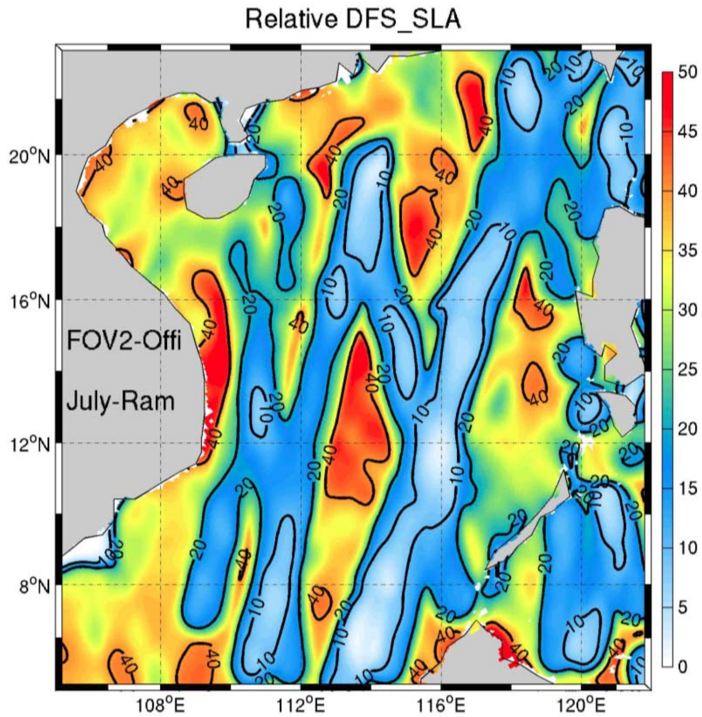
NERSC, Norway

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 recon-struction with GNSS-R F-FoV2 compared to use of traditional altimetry satellite data only
up to 50%
(for GEROS up to 20%)

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 Phase A with two competitive industrial studies and a related science activity GARCA, initiated by ESA, 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 under review