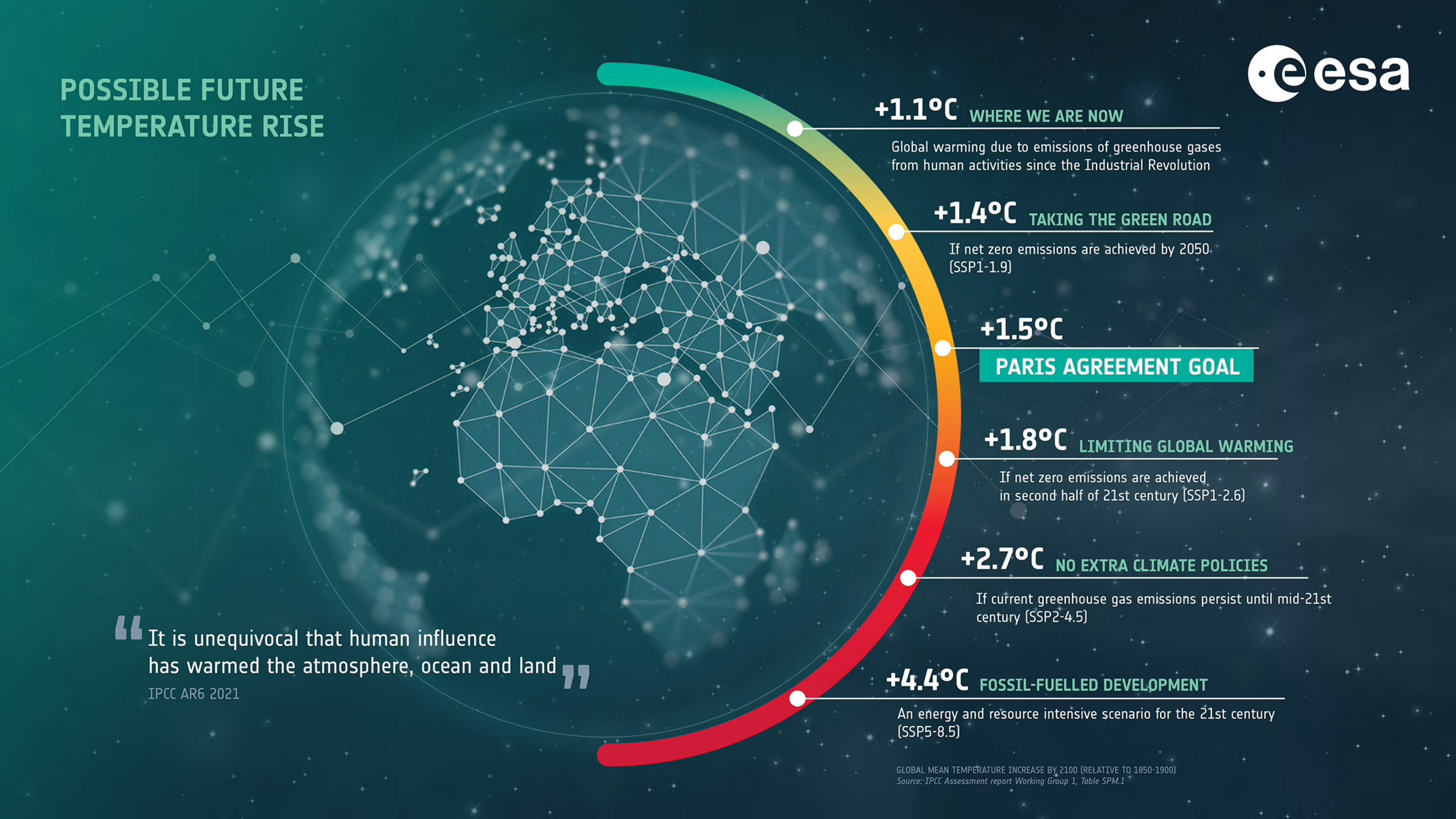
Future Missions for Polar science

Dr. Craig Donlon

Head Earth Surface and Interior,

ESA/ESTEC, Noordwijk, The

Netherlands


POSSIBLE FUTURE TEMPERATURE RISE
+1.1°C WHERE WE ARE NOW
Global warming due to emissions of greenhouse gases from human activities since the Industrial Revolution
+1.4°C TAKING THE GREEN ROAD
If net zero emissions are achieved by 2050 (SSP1-1.9)
+1.5°C
PARIS AGREEMENT GOAL
+1.8°C LIMITING GLOBAL WARMING
If net zero emissions are achieved in second half of 21st century (SSP1-2.6)
+2.7°C NO EXTRA CLIMATE POLICIES
If current greenhouse gas emissions persist until mid-21st century (SSP2-4.5)
+4.4°C FOSSIL-FUELLED DEVELOPMENT
An energy and resource intensive scenario for the 21st century (SSP5-8.5)
"It is unequivocal that human influence has warmed the atmosphere, ocean and land"
IPCC AR6 2021
GLOBAL MEAN TEMPERATURE INCREASE BY 2100 (RELATIVE TO 1850-1900)
Source: IPCC Assessment report Working Group 1, Table SPM.1
esa

TAKING THE PULSE OF THE PLANET

Essential Climate Variables are key indicators that describe Earth's changing climate. Scientists use these variables to study climate drivers, interactions and feedbacks, as well as reservoirs, tipping points and fluxes of energy, water and carbon.

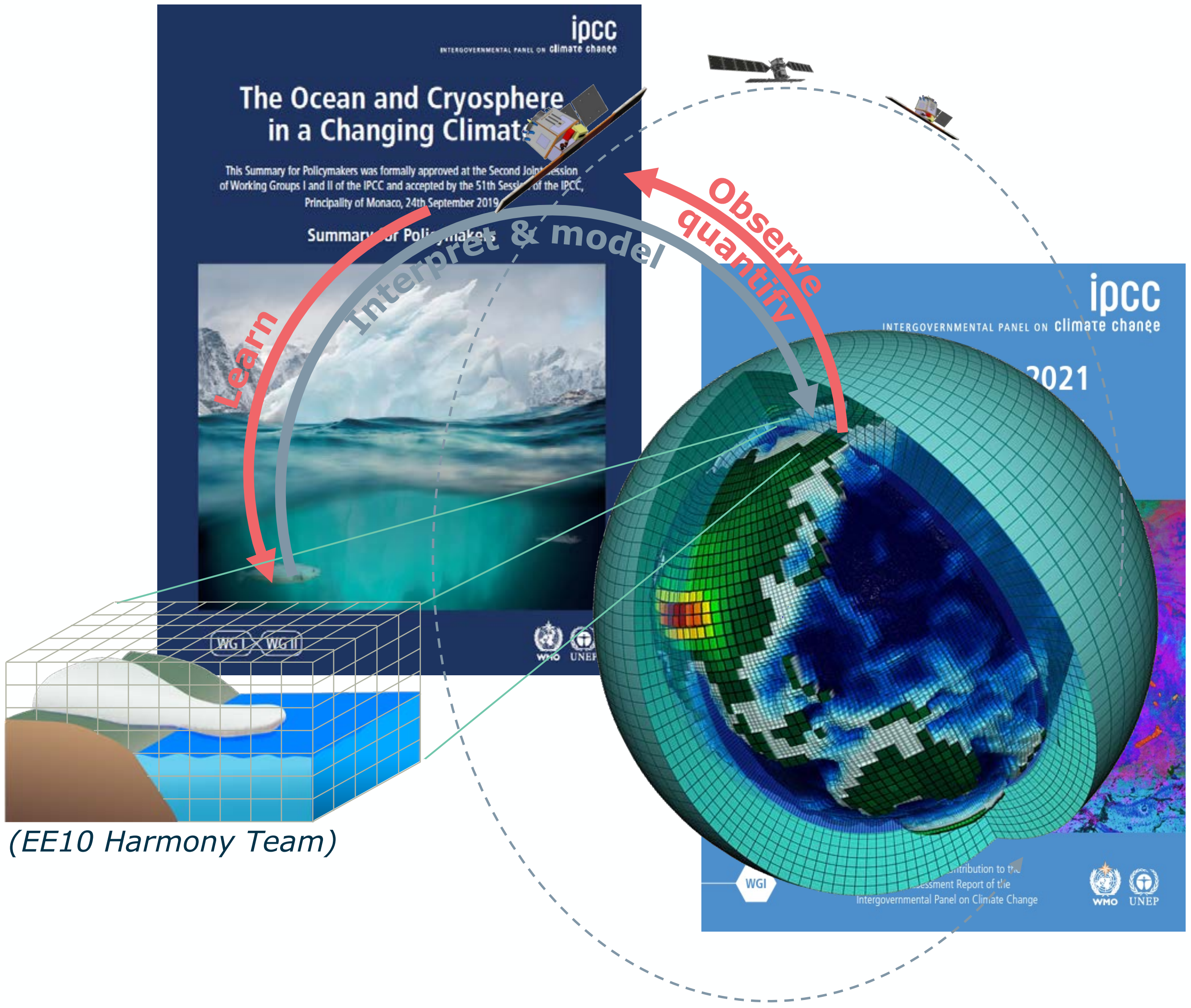
The climate-quality datasets produced by the Climate Change Initiative are a major contribution to the evidence base used to understand climate change.

