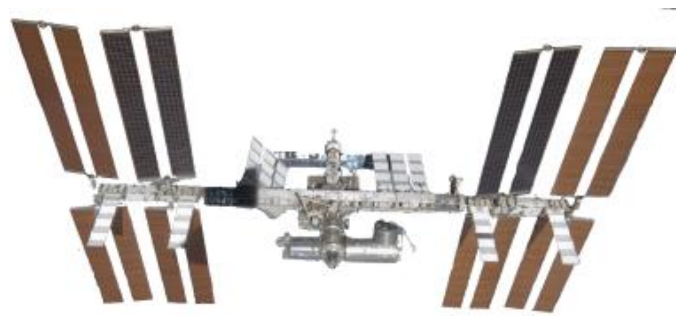
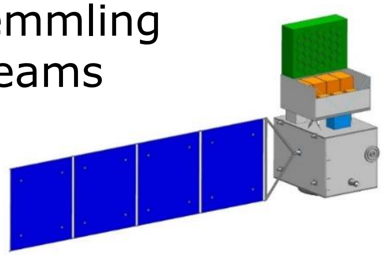




GNSS Reflectometry from Space for Earth Observation: GEROS-ISS and G-TERN

(complemented by information on GRACE-FO/AtmoSat)

J. Wickert, E. Cardellach, A. Camps, N. Catarinho, C. Gommenginger, G. Foti,
S.V. Nghiem, H. Park, N. Pierdicca, J. Saynisch, M. Semmling
& many others from the GEROS-ISS and G-TERN teams



GFZ Helmholtz Centre Potsdam

IEEC

IROWG 2017
Sep 25, Estes Park

esa

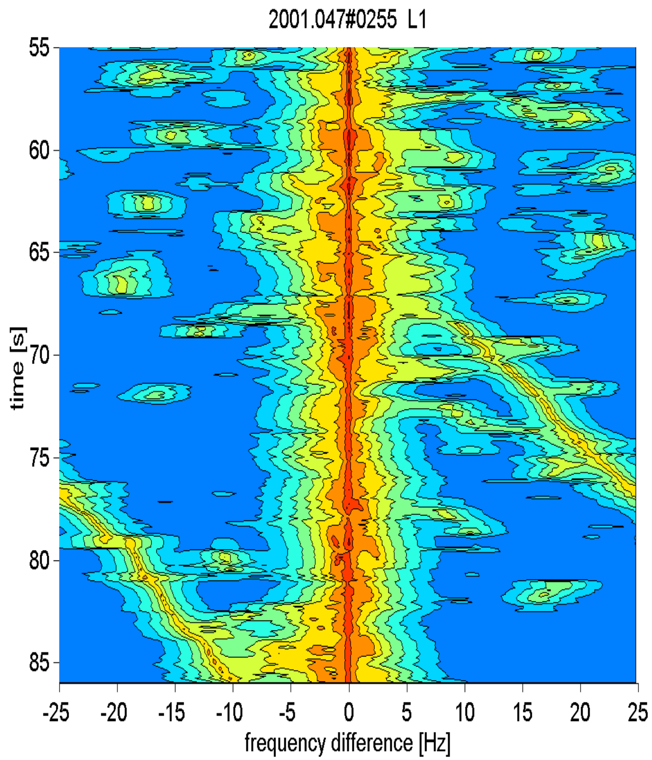
Outline

- Some motivation
- Overview on GEROS-ISS activities
  GNSS rEflectometry Radio Occultation and Scatterometry aboard the ISS
- Introduction G-TERN
  GNSS-Transpolar Earth Reflectometry moNitoring System
- Some information on GRACE-FO and AtmoSat
- Short Summary

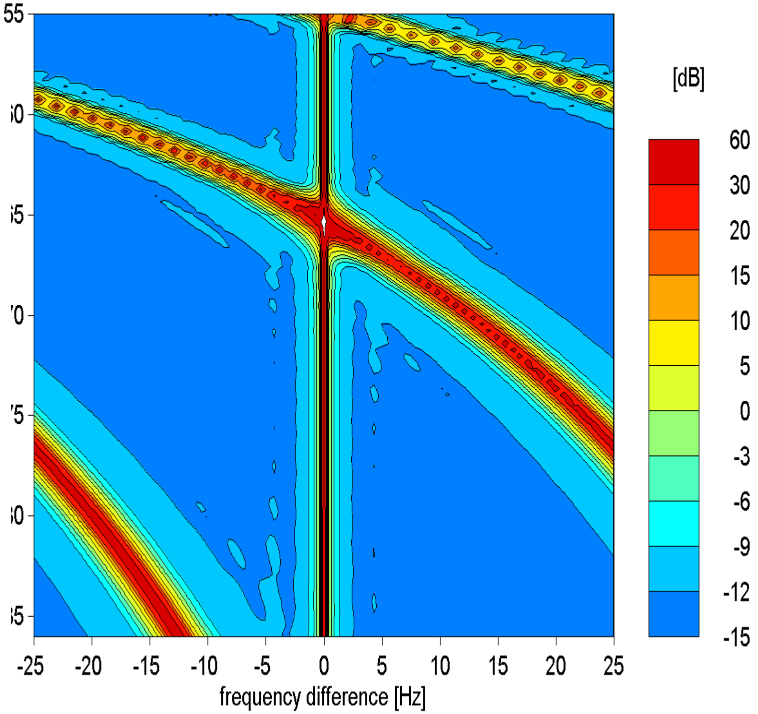
Motivation

Signatures of reflected signals in GPS/MET data

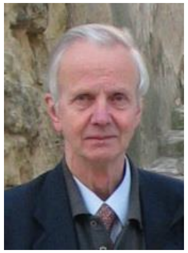
Observation



Model



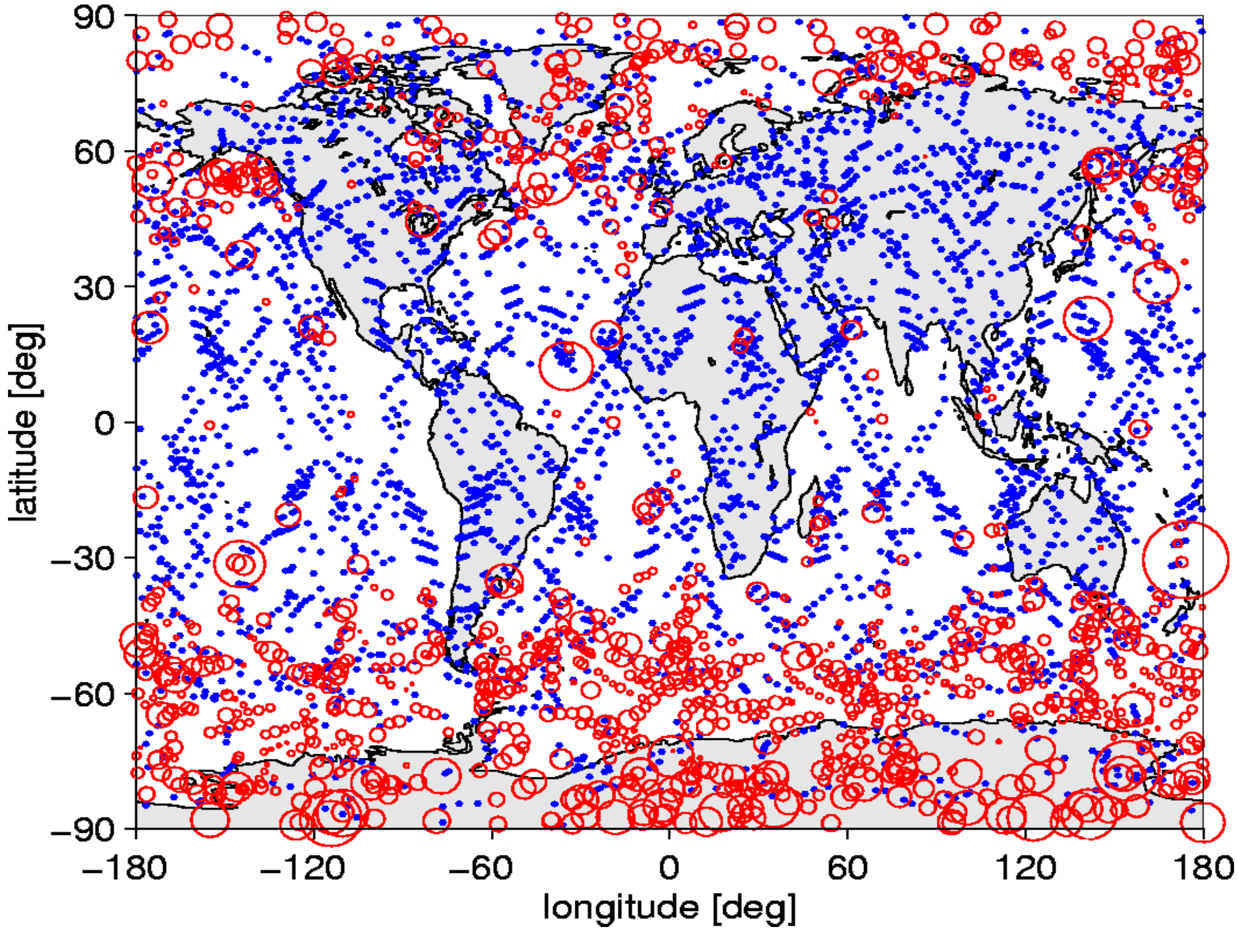
Beyerle and Hocke, GRL, 2001 with GPS/MET data



A. Pavelyev

Visiting Scientist stays DLR/GFZ

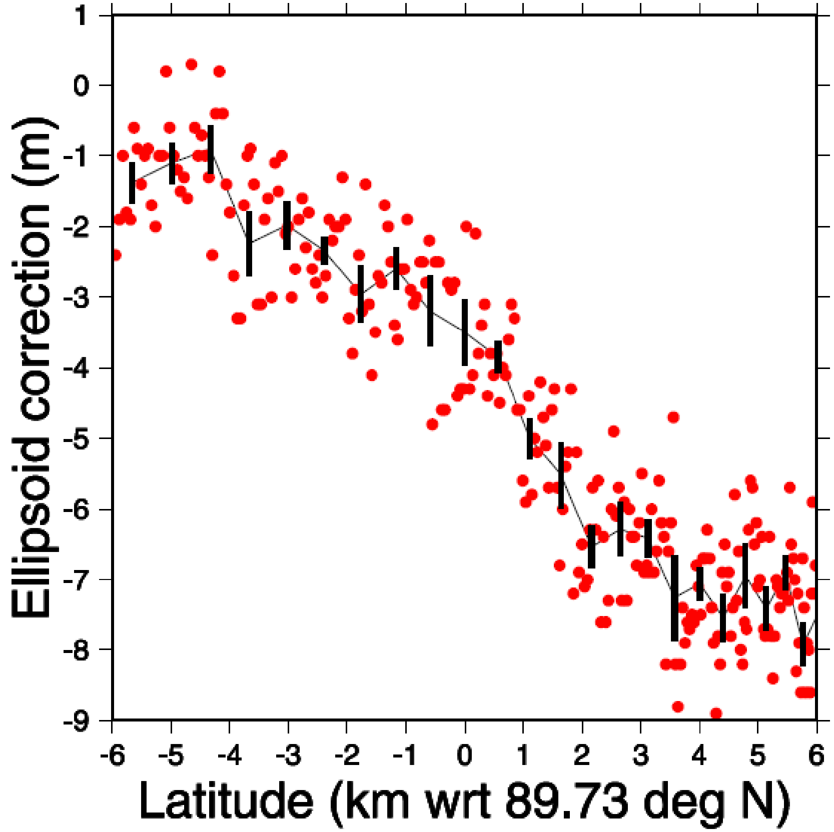
Global distribution of reflection events (CHAMP)



red Reflection **blue** Occultation w/o reflection

Beyerle et al., JGR, 2002

Carrier phase altimetry with CHAMP



- Topographic ice-profile at North-Pole
- 70 cm precision, ~ 1 km horizontal sampling

Cardellach et al., GRL, 2004

Why not proposing combined RO/Reflectometry mission(s)?