> “Satellite products provide a valuable complement to in-situ measurements. These observations are valuable (high confidence) for regional applications since they provide multi-channel images at very high spatiotemporal resolutions”

IPCC AR6 2021

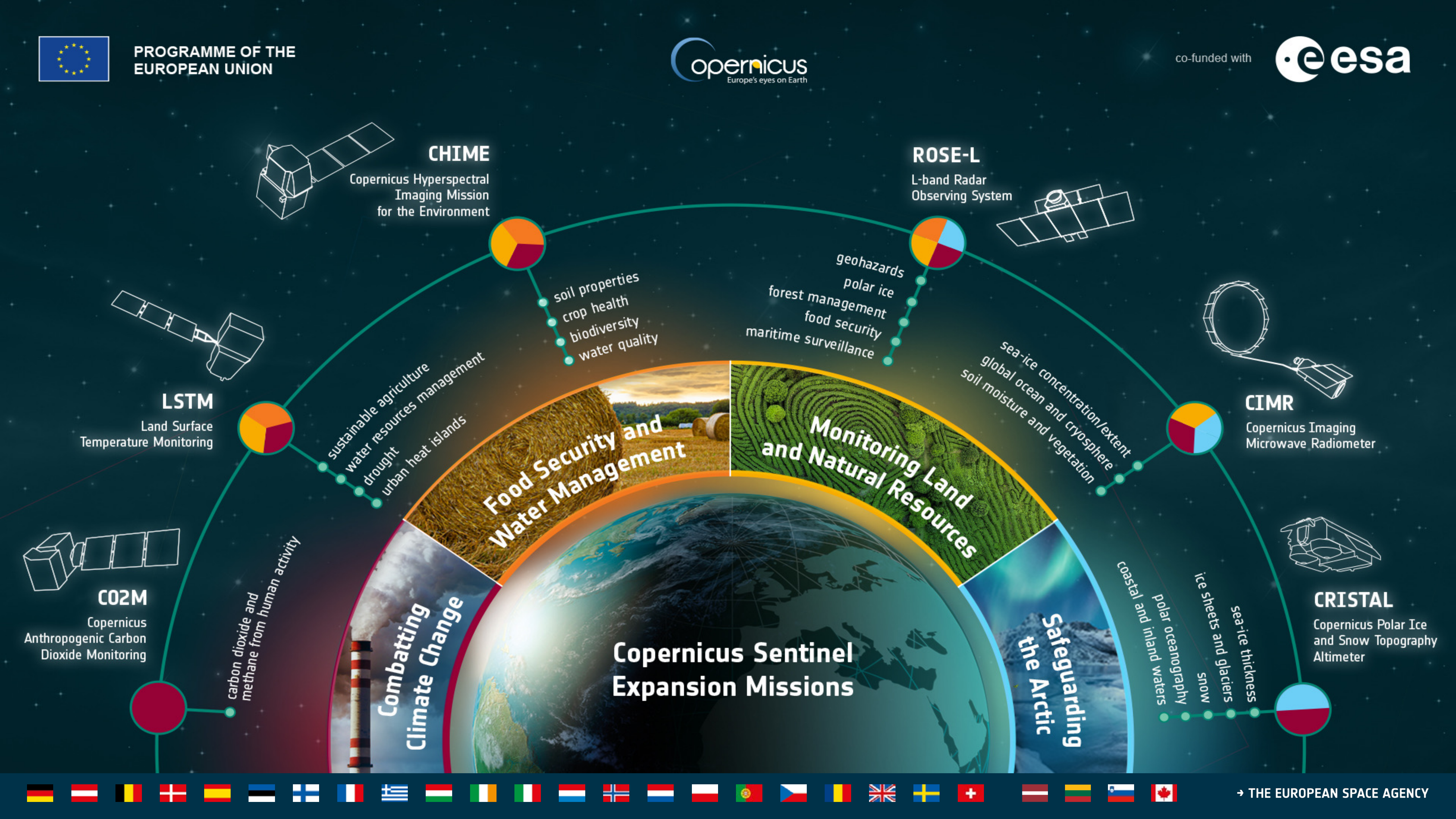
Overview

- The unique nature of our Earth Observation Evidence Base
- Exploring the Earth – the challenge of individual measurements vs the bigger global picture
- We are 'in for the long-term' – Copernicus measurements
- New measurements and new techniques - Earth Explorer Science Missions
- Amazingly - we can't cover everything today…



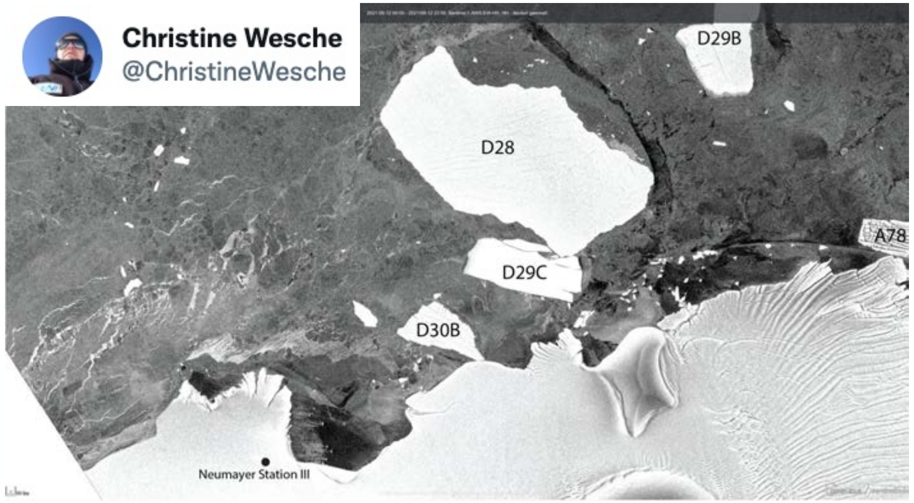
(EE10 Harmony Team)

ESA-DEVELOPED EARTH OBSERVATION MISSIONS

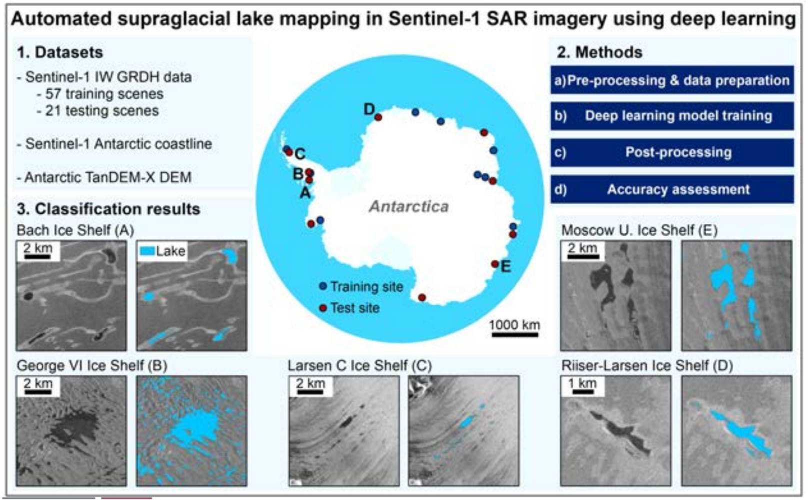


PROGRAMME OF THE EUROPEAN UNION
Copernicus
Europe's eyes on Earth
co-funded with
esa
CHIME
Copernicus Hyperspectral Imaging Mission for the Environment
soil properties
crop health
biodiversity
water quality
ROSE-L
L-band Radar Observing System
geohazards
polar ice
forest management
food security
maritime surveillance
LSTM
Land Surface Temperature Monitoring
sustainable agriculture
water resources management
drought
urban heat islands
CIMR
Copernicus Imaging Microwave Radiometer
sea-ice concentration/extent
global ocean and cryosphere
soil moisture and vegetation
CO2M
Copernicus Anthropogenic Carbon Dioxide Monitoring
carbon dioxide and methane from human activity
CRISTAL
Copernicus Polar Ice and Snow Topography Altimeter
coastal and inland waters
polar oceanography
snow
ice sheets and glaciers
sea-ice thickness
Food Security and Water Management
Monitoring Land and Natural Resources
Combatting Climate Change
Safeguarding the Arctic
Copernicus Sentinel Expansion Missions
→ THE EUROPEAN SPACE AGENCY


European Commission
esa
European Space Agency
Sentinel-1
→ RADAR VISION FOR COPERNICUS

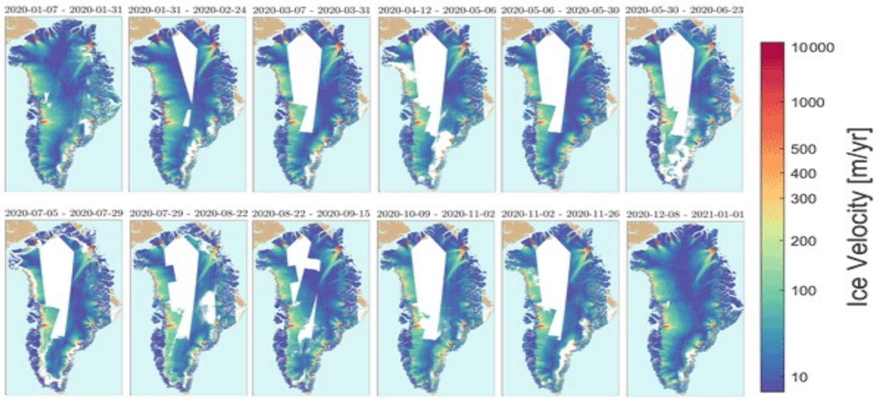


#icebergs close to #EkstroemIceShelf. The 57 km long #D28 broke off of #AmeryIceShelf in September 2019 and hit the #BaudouinIceShelf in June 2021, creating icebergs #D30B, #D29B and #D29C.



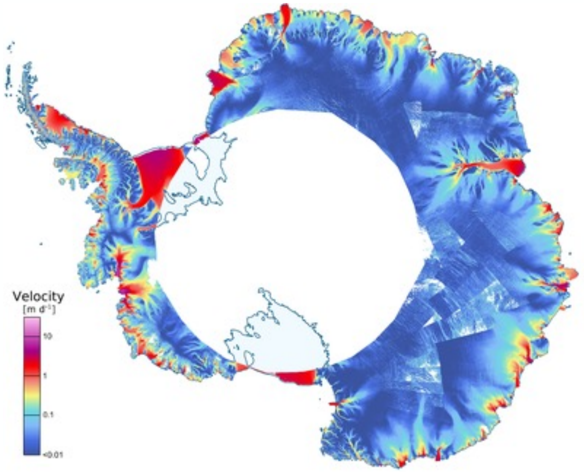
A Novel Method for Automated Supraglacial Lake Mapping in Antarctica Using Sentinel-1 SAR Imagery and Deep Learning

by Mariel Dirscherl[1,*], Andreas J. Dietz[1], Christof Kneisel[2] and Claudia Kuenzer[1,2]

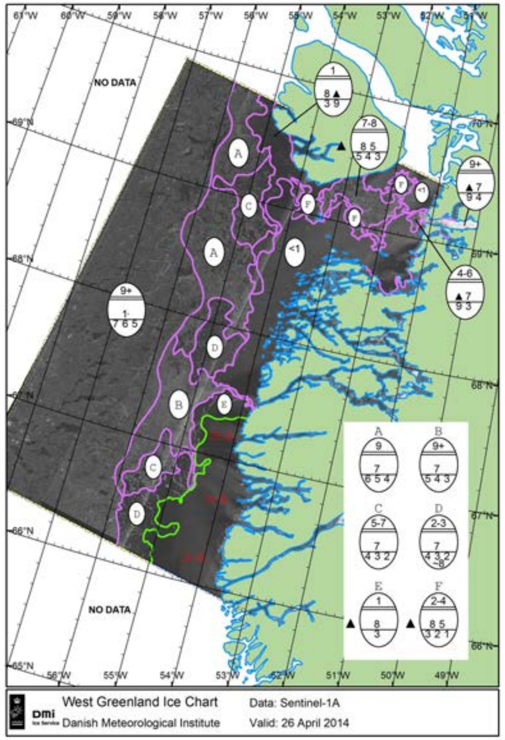


Greenland ice velocity maps from the PROMICE project

Anne Solgaard[1], Anders Kusk[2], John Peter Merryman Boncori[2], Jørgen Dall[2], Kenneth D. Mankoff[1], Andreas P. Ahlstrøm[1], Signe B. Andersen[1], Michele Citterio[1], Nanna B. Karlsson[1], Kristian K. Kjeldsen[1], Niels J. Korsgaard[1], Signe H. Larsen[1], and Robert S. Fausto[1]



Antarctic_Ice_Sheet_cci+ project will continue the generation of GLL from recent Sentinel-1A/B acquisitions on selected key glaciers and thus extending the temporal extension of GLL datasets.

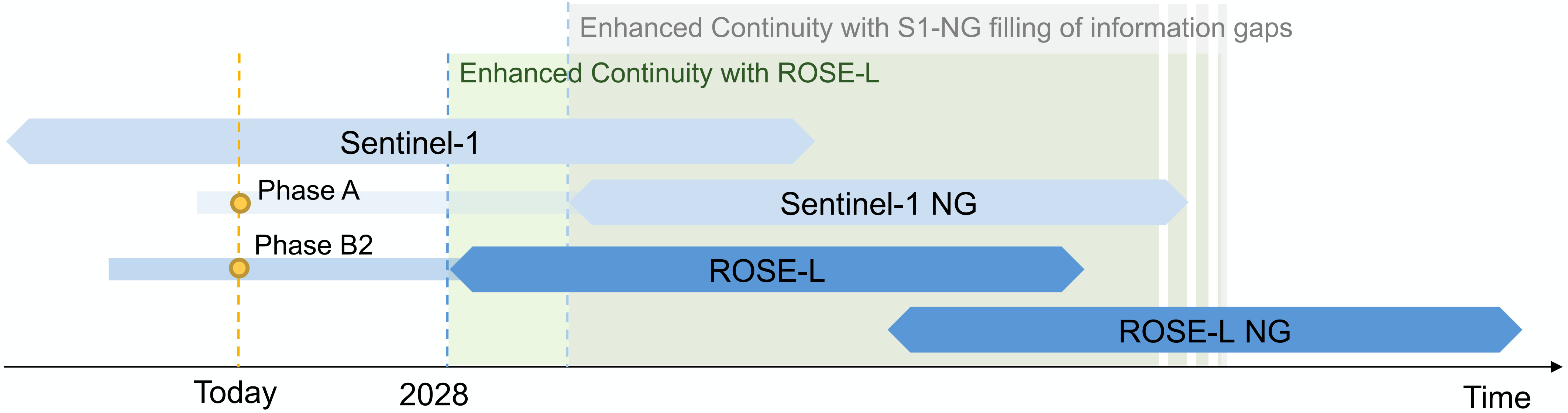


Ice Charts

THE EUROPEAN SPACE AGENCY

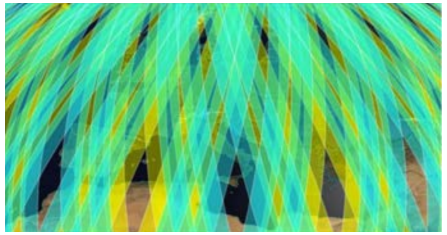
ROSE-L Mission Background and Justification

- Copernicus Expansion mission
  - Responds directly and traceably to Copernicus user needs
  - Provides new information not yet available through current Sentinel missions (Gaps)
  - Provides enhanced information in combination with current Sentinel missions (Enhanced continuity)
- Same orbit and acquisition geometry as Sentinel-1 (IWS) providing an operational dual-frequency system of satellites and enhanced information products
- Two ROSE-L satellites : PFM & FM2 + options currently under Phase B2+ study

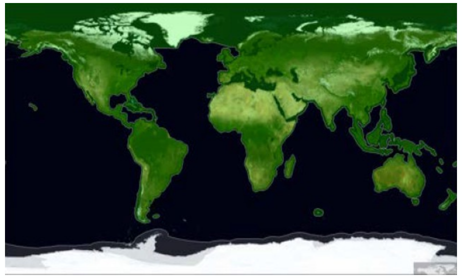


ROSE-L Mission Requirement

- High-resolution e.g. < 50m^2 for enhanced continuity
- Swath width > 260 km for co-location with Sentinel-1 Interferometric Wide mode
- Revisit: 6 days Global, 3 days Europe and 1 day Arctic
- 6-day Repeat Pass Interferometry (with 2 satellites) to monitor surface deformation and motion
- Polarisation diversity to maximise information content and robustness of information extraction (dual and full polarimetry)
- Low Noise Equivalent Sigma Zero (< -28 dB)
- Stringent data latency requirements: 10min over Europe, 200min Global
- AIS-onboard to support Maritime Monitoring
- Wave-mode to operate over oceans and open seas

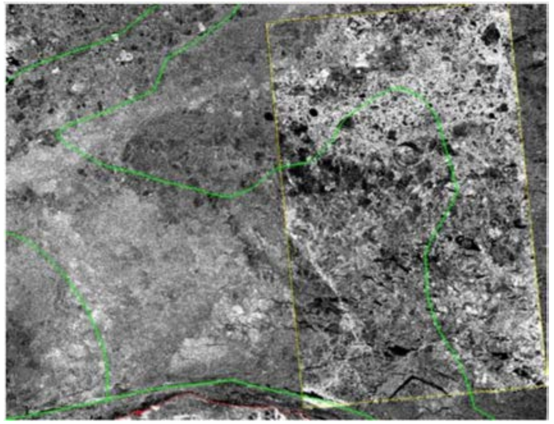


Europe: 3-day revisit



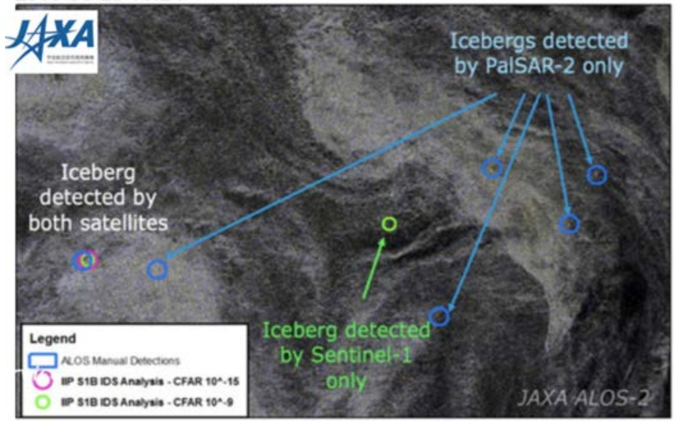
12-day Coverage Mask

Cryosphere	• Enhanced high-resolution sea ice information • Snow Water Equivalent through InSAR
Maritime Monitoring	• Improved Maritime Monitoring (Iceberg, Oil Spills and Vessel Detection and Mapping)



Sea Ice Mapping

ALOS WBD - HH/HV - RGB COMPOSITE
2019-05-23 16:24



Iceberg Detection

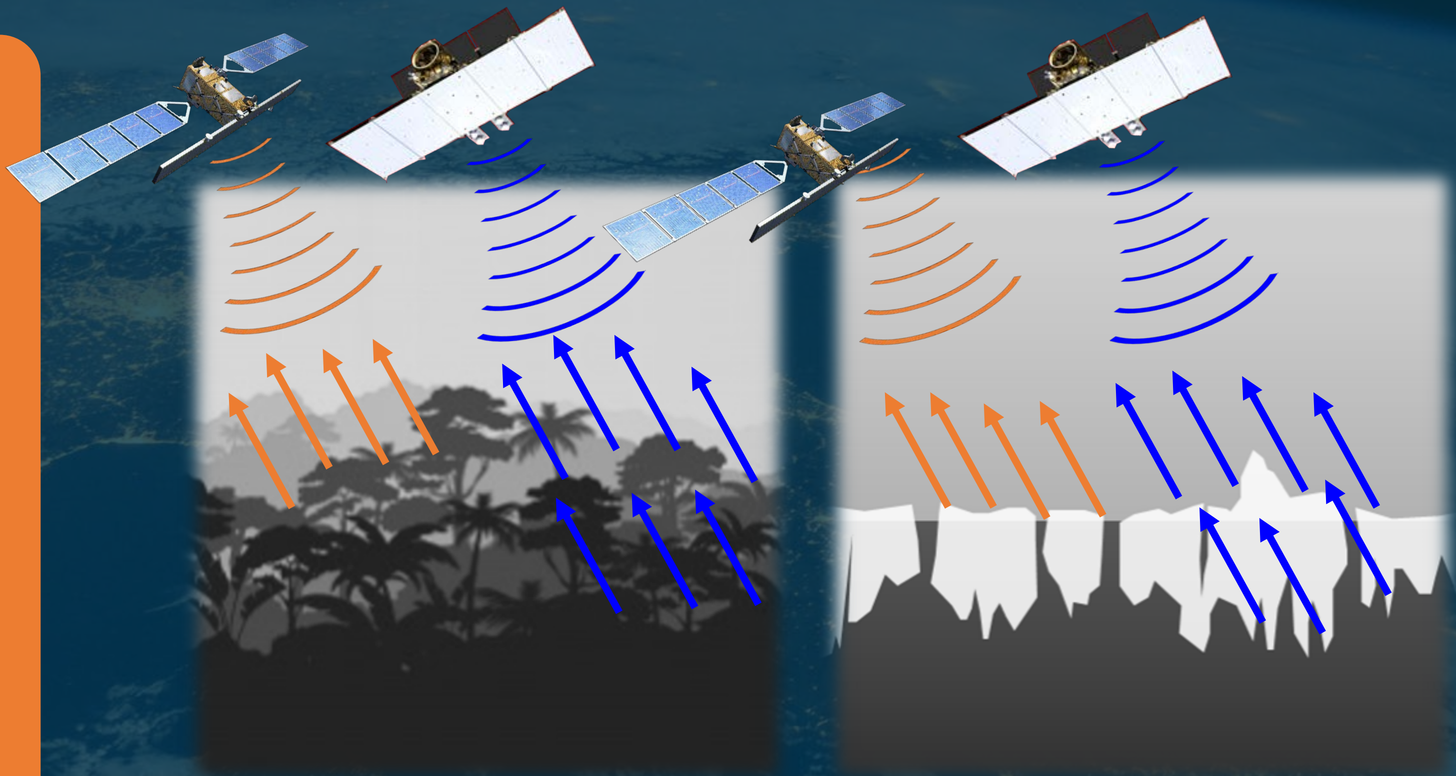
ROSE-L and Sentinel-1 NG - Synergy

ROSE-L

- L-Band (1.27 GHz)
- Revisit
  - 6 days Global
  - 3 days Europe
  - 1 day (Pan)Arctic
- Resolution < 50 m2
- Dual-Pol (DP) and Quad-Pol (QP)
- Swath (DP) 260 km
- Launch: 2028