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

*   *   *   *   *

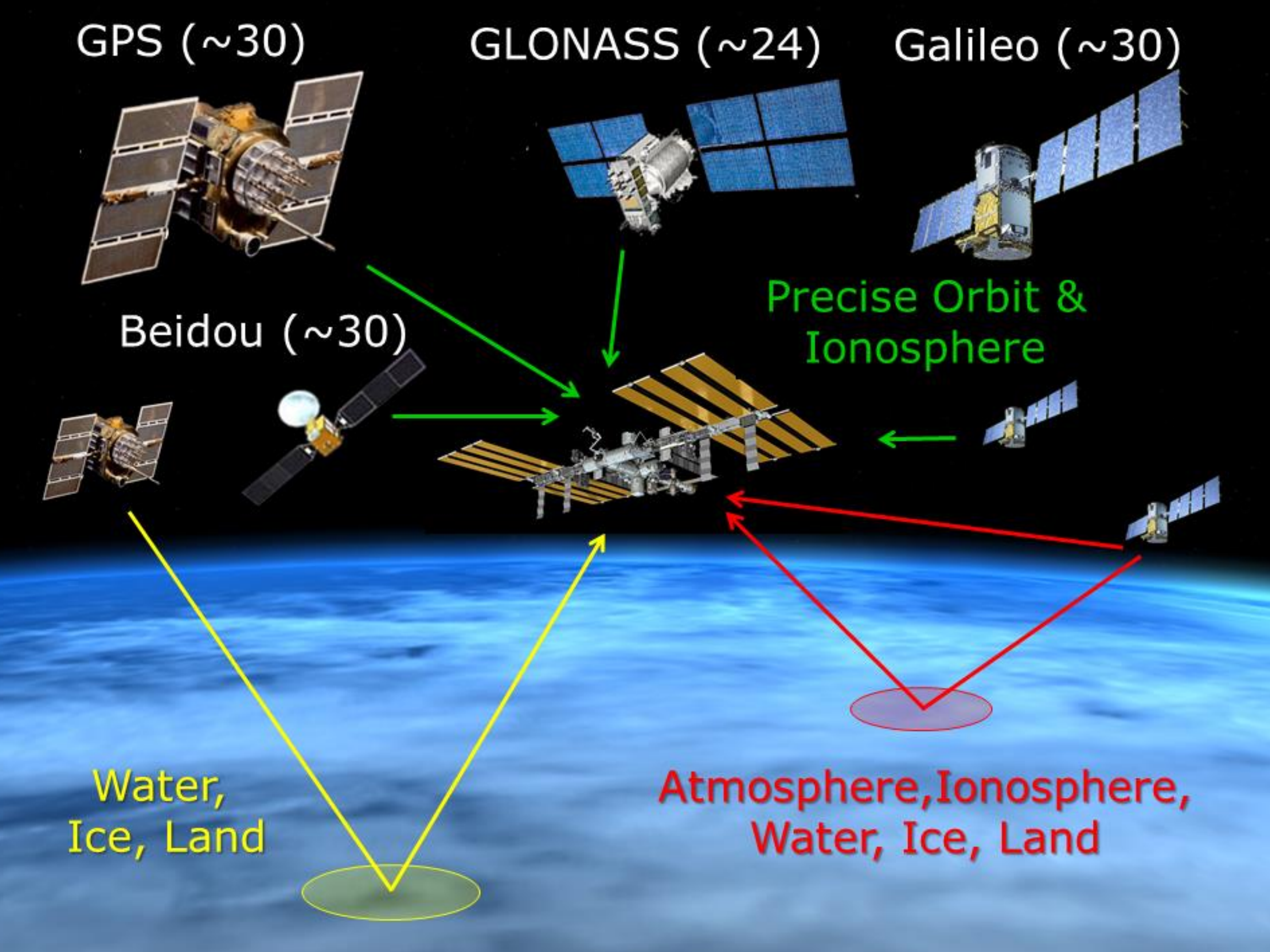
Proposal due:

4th November 2011

25 letters of intent submitted, 237 science team members

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

Proposing Team from:
Germany, Spain, U.S., Denmark, Switzerland, Sweden

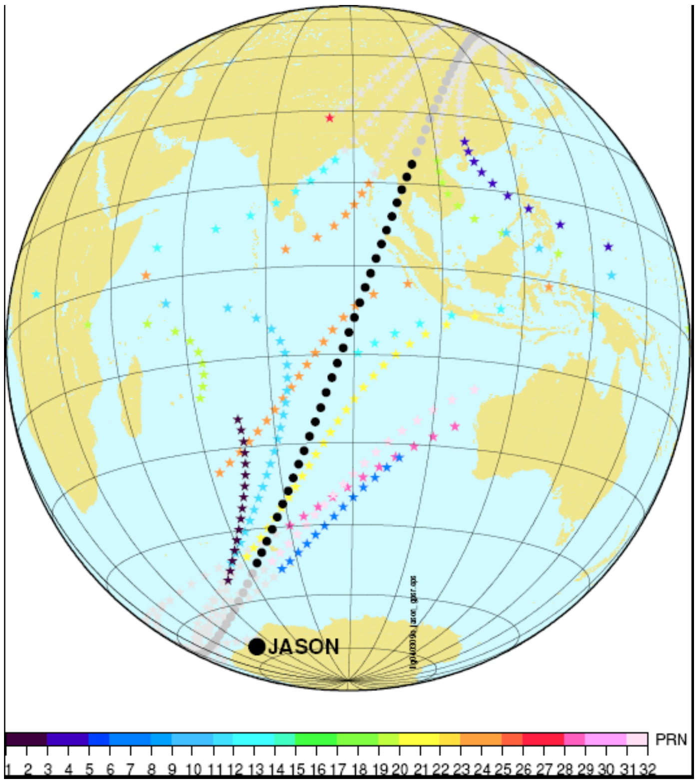

GPS (~30)
GLONASS (~24)
Galileo (~30)
Beidou (~30)
Precise Orbit &
Ionosphere
Water,
Ice, Land
Atmosphere,Ionosphere,
Water, Ice, Land

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)



Main Mission objectives of GEROS

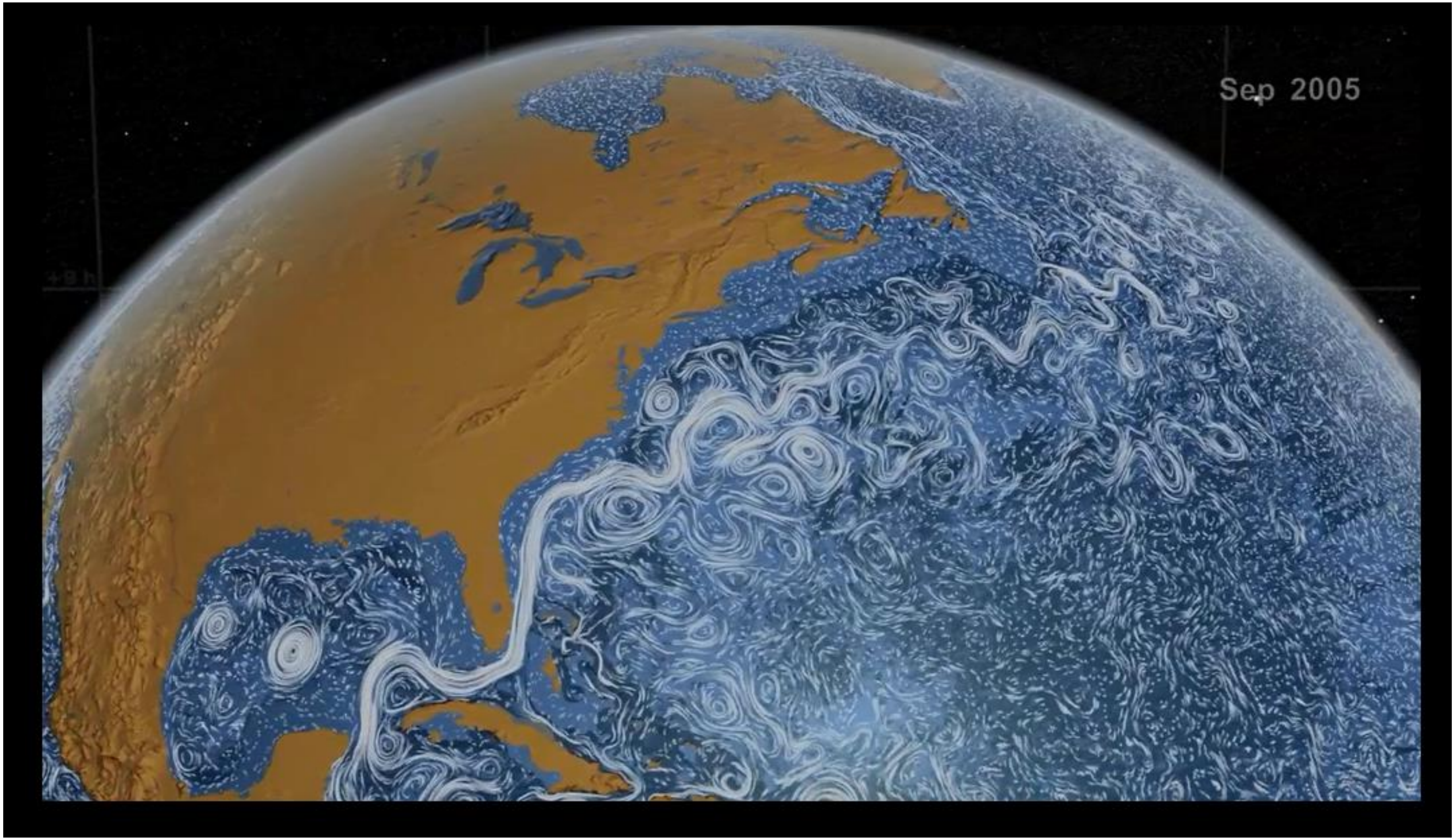
Primary:

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)



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) 2022

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

GEROS-ISS: Status

Interdisciplinary Science Advisory Group (SAG) 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)

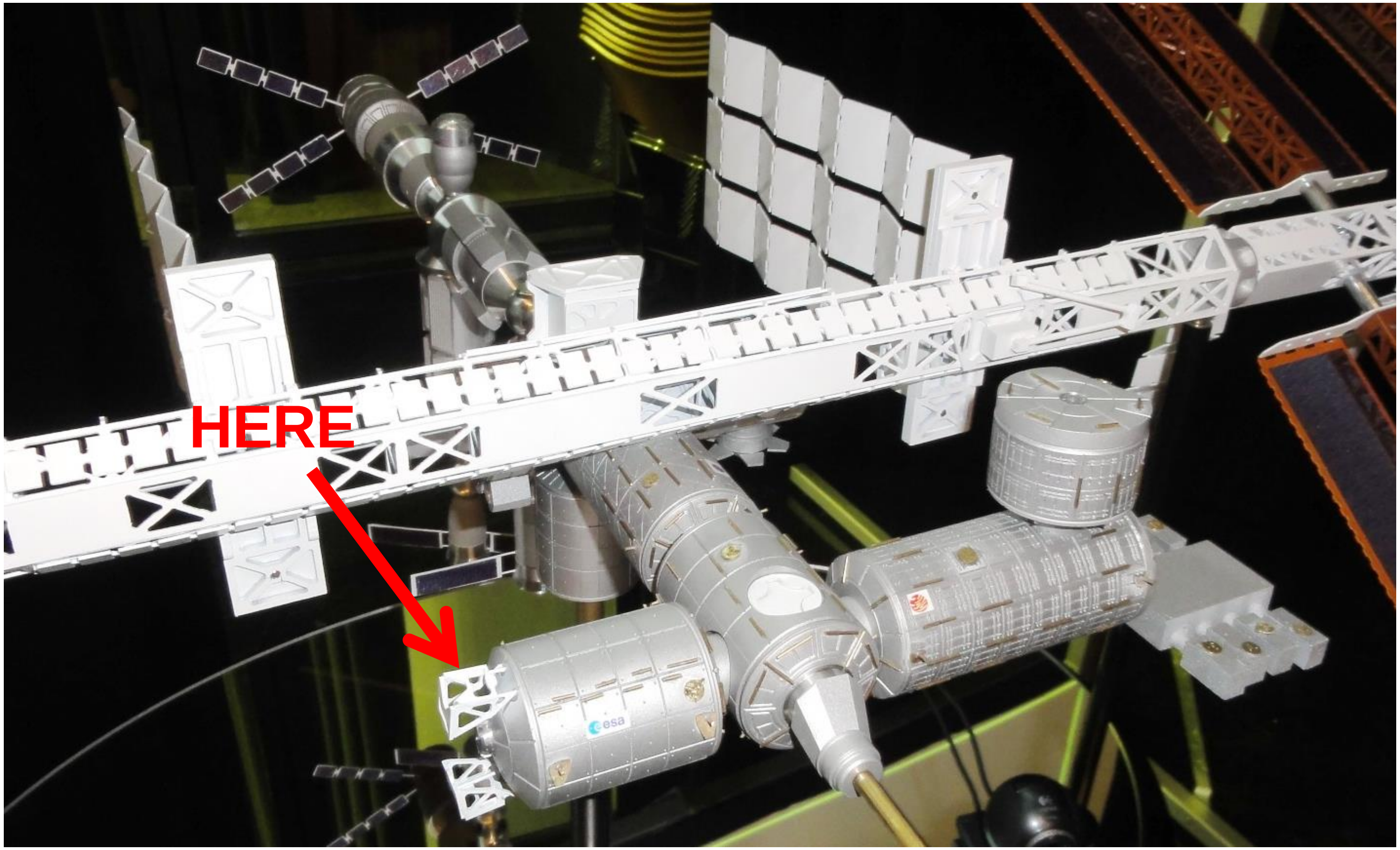
Link to other missions/projects (CYGNSS, TDS-1, E-GEM)

Three OSSE ocean observations (JPL, GFZ, NERSC)

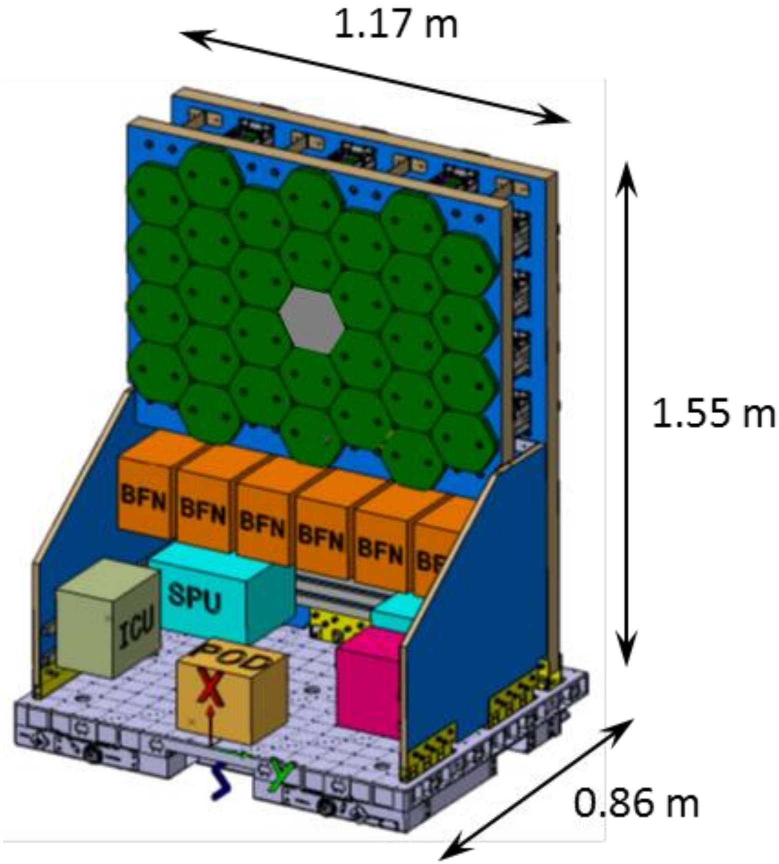
Currently cost reduction exercise finished and EE-9 proposal with strong GEROS heritage submitted (G-TERN)

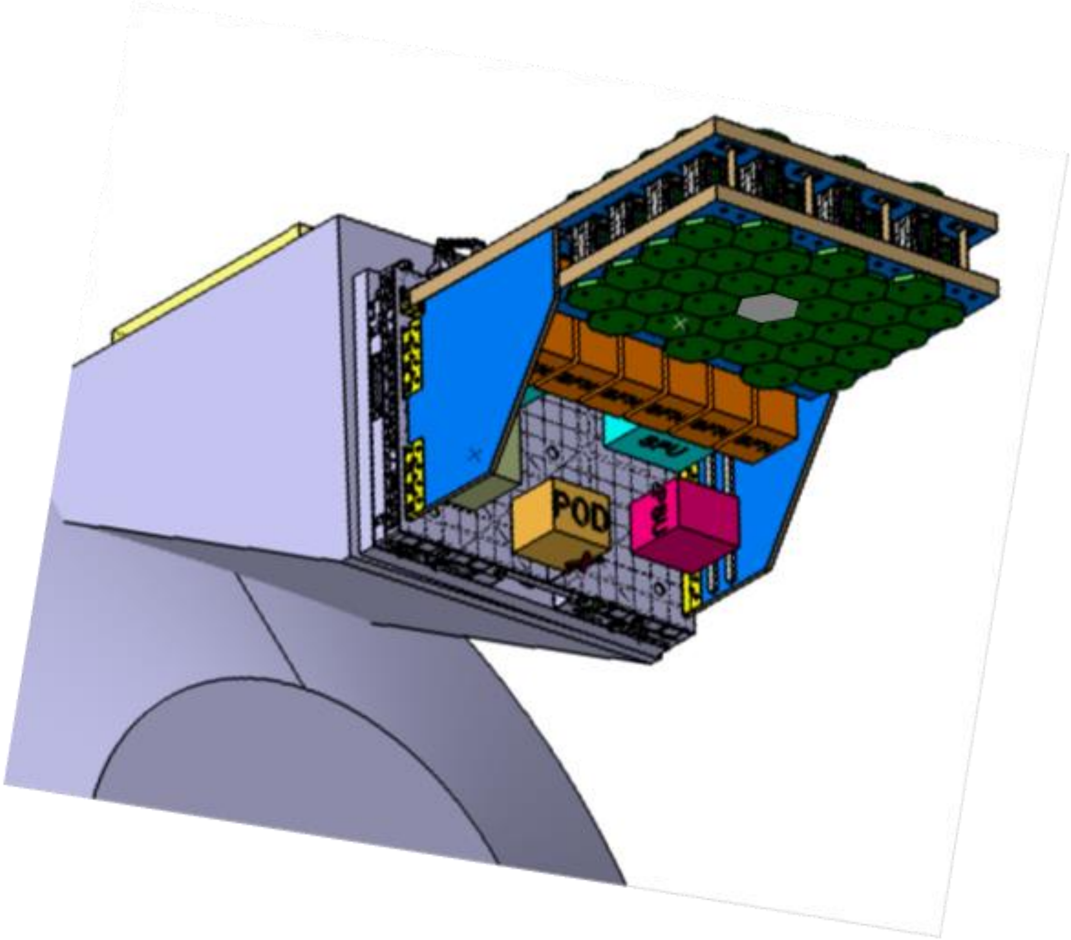
GEROS payload

GEROS: Where to mount?



GEROS Payload on Columbus





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

Courtesy: ADS-CASA

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 are public

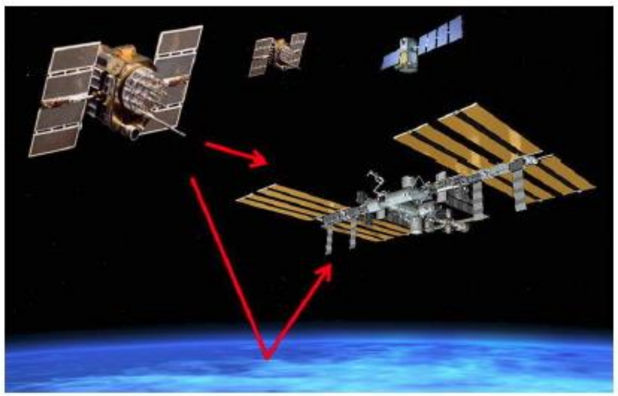
	GARCA Final Report	Ref. GARCA-FR Date 08/11/2016 Version 1.0 Page 1 / 464

Final Report

ESA-AO1-7850/14-GARCA-FR

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

GARCA



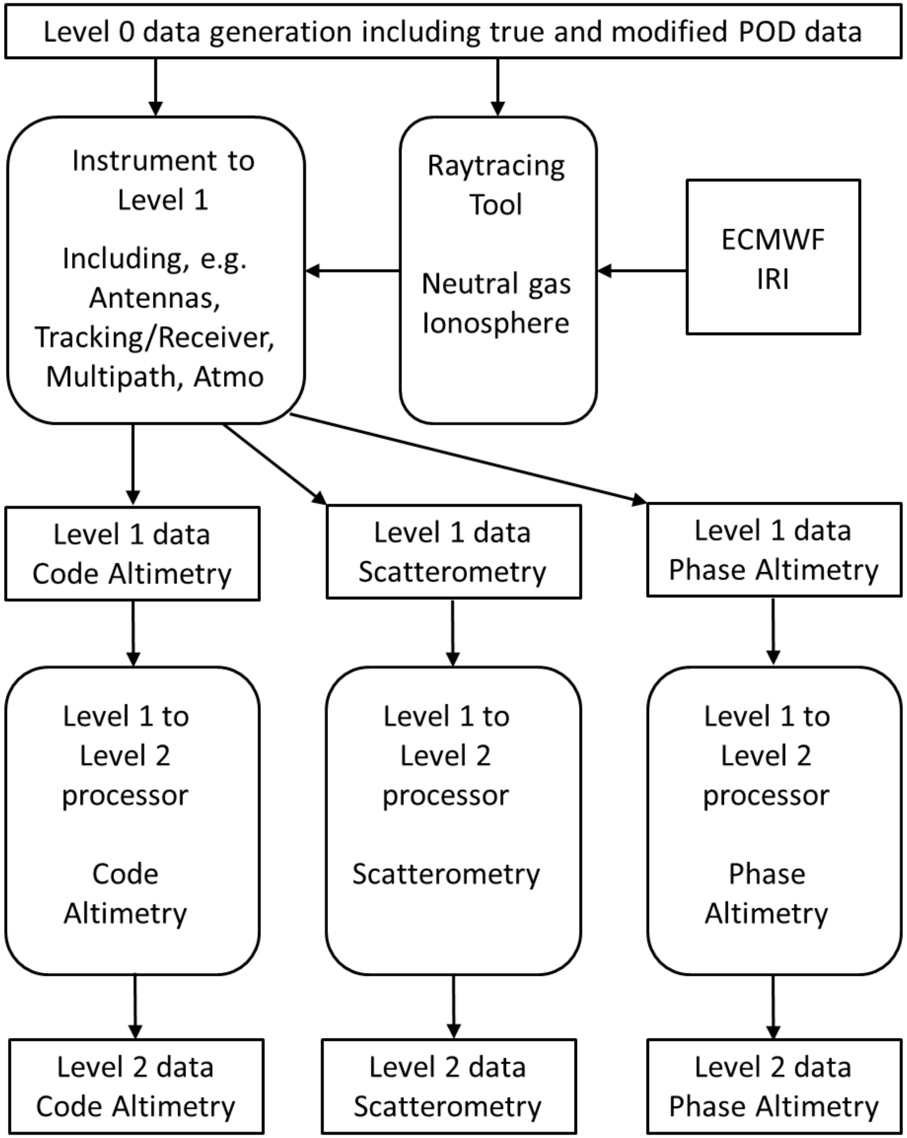
Potsdam, November 8, 2016

Contributors: J. Bandeiras (JB, DEIMOS), L. Bertino (LB, NERSC), E. Cardellach (EC, IEEC), N. Catarino (NC, DEIMOS), A. Camps (AC, IEEC), B. Chapron (BC, Ifremer), F. Fabra (FF, IEEC), G. Foti (GF, NOC), C. Gommenginger (CG, NOC), H. Park (HP, IEEC), A. Rius (AR, IEEC), M. Semmling (MS, GFZ), A. Sousa (AS, DEIMOS), J. Wickert (JW, GFZ), J. Xie (JX, NERSC)

GARCA Final Report

pp 464; Nov 8, 2016

GARCA: GEROS-SIM



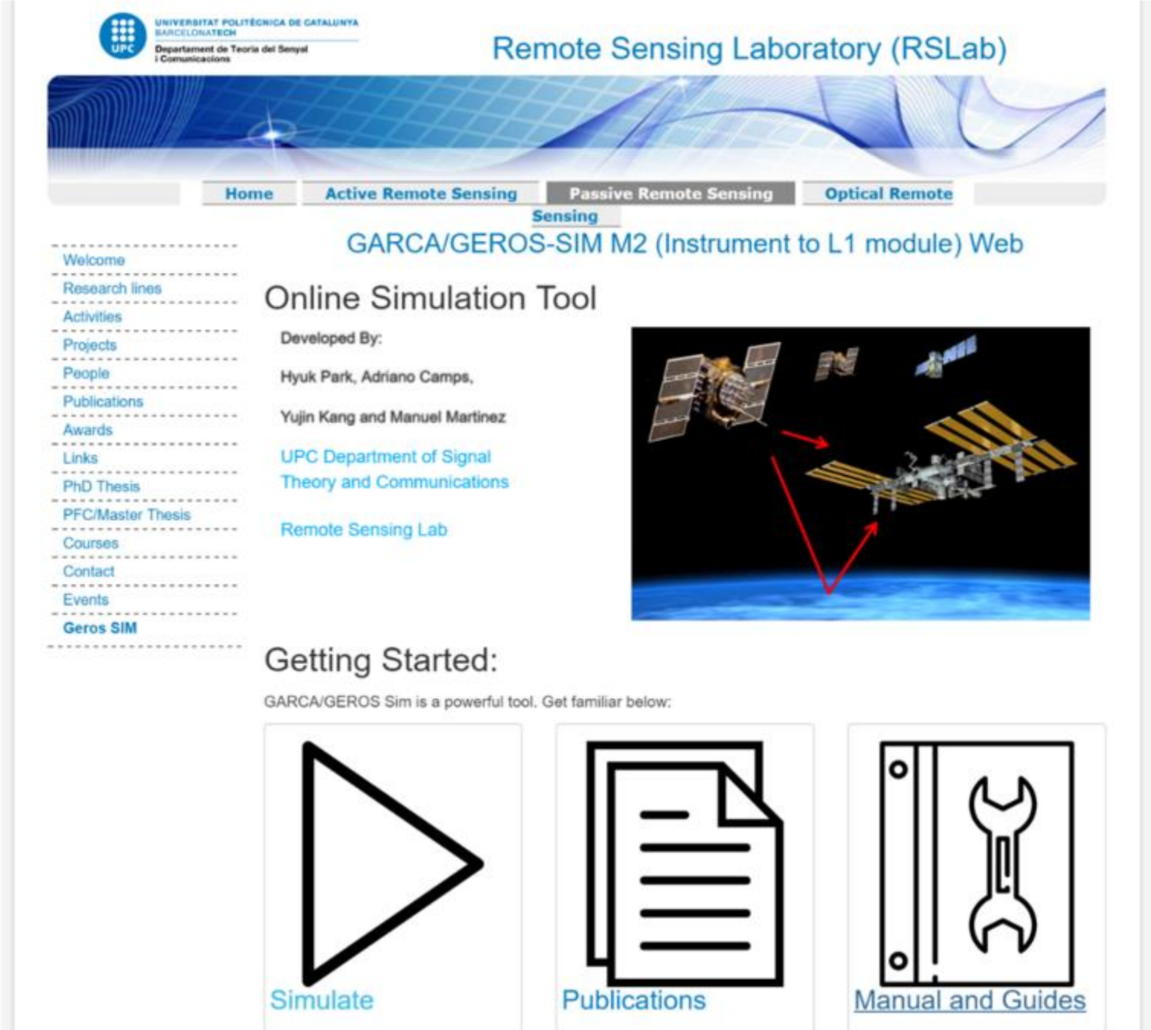
Instrument parameters, GNSS-R observables (Level 1) and geophysical observables (Level 2)