Sentinel 1 NG

- C-Band (5.4 GHz)
- Revisit
  - 3 days Global
  - 0.5 day Arctic
- Resolution < 25 m2
- Dual-Pol and Quad-Pol
- Swath > 400 km
- Launch: > 2032



C- and L-Band combined acquisitions enhance the sensitivity to the geophysical parameters of interest (e.g. different penetration in vegetation, snow and ice)

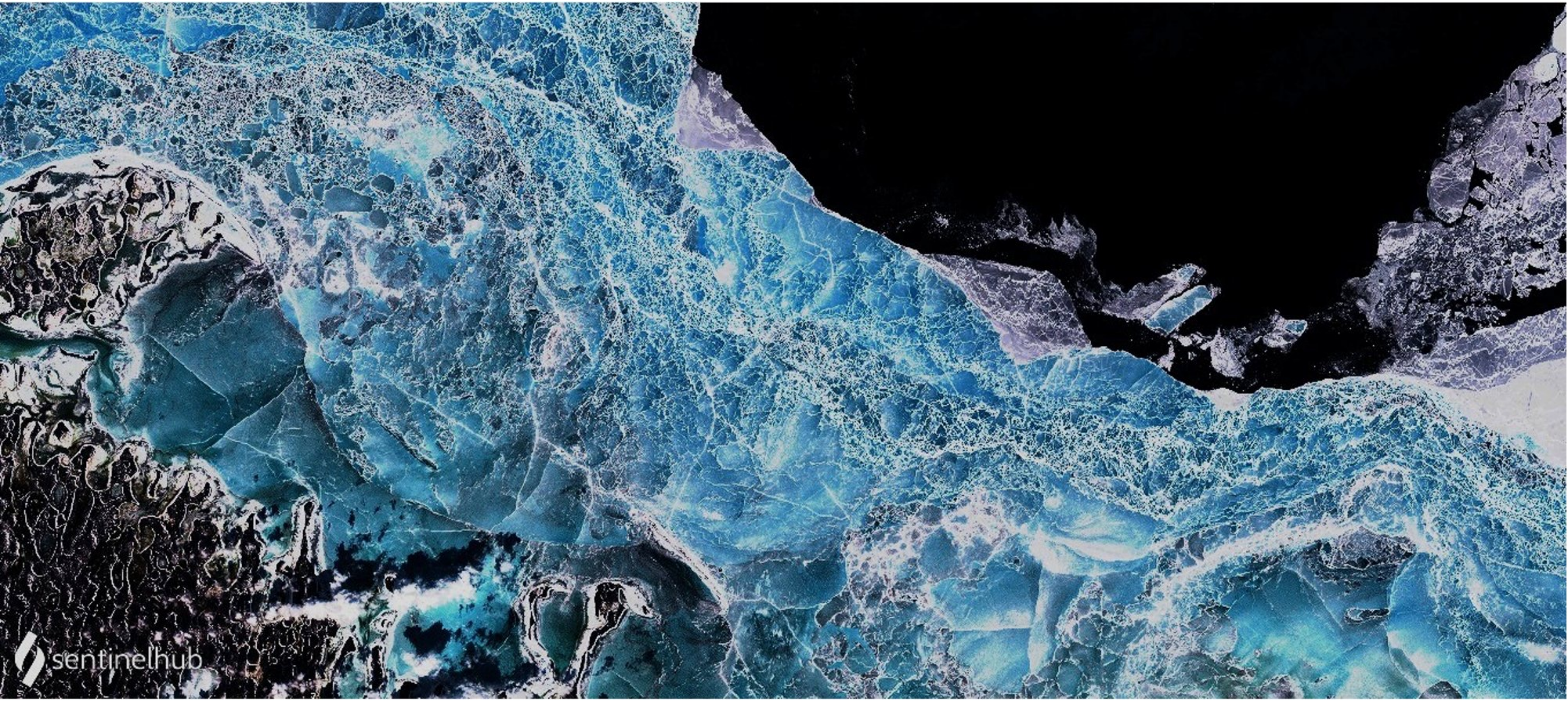
European Commission

esa
European Space Agency

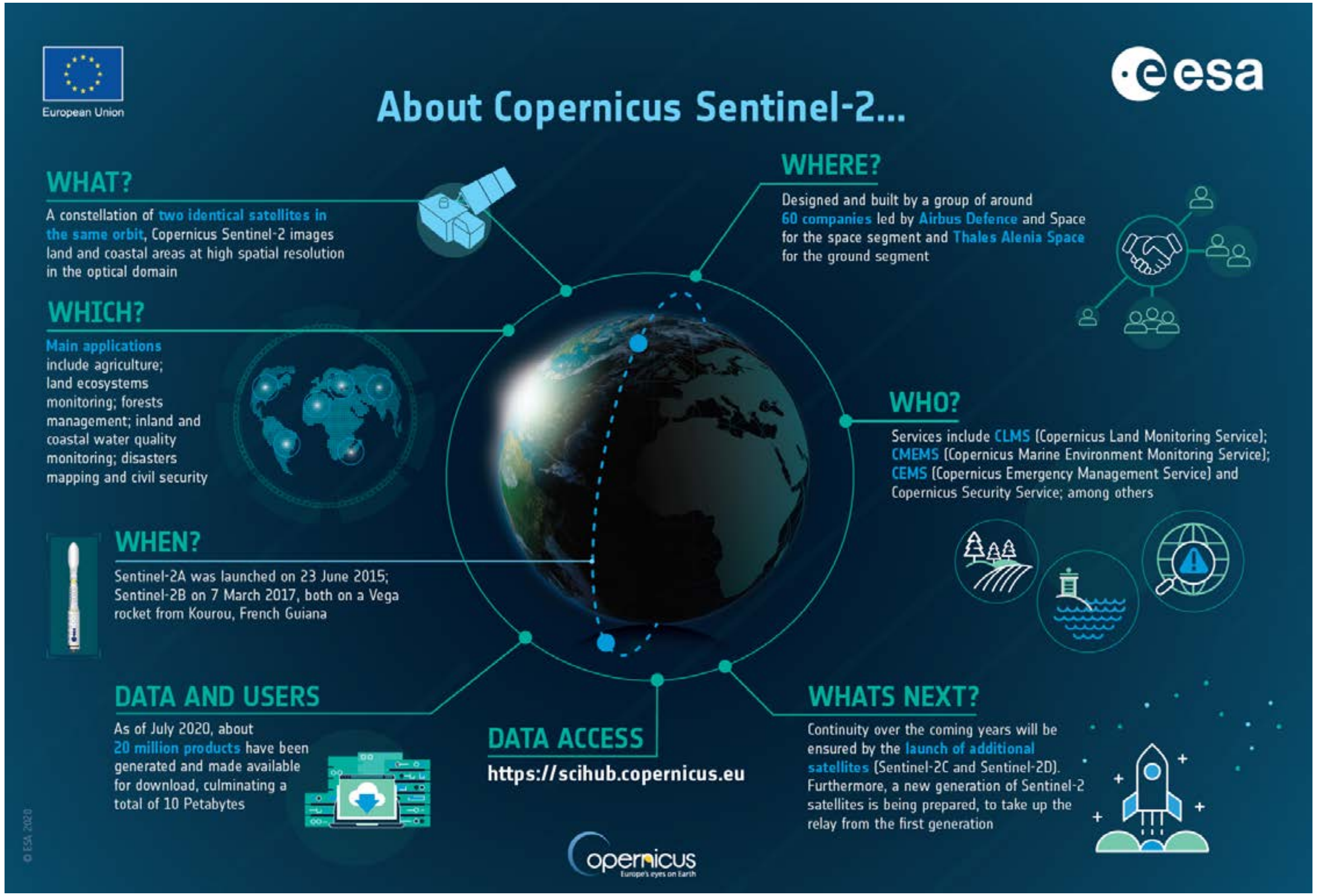
Sentinel-2

→ COLOUR VISION FOR COPERNICUS

Melt ponds visible on satellite (blue shading) across much of the landfast sea ice along Siberia above the Lena River Delta (Sentinel-2 6th June)



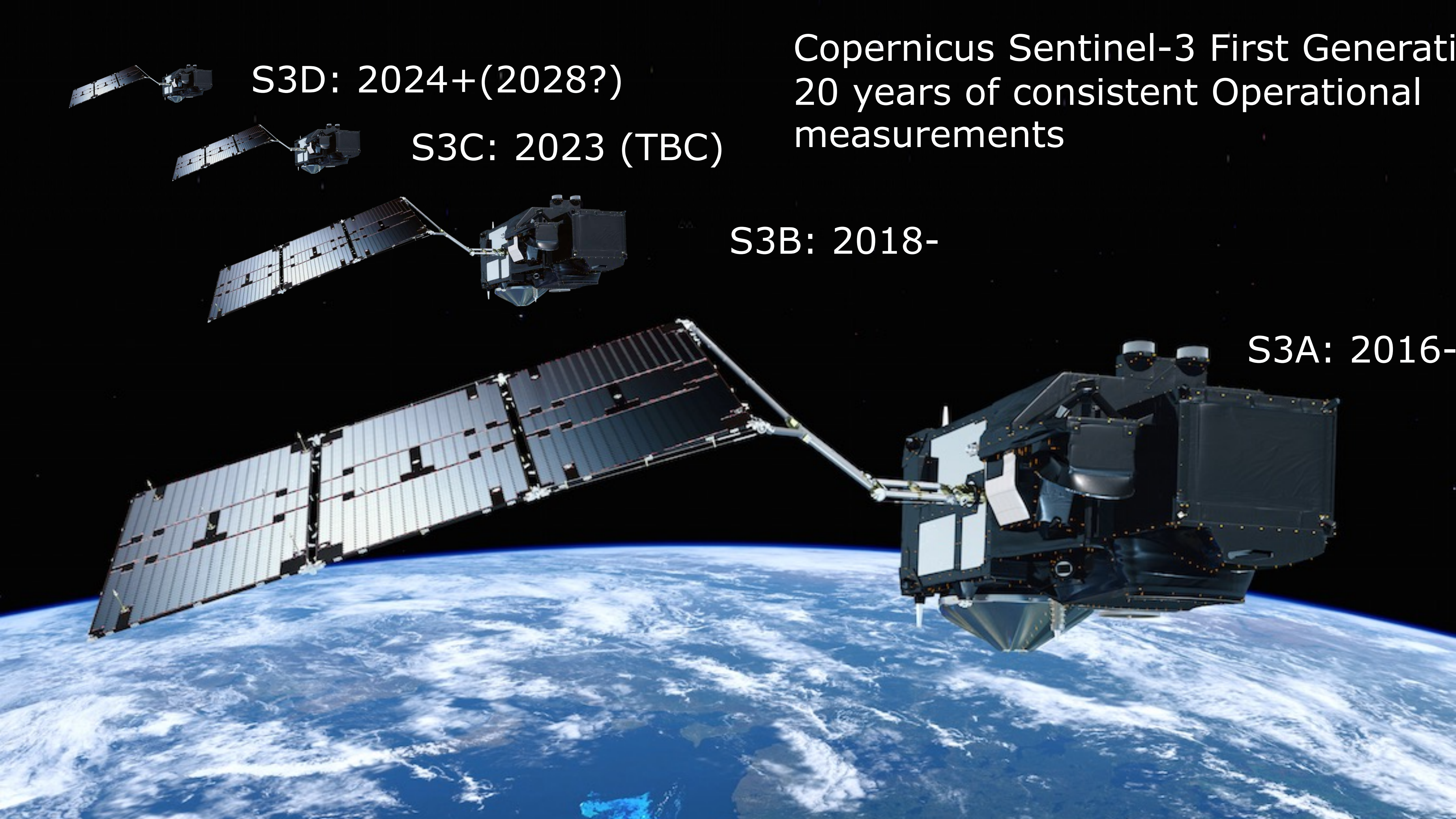
S2 and S2-NG



Sentinel-2 Next Generation

- future **European wide(er)-swath, moderately to high-resolution, multi-spectral imaging mission**
- **high radiometric accuracy**
- **high revisit frequency** (maximising the number of cloud free acquisitions)
- focus on **land and coastal areas**