Core: PAU/PARIS
E2E Performance Simulator
IEEC

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

GEROS-SIM: Web-Interface

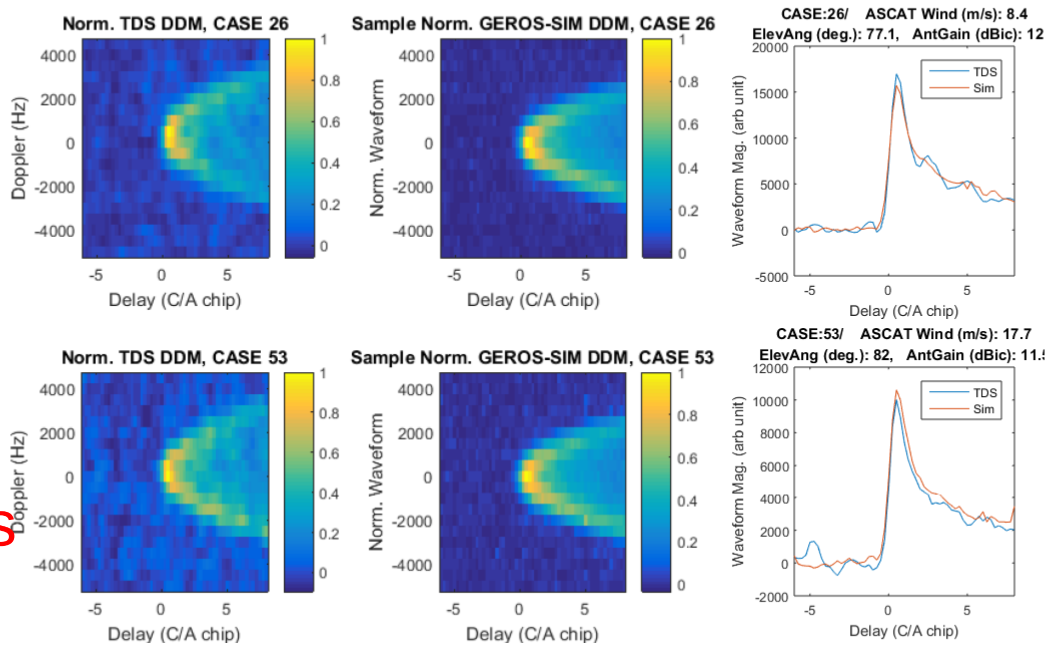
www.tsc/upc.edu/rslab/gerossim



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

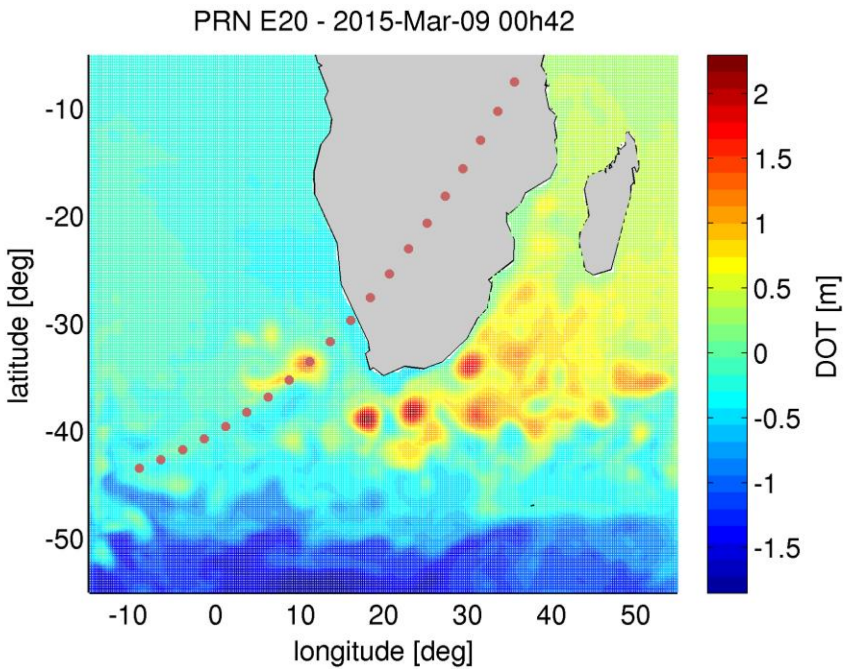
Integration time:	Along-track resolution:	Across-track resolution:	Precision figure:
L5 with 'clean' ionospheric correction			
1 second	7.5 km	4 km	11.3 cm
14 seconds	100 km	4 km	3.0 cm

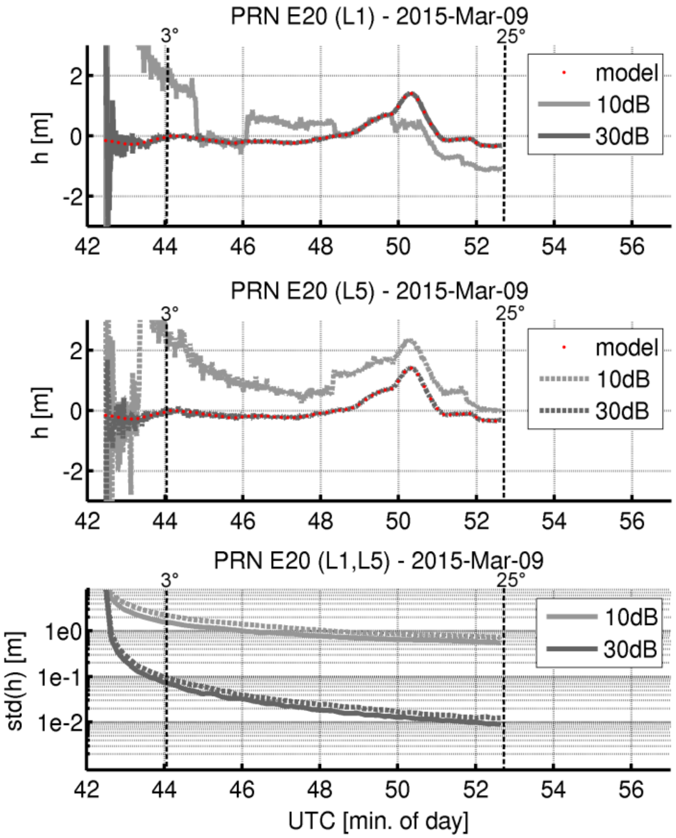
precision 3.0 cm

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

GEROS-SIM: Phase Altimetry

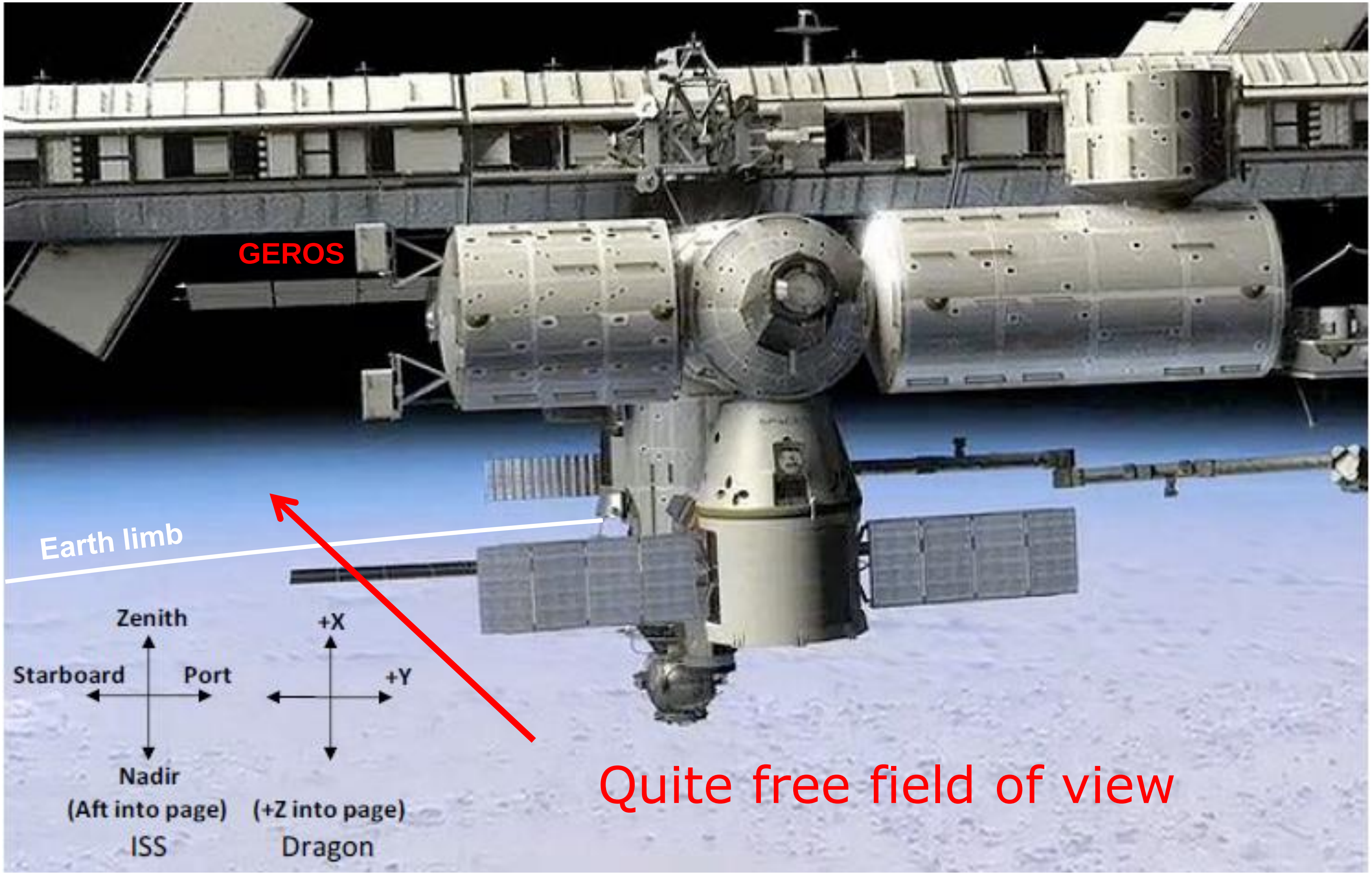
SSH reconstructions (L1,L5)



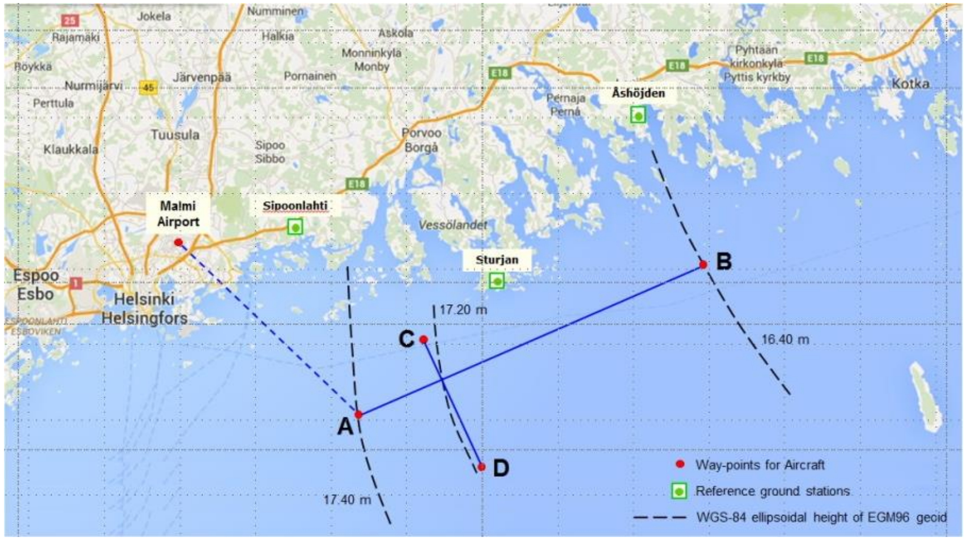


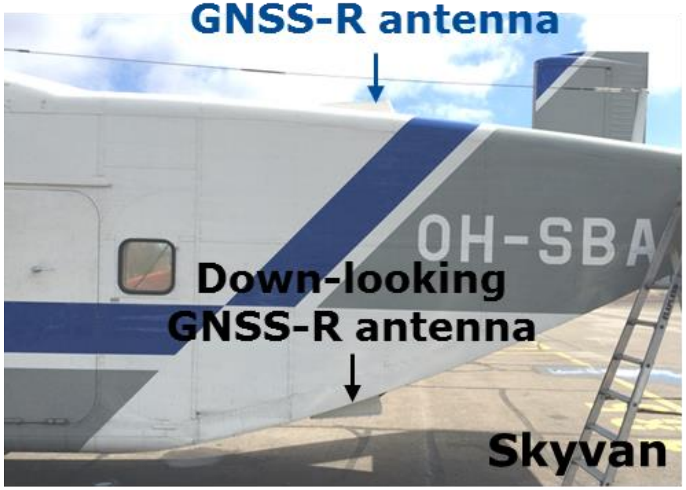
Ground track for the ISS example event in Agulhas region (left)
Retrieved SSH and precision estimate for different SNR (right)
Precision (1s, 7.5/0.5km along/across-track: **0.11 m** (30 db, 5 cm POD)

Anti-Velocity Radio Occultation

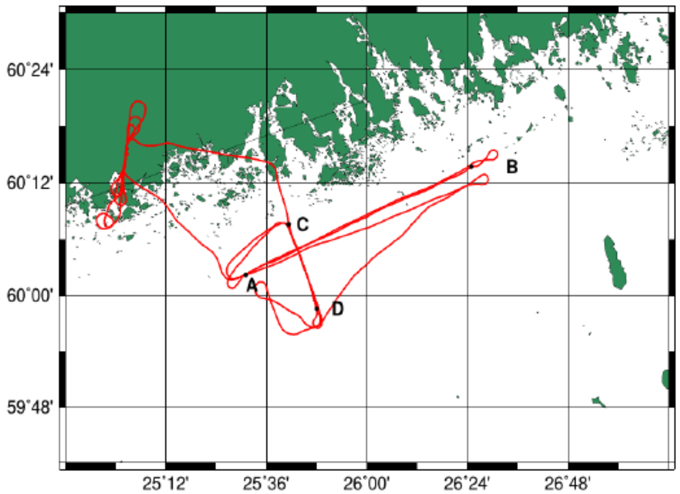


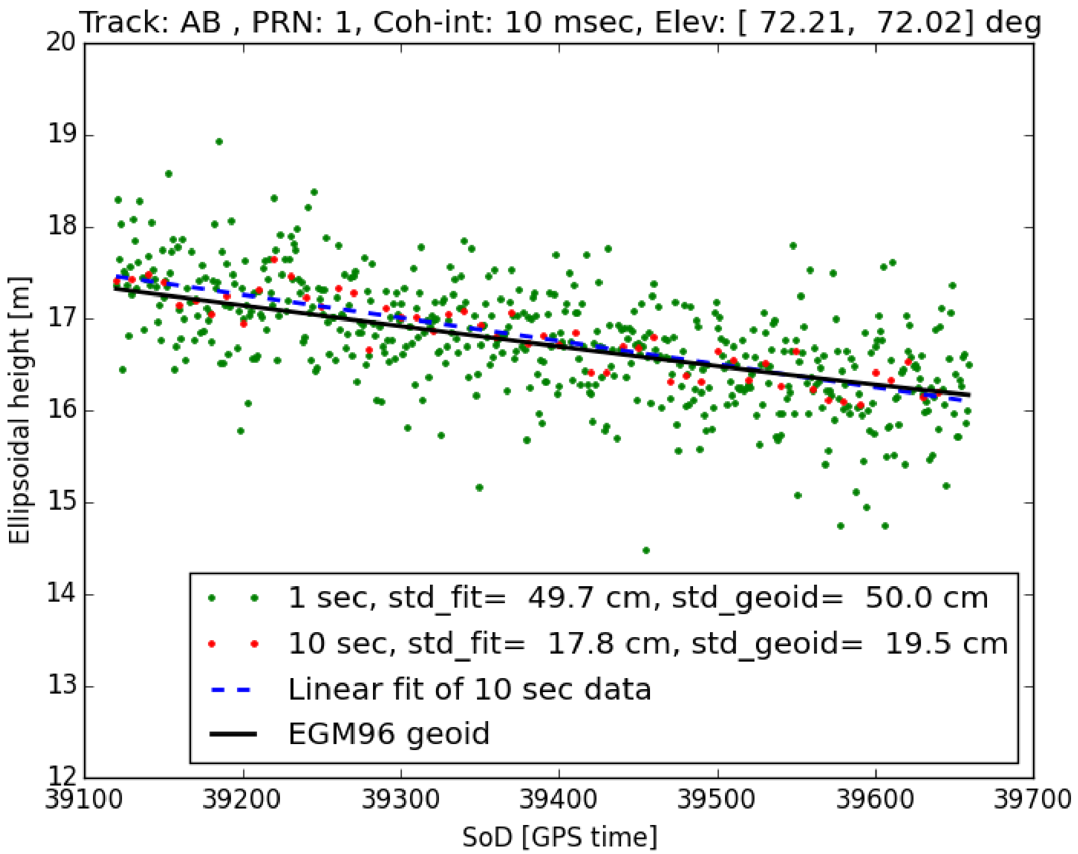
Baltic flight experiment (1/2)





Baltic flight experiment (2/2)





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 in South China Sea during Typhoon Rammsun

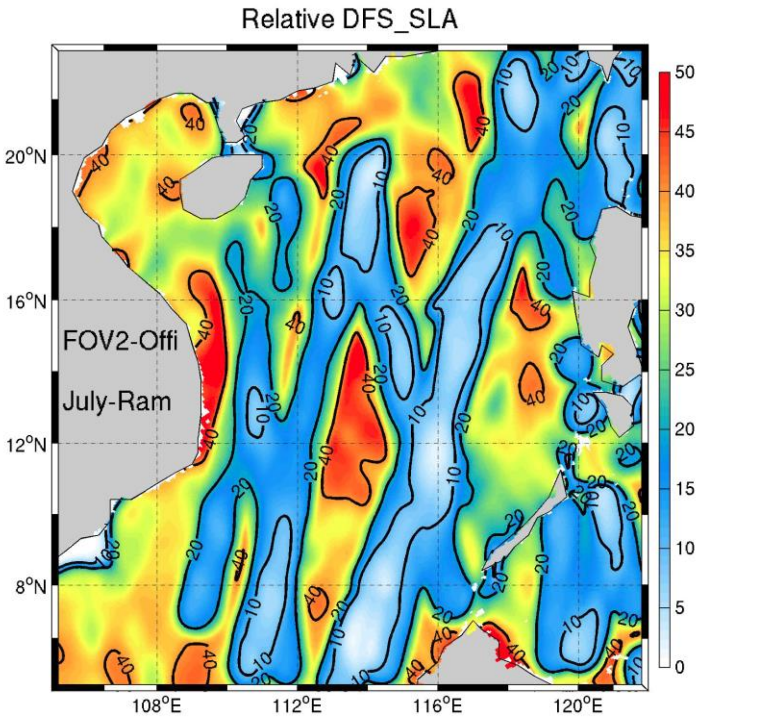
NERSC, Norway

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, 2017)



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%)

Recently finished: Cost reduction exercise

Cost reduction exercise

Objective: to bring the cost of GEROS-ISS payload from >50 significantly down, ~25% reduction was reached

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

Simplifications at science level:

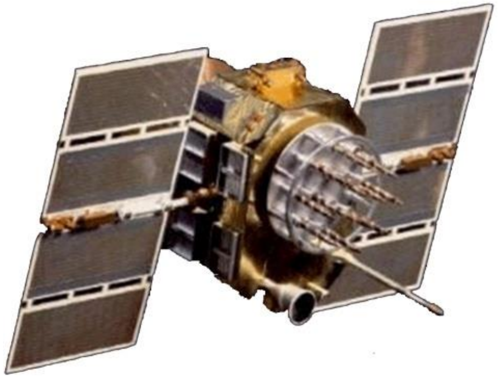
Simultaneous measurement of the 2 polarizations (RHCP and LHCP) is not required
Polarimetric Radio-Occultation is not required

Schedule: begin Phase B in 2018, Launch 2022

But in general funding decision pending: Decision to apply in Earth Explorer 9 call from ESA

Earth Explorer Programme ESA

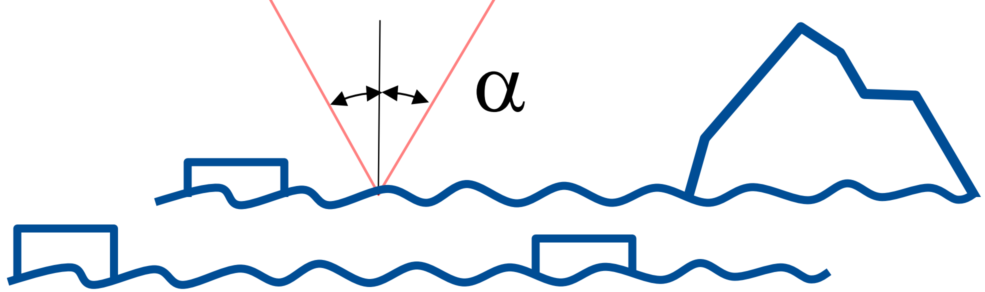
- Earth Explorer missions form the science and research element of ESA's Living Planet Programme and focus on the atmosphere, biosphere, hydrosphere, cryosphere and Earth's interior.
- However, the emphasis is also on learning more about the interactions between these components and the impact that human activity is having on natural Earth processes.
- Core and opportunity missions (smaller, “low-cost”, quick to implement, immediate environmental concern)
- Core (4): GOCE, Aeolus, EarthCARE, Biomass
- Opportunity (4): SMOS, CryoSat, Swarm, FLEX
- Earth Explorer 9 revised call for opportunity mission, deadline June 15, 2017, margin 150 Mio €

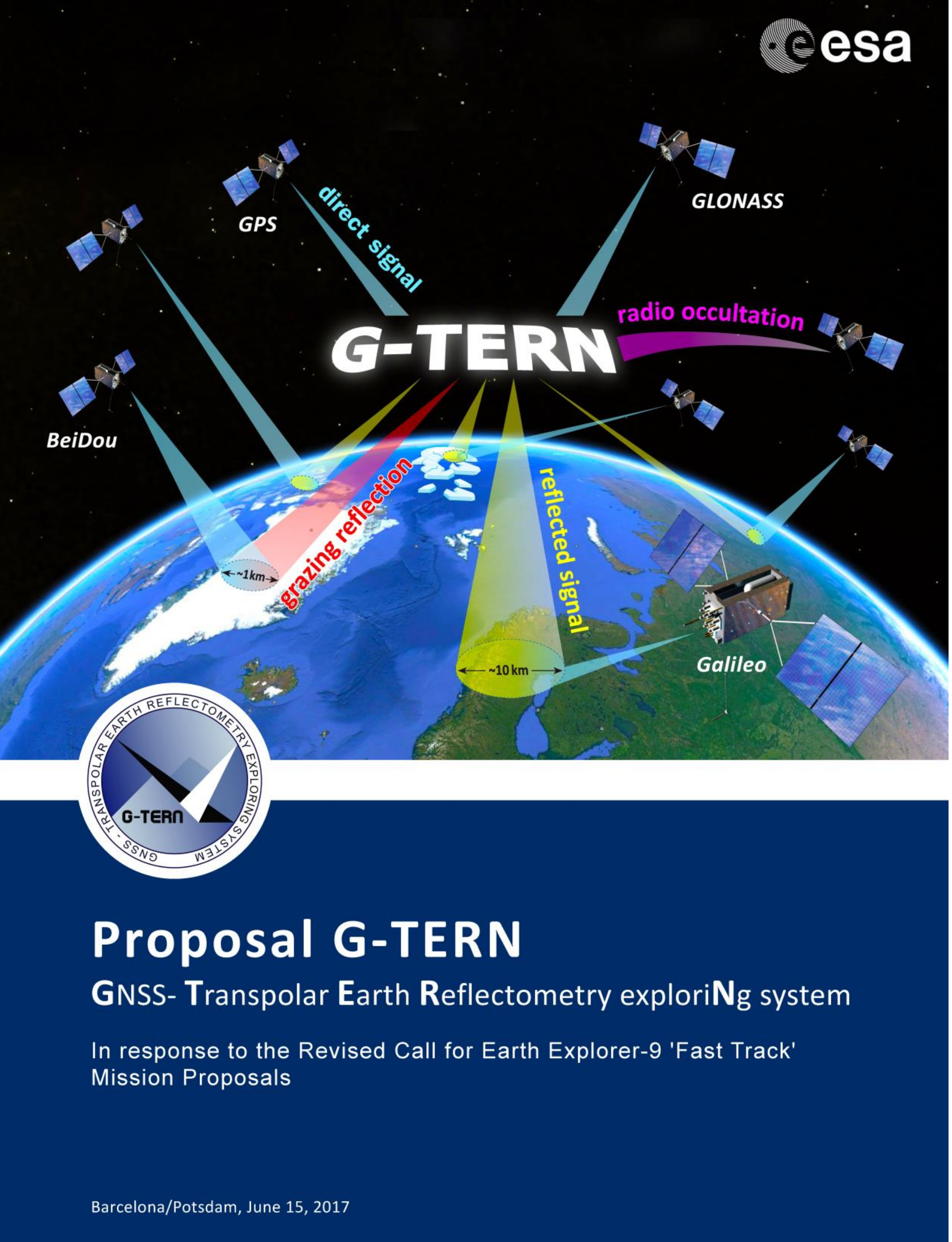


Earth Explorer 9 proposal

G-TERN

GNSS – Transpolar Earth Reflectometry exploriNg system





Principal Investigators:

J. Wickert (GFZ, Germany)
E. Cardellach (IEEC, Spain)

Interdisciplinary science team:

Polar science
Oceanography
Sea level
Climate
Meteorology
Land applications
Geodesy and GNSS
Space engineering
Space weather

25 colleagues from 11 countries

Industry team:

8 colleagues from 7 companies in
5 countries, including
OHB (prime), Airbus, RUAG

G-TERN team by countries (12)

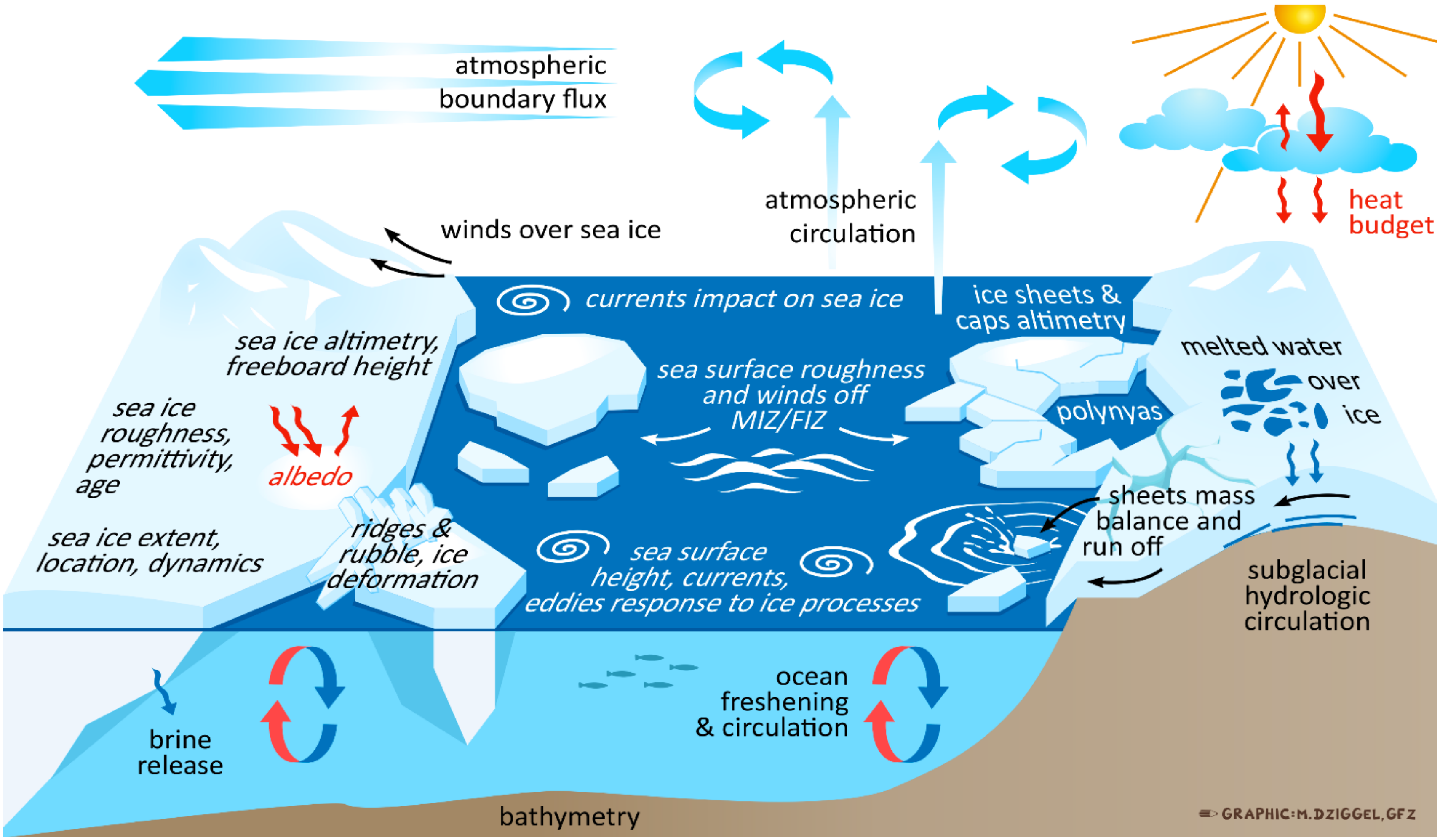
Principal Investigators

Germany and Spain: J. Wickert and E. Cardellach

Science and technical team members

Austria:	H. Fragner, A. Steiner
Canada:	G. Flato
Denmark:	P. Høeg, S. Abbas Khan
Finland:	J. Kainulainen, K. Rautiainen
France:	B. Chapron, F. Soulat
Germany:	R. Baggen, C. Haas, N. Lemke, I. Sasgen, M. Semmling, S. Tailhades, M. Thomas
Italy:	N. Pierdicca
Portugal:	N. Catarinho
Spain:	J. Benito, A. Camps, M. Hernandez-Pajares, C. Gabarró, M. Portabella, A. Rius, R. Vilaseca
Switzerland:	A. Jäggi
U.K.:	C. Gommenginger, S. Healy
U.S.A.:	S. V. Nghiem, C.K. Shum, C. Zuffada

G-TERN's focus is cryosphere and interations with hydrosphere, atmosphere and land surface



G-TERN: Main science objectives

(1) how will highly dynamic forcings and couplings between the various components of the ocean, atmosphere and cryosphere modify or influence the processes governing the characteristics of the sea ice cover (ice production, growth, deformation and melt)?

(2) Influence of extreme events and feedback mechanisms on sea ice evolution

(3) Effects of cryosphere on the global oceanic and atmospheric circulation and mid-latitude extreme events

G-TERN: Secondary objectives (1/2)

potential to extract (additional) cryosphere data products as:

- snow cover over sea ice, its thickness and density
- sea ice permittivity, density and/or brine content
- sea ice surface melt onset and melt pond fraction
- distinction between modal (thermodynamic) and dynamical (deformation) growth of the sea ice?
- ice sheets and large caps, their surface elevation changes, mass balance, run offs, melting episodes, surface and sub-surface snow properties
- permafrost active layer changes, freeze and thaw phase, surface deformations
- seasonal snow in mid latitudes, its thickness and snow properties
- glacier evolution

G-TERN: Secondary objectives (2/2)

Land component:

(1) How the water coverage is changing in wetland areas (particularly swamp forests) in view of the rapid rate of wetland collapse?

(2) What is the role of wetlands in methane emission processes, especially in view of new pathways for methane emissions that can be potentially identified with frequent observations including densely vegetated and forested regions?

(3) How regional conditions, especially soil moisture, impact wetland inundation dynamics and affect regional atmospheric patterns that in turn impact the transport and distribution of methane emitted from wetlands?

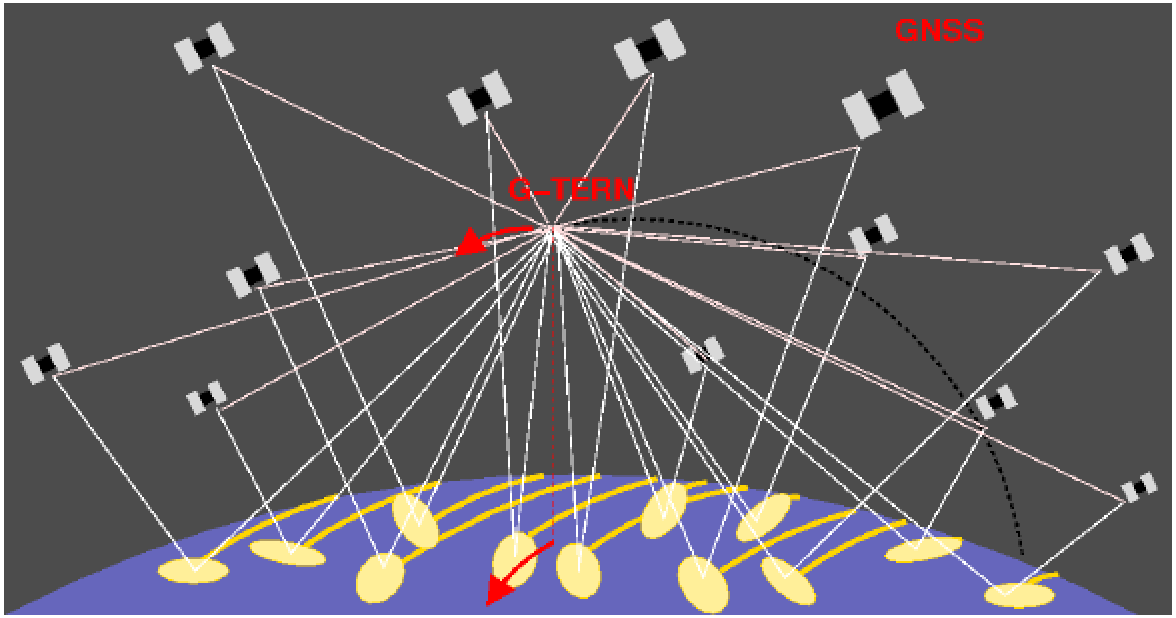
Main data products and observation requirements

Geophysical variables needed for the PRIMARY OBJECTIVE (Q1-Q3): requirements				
Variable:	Scope:	Spatial resolution:	Temporal resolution / coverage	Accuracy within spatio-temporal resolution
Sea ice elevation	P	30 km	3 d	10 cm
Sea ice roughness	P	30 km	3 d	10% of dynamic range → 0.0015 mss
Ocean surface elevation	P	30 km	3 d	10 cm
	G	0.5 deg	10 d	10 cm
Ocean surface roughness	P	10 km along-track	1 s / 3 d	0.002 mss or 10%
	G	10 km along-track	1 s / 10 d	0.002 mss or 10%

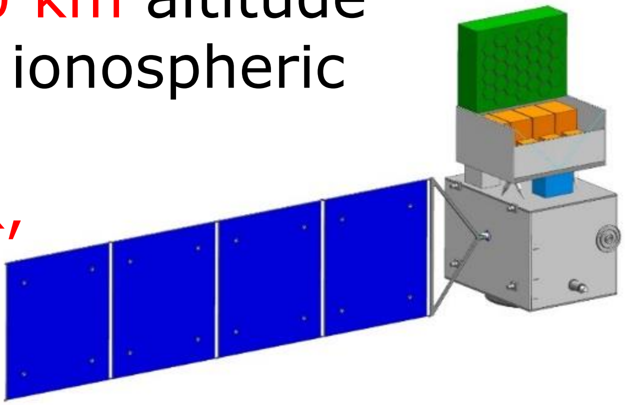
Table 2.0: Scientific observational objectives here expressed as level-3 (gridded or averaged) products.