- **Continuity with the current S2 generation**
- Towards **long-term availability of consistent high spatial resolution products**
- **Enhancement** of **land** (e.g. land-use / land-cover, LAI) **and water products** (e.g. water color, pigments)


Copernicus Sentinel-3 First Generati
20 years of consistent Operational
measurements
S3D: 2024+(2028?)
S3C: 2023 (TBC)
S3B: 2018-
S3A: 2016-

Sentinel-3 SRAL: Sea Ice freeboard and Ice sheet elevation change

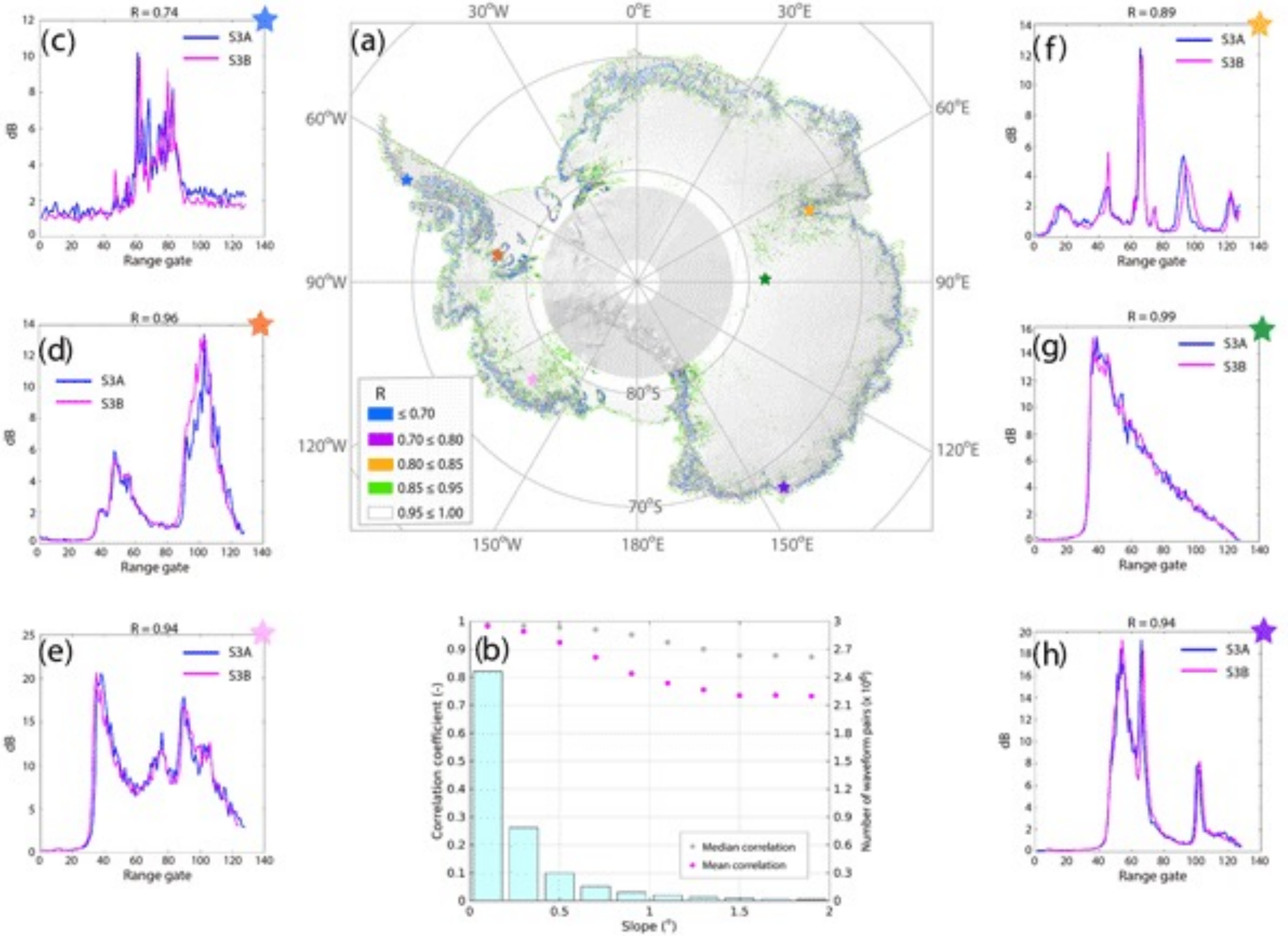
The Cryosphere, 15, 3129–3134, 2021
https://doi.org/10.5194/tc-15-3129-2021

Article | Peer review | M

Brief communication

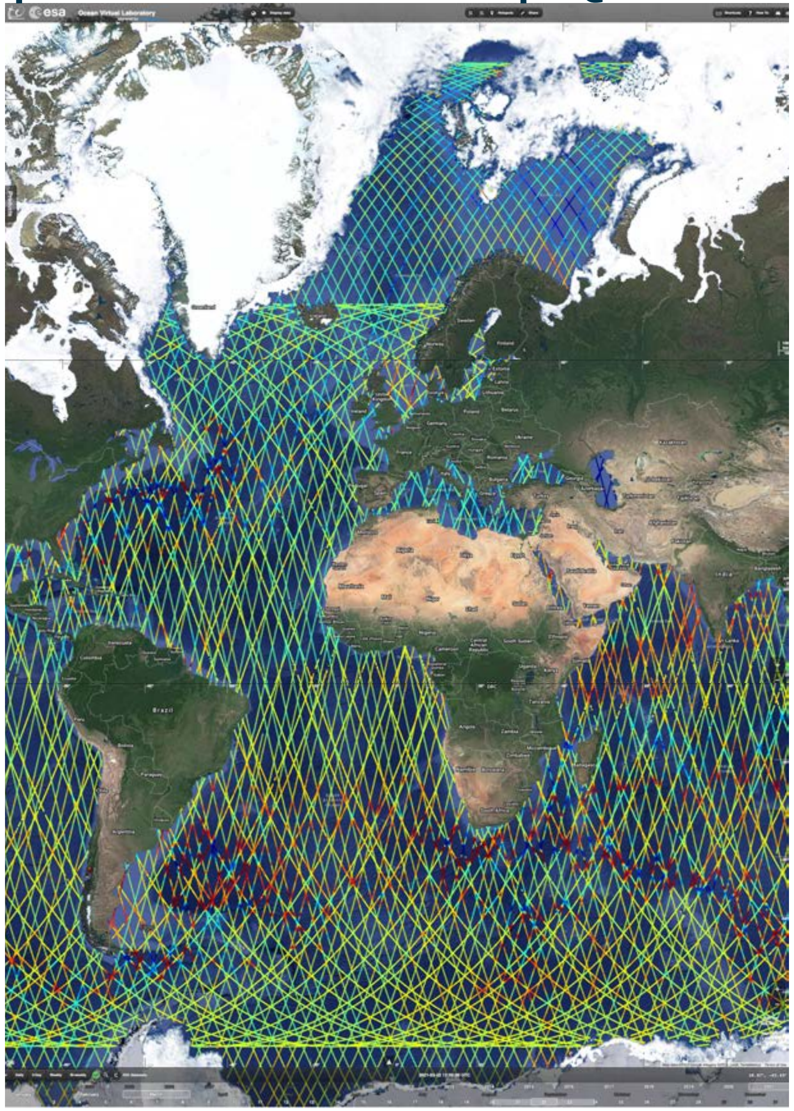
Brief communication: Ice sheet elevation measurements from the Sentinel-3A and Sentinel-3B tandem phase

Malcolm McMillan[1], Alan Muir[2], and Craig Donlon[3]

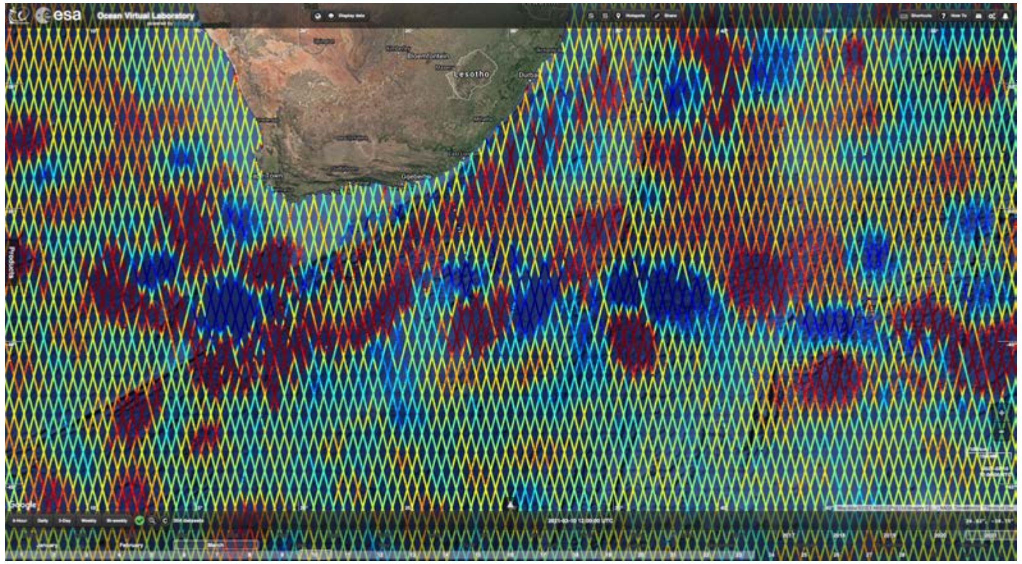


S3A+S3B+S6 sampling today

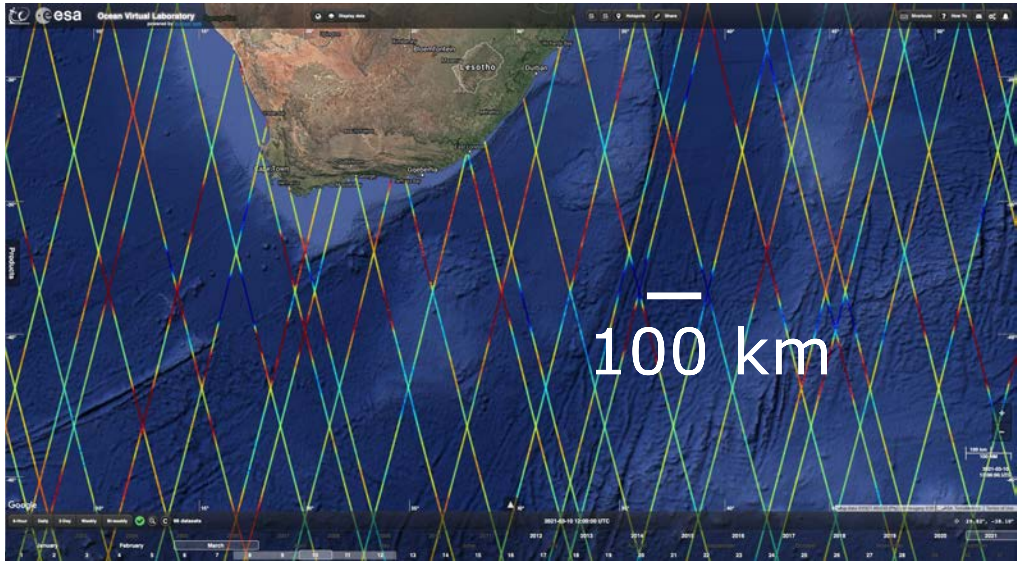
https://odl.bzh/VFpQoP-a



S3A+S3B+J3(S6) after 10 days



S3A+B after 27 days



S3A+B after 5-days

Primary User Need: Better sampling a

S3NG-T Mission Aim and Objectives

estec

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Copernicus Sentinel-3 Next Generation Topography (S3NG-T) Mission Requirements Document (MRD)

Prepared by	Earth and Mission Science Division
Reference	ESA-EOPSM-S3NG-MRD-3821
Issue/Revision	0.3
Date of Issue	15/04/2021
Status	DRAFT
Document type	Mission Requirements Document (MRD)
Distribution	ESA Unclassified – For Official Use

4 S3NG-T MISSION AIMS AND OBJECTIVES

4.1 S3NG-T Mission Aim

Considering the User needs expressed by the European Commission and concisely articulated in the previous sections, the **aim** of the Copernicus Next Generation Sentinel-3 Topography (S3NG-T) Mission is:

To ensure continuity of Sentinel-3 in flight performance topography capability in the 2030-2050 timeframe.

4.2 S3NG-T Objectives

Mission requirements are then derived from mission Objectives.

The primary objectives of the S3NG-T mission are to:

PRI-OBJ-1. **Guarantee continuity of Sentinel-3 topography measurements** for the 2030-2050 time frame **with performance at least equivalent to Sentinel-3 in-flight performance** as defined in Table 2.4-1 ('baseline mission').

PRI-OBJ-2. Respond to evolving user requirements and **improve sampling, coverage and revisit** of the Copernicus Next Generation Topography Constellation (S3NG-T and Sentinel-6NG) to ≤50 km and ≤5 days (CMEMS, 2017) in support of Copernicus User Needs.

PRI-OBJ-3. **Enhance sampling coverage, revisit and performance for Hydrology Water Surface Elevation** measurements in support of Copernicus Services.

PRI-OBJ-4. Respond to evolving user requirements and **enhance topography Level-2 product measurement performance**.

The secondary objectives[9] of the S3NG-T mission are to:

SEC-OBJ-1. Provide directional wave spectrum products that address evolving Copernicus user needs.

SEC-OBJ-2. Provide new products[10] that address evolving Copernicus user needs.

S3NG-T Constellation Concepts ESA Phase A/B1 System Study.

For S3NG-T we have three basic hybrid Constellation scenarios to be down-selected in July 2022:

Scenario-1: Replacement of Sentinel-3C and Sentinel-3D using a constellation of 2-*n* nadir-pointing altimeters.

Constellation (10-12) of mini-satellites with Ka-band altimeter and integrated radiometer (AlTiKA heritage)

Excellent Agile and scalable mini satellite constellation option with hybrid cross calibration with S6NG

Scenario-2: Implementation of 2..*n* swath altimeter including a nadir altimeter

Phase-0/ESA SAOO design with different combinations of payload complement (The Nadir Altimeter is considered essential for accurate phase unwrapping and long-wavelength stability + continuity of Hs) (No heritage: SWOT to demonstrate)

Includes hybrid cross calibration with S6NG

Scenario-3: Hybrid approach.

Combinations of different approaches could be used to meet S3NG-T requirements. A staggered development could be adopted.

Allows all of the lessons learned from NASA/CNES SWOT in orbit results to be pulled through into an optimised European swath altimeter design - this could then be launched at an appropriate time.

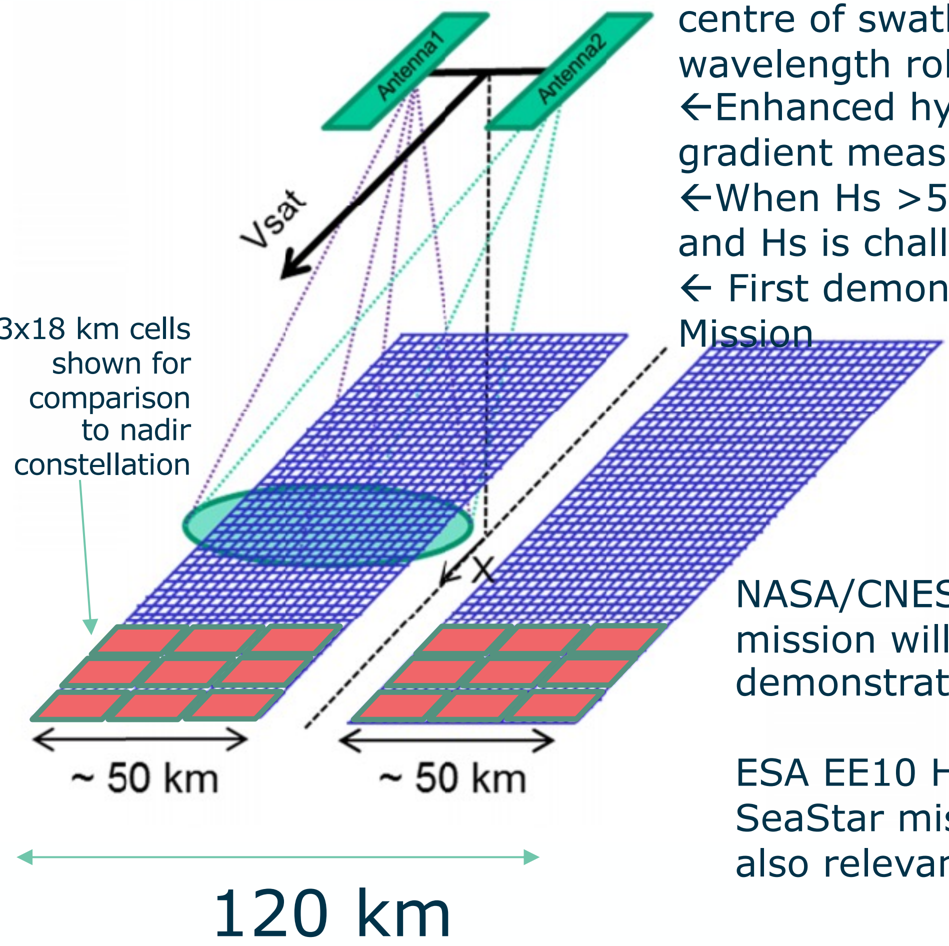
Such an approach offers at flexible risk-reduction solution to meet Copernicus User Needs.

Includes elements of Variant A mini satellite constellation and hybrid cross calibration with S6NG

Where are we today? What does it look like in terms of satellite Constellations?

S3NG-T Basic Concepts ESA Phase A/B1 System Study

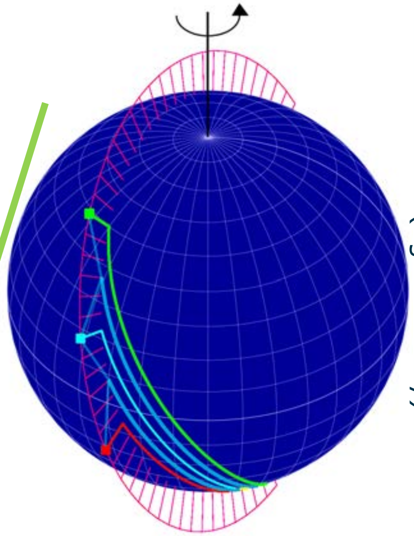
Constellation of 2-3
swath altimeter satellit



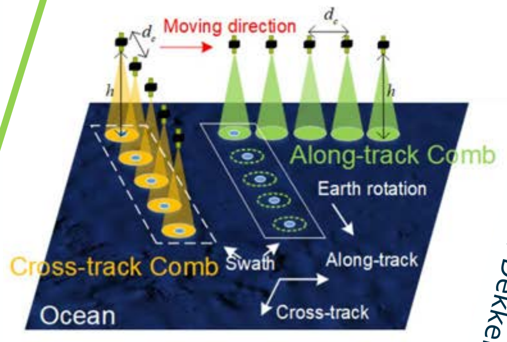
← New Technologies with great potential
←18km ka-band (SAOO) for ocean surfaces (higher native posting)
←Ku-band Nadir altimeter required at centre of swath for Hs and long wavelength roll error.
←Enhanced hydrology and ocean height gradient measurement
←When Hs >5m performance in (SSH) and Hs is challenged
← First demonstration in space US SWOT Mission

NASA/CNES SWOT R&D mission will be the first demonstration in 2023+

ESA EE10 Harmony &EE12 SeaStar mission concepts) also relevant



(fig. K. Raney)



(fig. P. Dekker)

Constellation of 2-12 small
nadir pointing satellites

← Resolution ~0.3km along track x 2..n[10-12] tracks.