Actual spatial resolution of 1-snapshot reflection:
~ 300-600 m when coherent (e.g. sea ice)
~10 km when diffuse (e.g. ocean)

Observation concept (1/2)

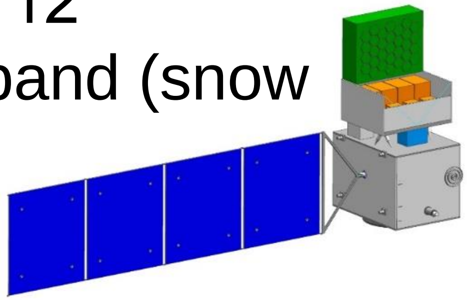


- One satellite, near-polar orbit at ~ 600 km altitude
- Sun-synchronous 6AM/6PM (to reduce ionospheric effects in altimetric retrievals)
- Payload with 2-freq and 2-pol iGNSS-R, GNSS-RO, GNSS-POD



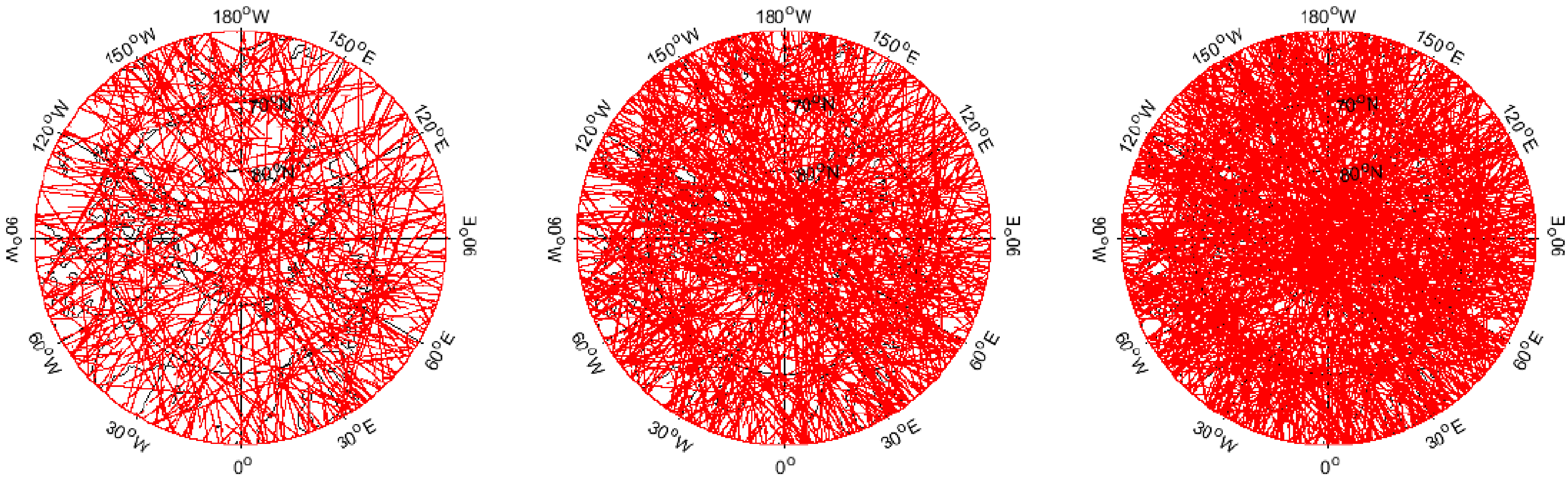
Observation concept (2/2)

- Strong heritage from GEROS-ISS observation concept, which was investigated within technical and scientific Phase-A studies
- iGNSS-R: interferometric GNSS-R, which has bandwidth 10 times larger than conventional GNSS-R (e.g. CYGNSS, TDS-1) for optimal altimetric performance.
- High directive antenna arrays looking up and down, each one with capability to synthesize and dynamically steer 12 beams. Each beam points to a single GNSS satellite transmitter (or its reflected specular point) → 12 simultaneous observations at 2-pol 2-freq L-band (snow penetration) within ~2,000 km swath.



Polar observation coverage

1 day | 2 days | 3 days



- Examples of the G-TERN's 12 simultaneous reflections, at 1Hz rate over the North pole.
- The distribution of reflection points does not follow a repeatable pattern, but it keeps the latitudinal statistics.
- Each observation point could provide altimetry (surface elevation), scatterometry (roughness), polarimetry information.

Examples with existing data (1/2)

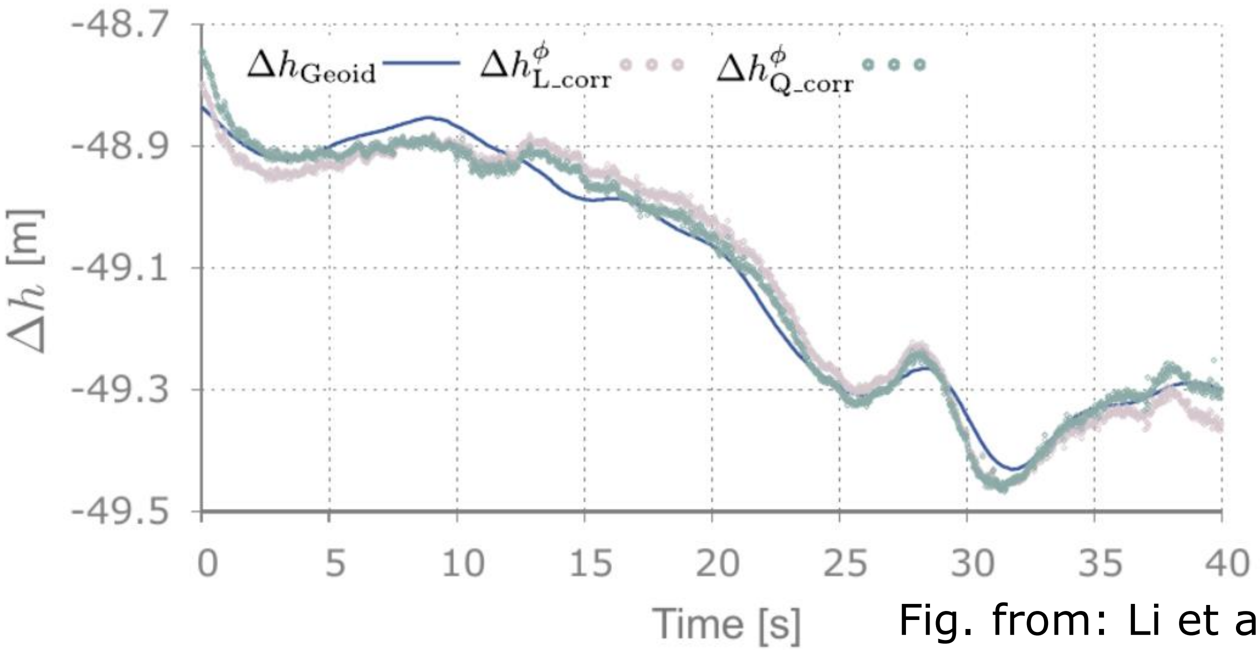
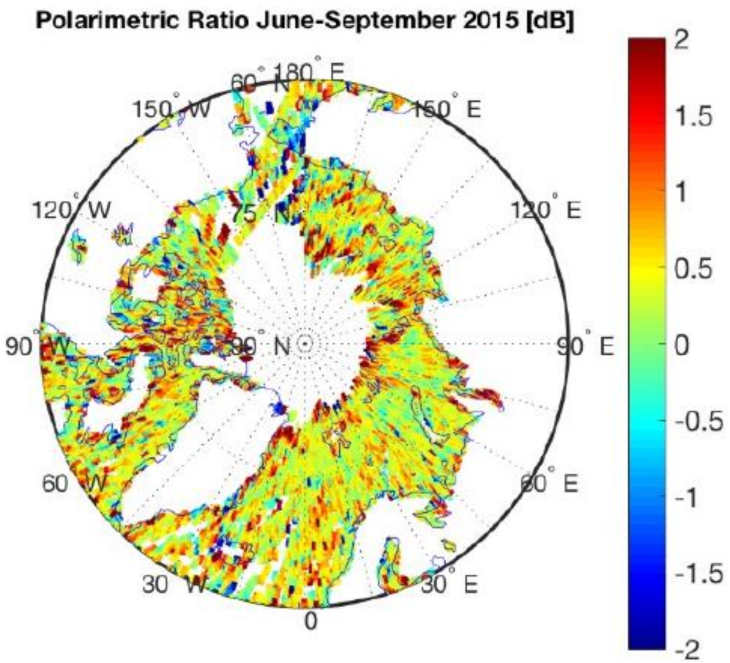
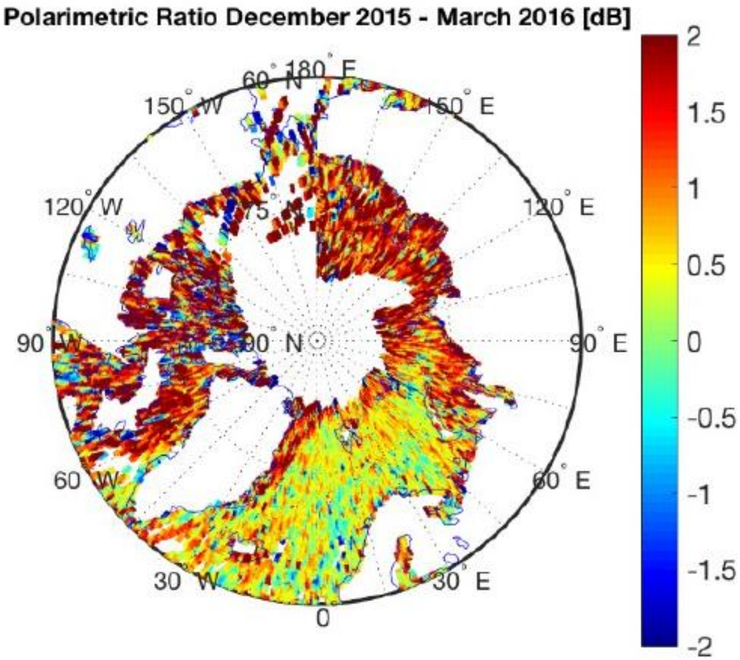


Fig. from: Li et al., 2017

- GNSS-R phase delay altimetry over Hudson Bay sea ice (TDS-1 at ~50 deg incidence in raw sampling and processed on ground).
- Dots: altimetric retrievals at 20 msec sampling using two different sets of corrections; Solid line: Canadian Geodetic Vertical Datum local geoid 2013.
- RMS differences with the geoid are 2.6 and 3.5 cm

Examples with existing data (2/2)





from Carreno-Luengo et al., 2017

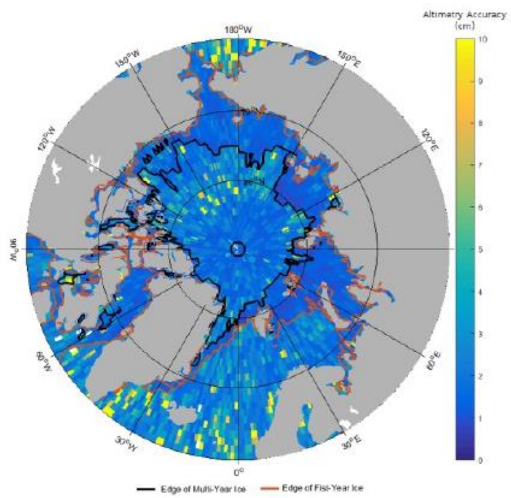
- GNSS reflected signals captured with the SMAP receiving chain of its radar after the transmission chain failed.
- Left/Right: polarimetric ratio during summer/winter months 2015/16

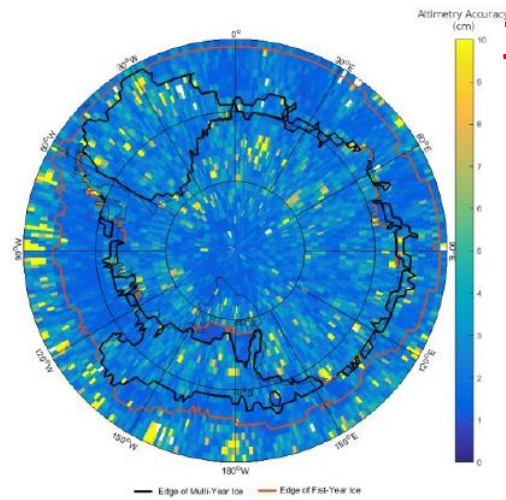
Can G-TERN meet the observation requirements?

(dedicated simulations for the proposal)

Final performance (1/2)

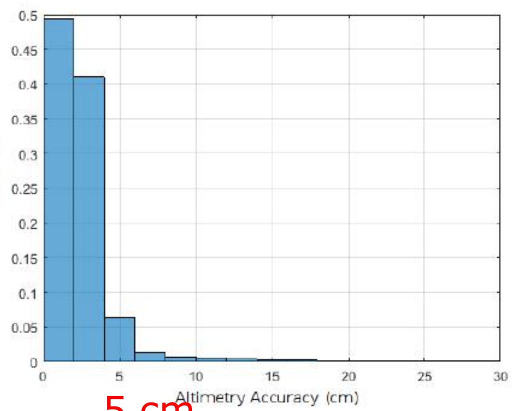
3 scenarios: 1) grazing angle phase altimetry 2) grazing + near nadir 3) nadir





10 cm

5 cm



Altimetric accuracy of one of the simulated scenarios (scenario-2) over **30 km x 30 km cells in 3 days of data**.