Ka-band FF-SAR meets all Sentinel-3 continuity performance requirements for **all variables over ocean, hydrology, sea ice and land ice.**

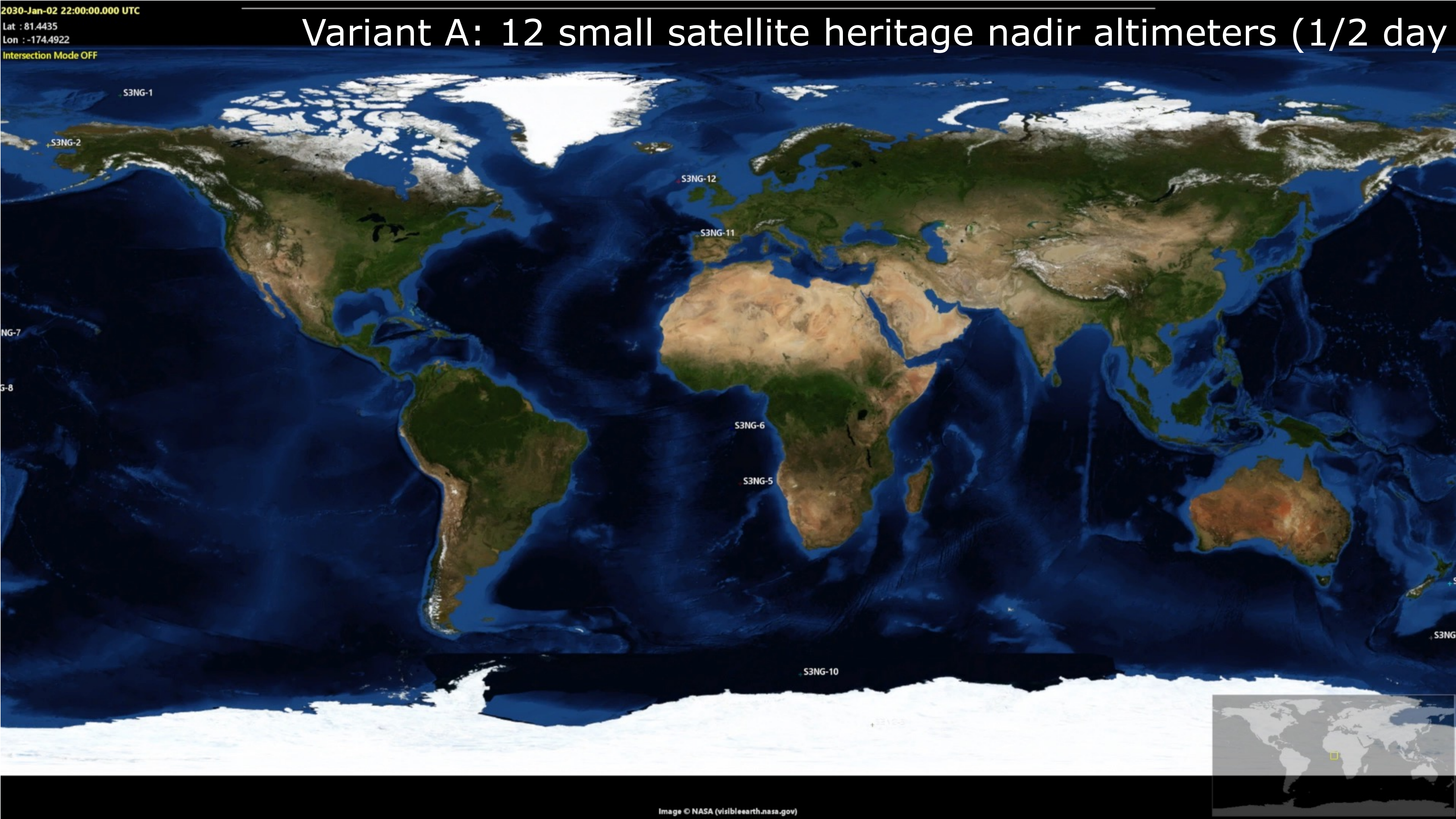
Provides significant enhanced performance using Ka-band (Heritage: AltiKa,CS2/S3/S6 SAR)

Constellation of 10-12 nadir fully performing altimeters provides unprecedented sampling in both space and time – **Agile and can be reconfigured in flight responding to user needs**

Scalable, and well understood with long in-flight heritage

Inter-constellation calibration

Variant A: 12 small satellite heritage nadir altimeters (1/2 day



Wave Directional Spectrum from Nadir Altimetry

Geophysical Research Letters

Research Letter | Open Access

SAR Altimetry Data as a New Source for Swell Monitoring

Ourania Altiparmaki, Marcel Kleinherenbrink, Marc Naeije, Cornelis Slobbe, Pieter Visser

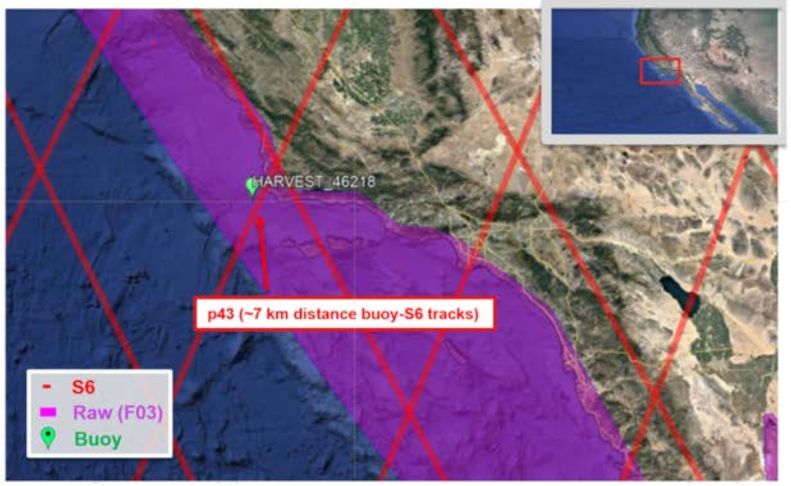
First published: 28 February 2022 | https://doi.org/10.1029/2021GL096224

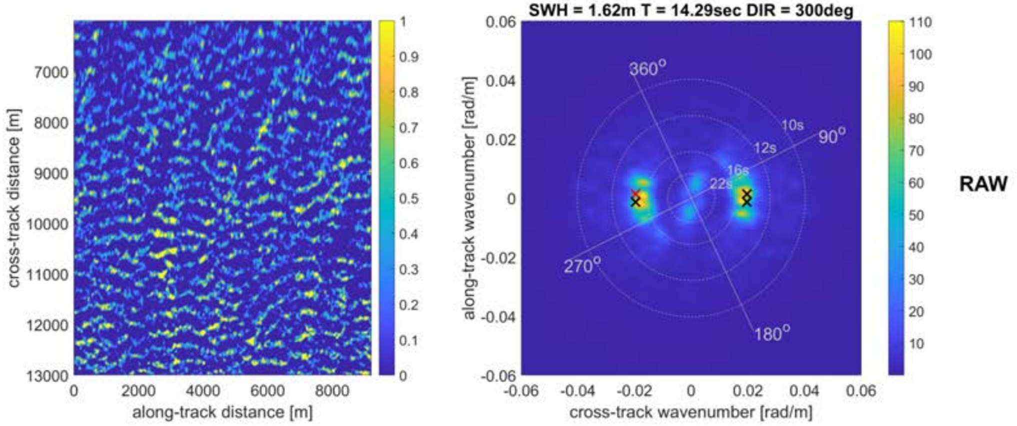
SECTIONS PDF TOOLS SHARE

Swells are long-crest waves induced by storms. They can travel thousands of kilometers and impact remote shorelines. They also interact with local wind generated waves and currents. It has been shown that the presence of swell lowers the quality of the geophysical parameters which can be retrieved from the delay/Doppler radar altimeter data. This, in turn, affects the estimation of small-scale ocean dynamics. In addition, the resolution offered by the delay/Doppler processing schemes, which is approximately 300 m in the along-track direction, does not allow to resolve swells. This work presents a method which demonstrates that Synthetic Aperture Radar (SAR) altimeters show potential to retrieve swell-wave spectra from fully-focused SAR altimetry processed data for the first time, and proposes thus, that SAR altimetry can serve as a source for swell monitoring.

Variant A *with no extra technical development* will bring unprecedented coverage of the ocean directional swell spectrum directly supporting CMEMS coupled ocean-atmosphere models and marine applications

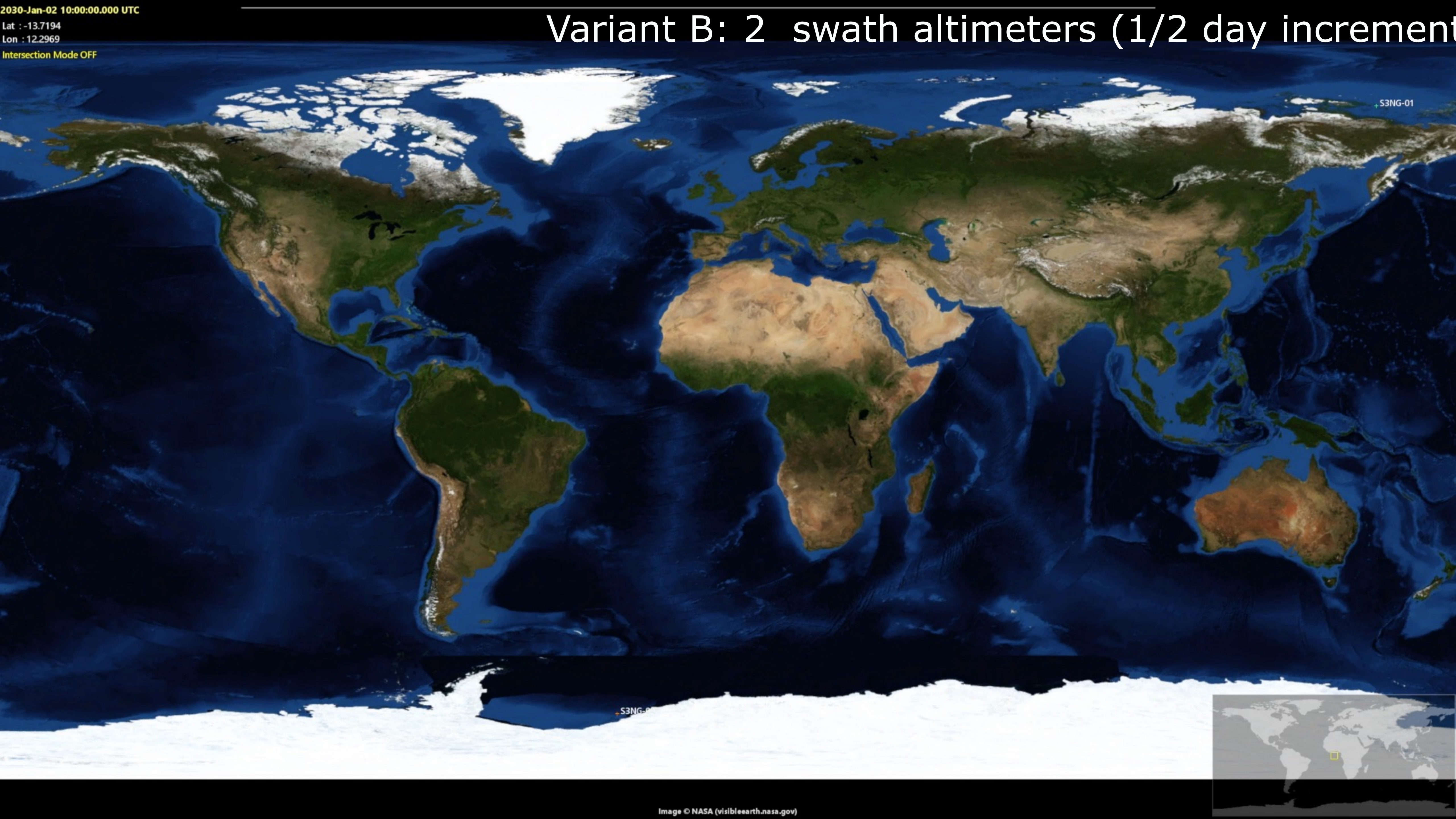
Sentinel-6 Nadir Altimeter 2D Wave Spectrum compared to Harvest Buoy