Final performance (2/2)

FULFILMENTOF THE MISSION REQUIREMENTS		
Scenario-1: grazing angle phase delay altimetry on 30 km x 30 km cells in 3 days, at ¦lat¦ >= 60 deg	99.1% of cells with accuracy < 10 cm	1.6 cm average accuracy of the cells
Scenario-1: combined grazing angle phase delay and near nadir group delay altimetry on 30 km x 30 km cells in 3 days, at ¦lat¦ >= 60 deg	95.5 % of cells with accuracy < 10 cm	2.7 cm average accuracy of the cells
Scenario-3: near nadir group delay altimetry on 0.5 deg x 0.5 deg cells in 10 days, at -70 deg <= ¦lat¦ <= 70 deg.	97.1 % of cells with accuracy < 10 cm	5.3 cm average accuracy of the cells

If selected for final implementation, the launch would be by 2024-2025, when approaching the Arctic summer *'ice free'* and possible *'tipping point'*

Costs and schedule

Preliminary **Cost Estimate**:

launch services, operations, ground segment, level 2 processor and ESA internal costs excluded
G-TERN is well in the cost limit of 150 Mio€ with some margin

Preliminary **Schedule**:

Confirmation for Phase A: Nov. 2017

Phase A:	Jan 2018 - June 2019	(18 months)	2 missions
Phase B1:	July 2019 - Dec 2019	(6 months)	2 missions

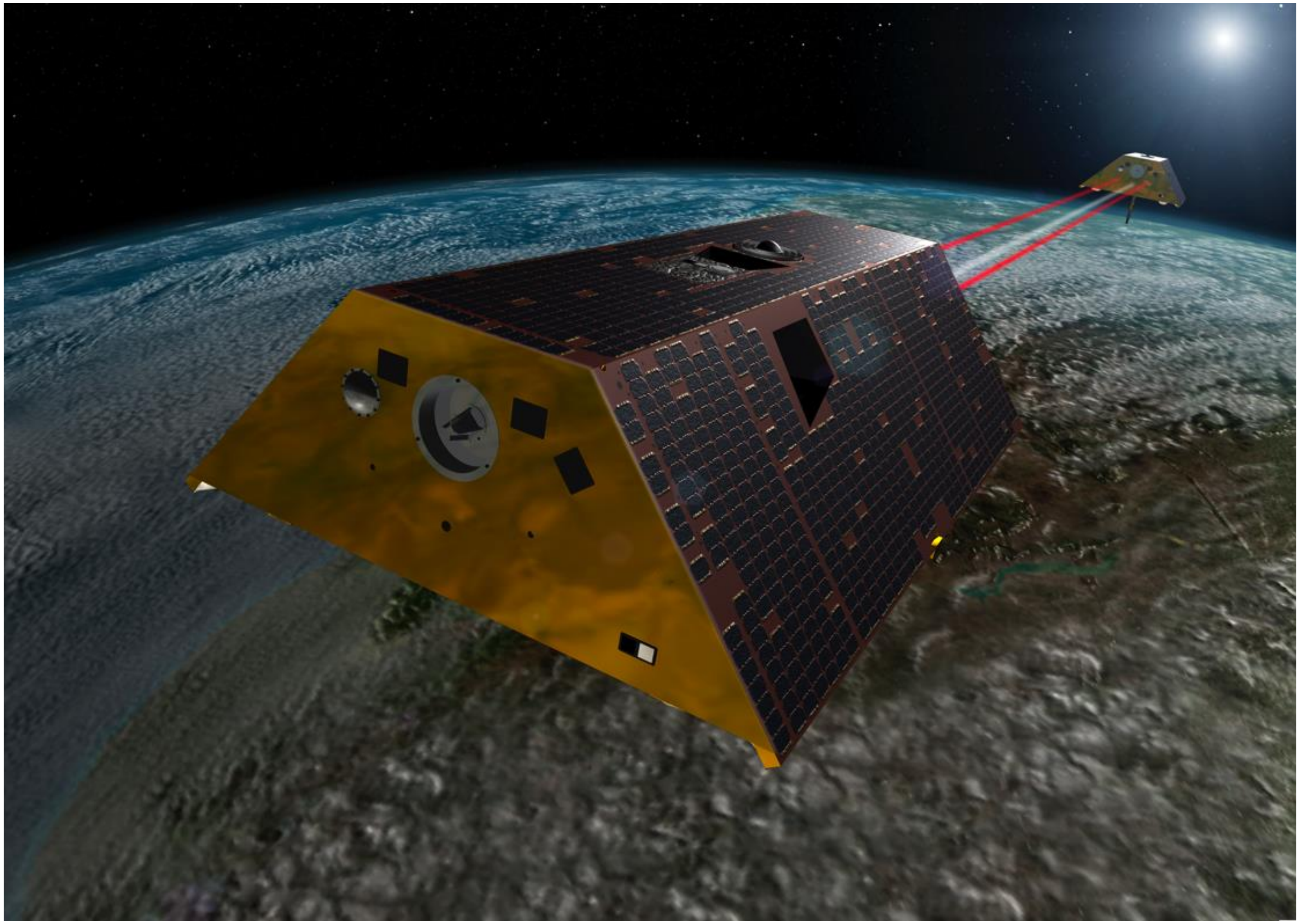
Decision for one mission (3 months)

Phase B2:	April 2020 - June 2021	(15 months)	1 mission
Phase C/D:	July 2021 - **Sept 2024**	(36+3 months)	
	(3 months margin for CDR etc ..)		

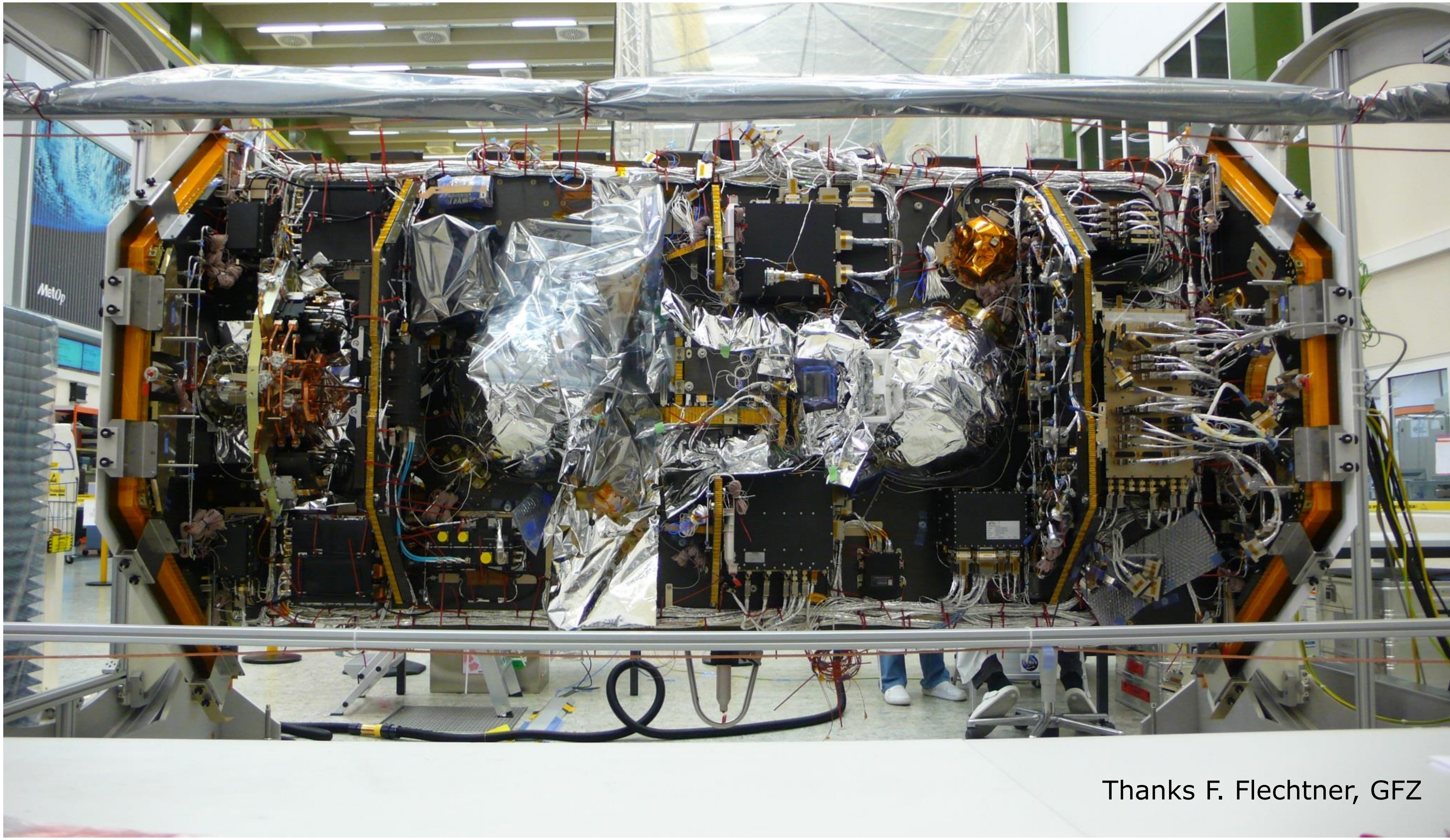
Back to “pure” GNSS-RO:

GRACE-Follow On
will be launched quite soon

GRACE-FO is foreseen for launch in March 2018



GRACE-FO integration



Thanks F. Flechtner, GFZ

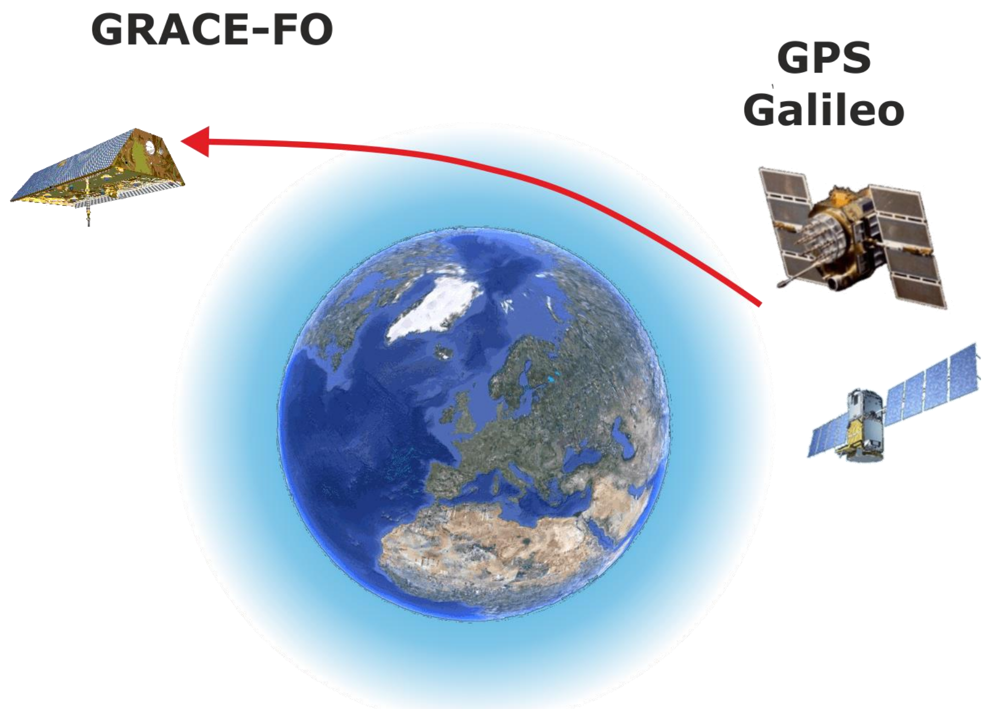
GNSS atmosphere sounding with GRACE-FO

GRACE-FO: Launch window in March 2018

New and improved GNSS receiver compared to GRACE: TriG

Aspects: Galileo ?, L2C/L5 is feasible, joint effort JPL/Moog/GFZ required

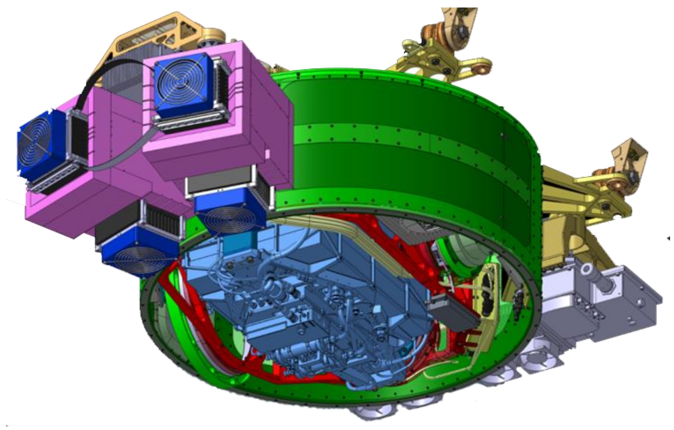
TriG RO receiver



AtmoSat:
A potential GNSS-RO platform

AtmoSat

- Satellite mission for the investigation of the atmospheric variability, Improvement of regional climate and mid term weather prediction
- KIT/FZJ leading, GFZ additional leading institution
- Strong heritage from PREMIER mission (proposed EE8 mission)
- Proposed in 2016 within large research structure investments in Germany (>50 Mio€)
- Recent scientific evaluation with highest possible result (July), final decision 2018
- Key payload: GLORIA (3D atmosphere mapping); GFZ plans to provide TriG RO receiver
- Launch planned for 2023



TriG RO receiver

Summary

- The activities and status of the combined GNSS-RO/-R mission GEROS-ISS from ESA was overviewed, recently a cost reduction study exercise was executed, funding decision is pending.
- G-TERN, another combined GNSS-RO/-R mission was introduced. It was proposed within Earth Explorer 9 with extended scientific goals, specifically focusing on cryosphere, but also includes global scale and hydro/atmo/pedosphere, decision on next phase is in Nov. 2017.
- Launch window for GRACE-FO is in March 2018, main mission goal is gravity field determination. TriG receiver will allow for operational GNSS-RO.
- AtmoSat is a german atmospheric science mission including GNSS-RO component, proposed within the national roadmap for large research infrastructure. Promising excellent scientific evaluation completed. Final decision expected for spring 2018.