Rania Altiparmaki <O.Altiparmaki@tudelft.nl>

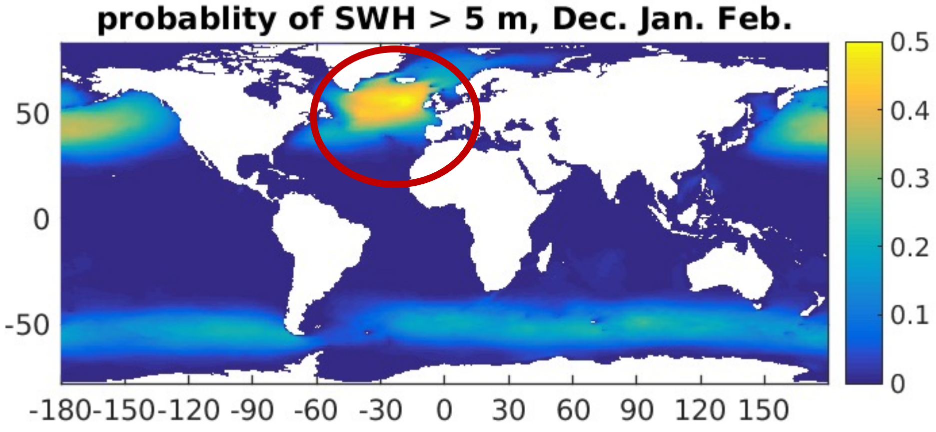
Variant B: 2 swath altimeters (1/2 day increment

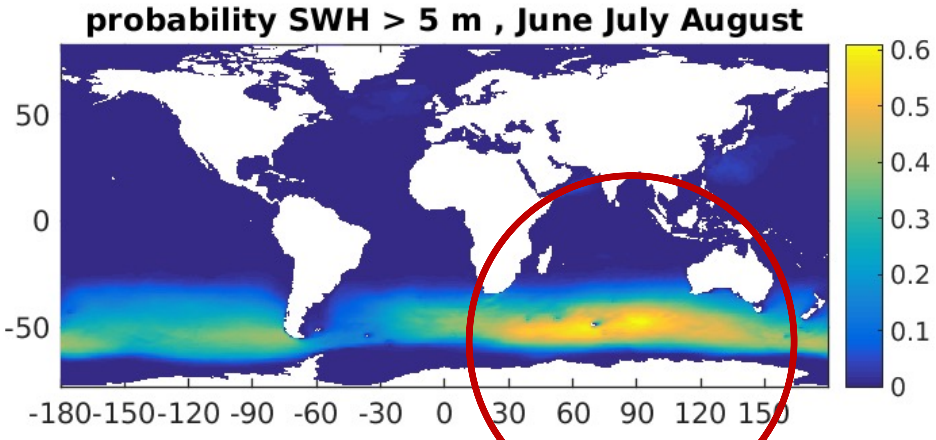


Potential coverage impact of Hs>5m taking InSAR swath altimeter SSH performance

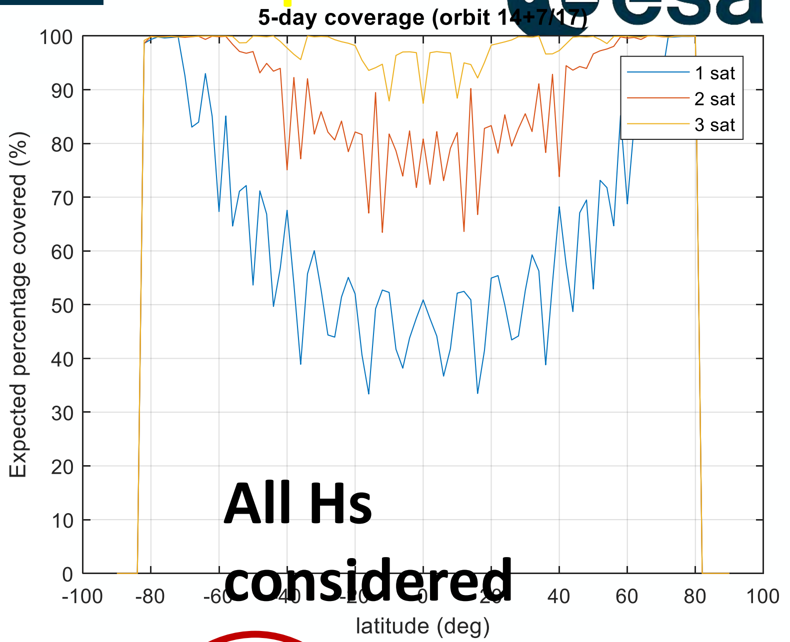
The analysis is "brute force" and reports seasonal averages for a latitude band. This obscures the dominant regional impacts (in particular storm tracks in both hemispheres in winter) where the impact will be greatest that can be identified in the Pe(Hs) maps.

The Hs climatology is from WaveWatch III (Produced by F. Ardhuin, LOPS) and does not consider the impact of future changes in Hs due to climate change.

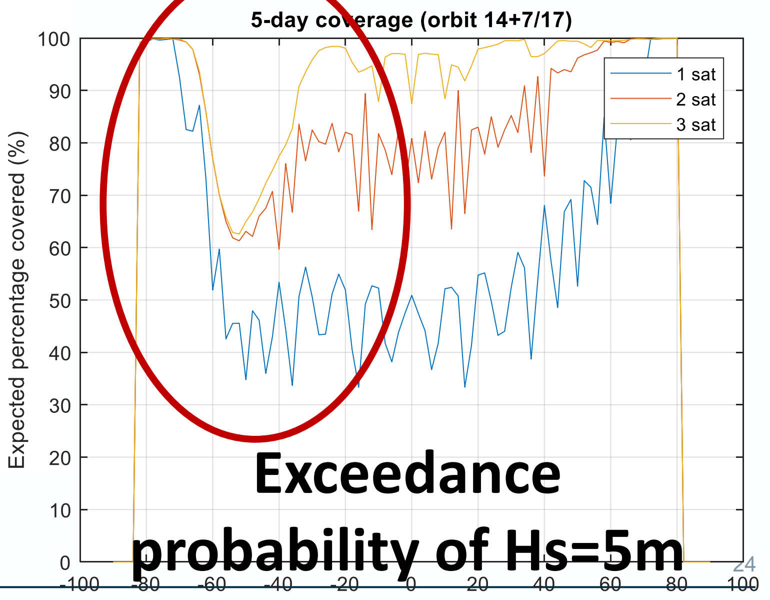




WaveWatch 3 Climatology (F. Ardhuin, LOPS)



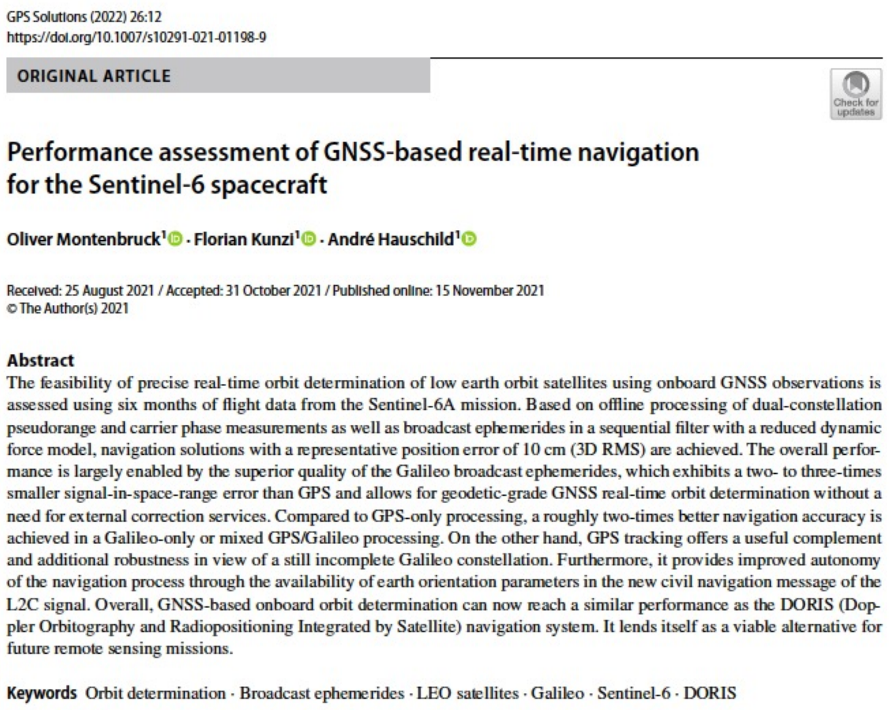
All Hs considered



Exceedance probability of Hs=5m considered

S3NG-T Calibration and Homogenisation

- Calibration → How to calibrate a constellation?
- Homogeneity → how to ensure a consistent measurement across the constellation?
- Variant A, B and C (Hybrid) ALL use Sentinel-6 as the CEOS Reference altimeter -- Well respected heritage approach followed using Jason1/Jason2/JAson3/Sentinel-6 +Sentinel-3/Cs2 etc
- In addition, in constellation, we make full use of all orbit crossovers within an hour to continuously monitor the constellation inter-calibration with itself.
- Since satellites are in the same orbit, we can also exploit improved orbit dynamics information as all spacecraft are of the same design → better orbit determination.
- We fully exploit the Galileo Constellation that provides excellent performance in Real Time and NRT3H → Recent work demonstrates that Galileo provides performance that is unprecedented for satellite Altimetry


GPS Solutions (2022) 26:12
https://doi.org/10.1007/s10291-021-01198-9

ORIGINAL ARTICLE

Performance assessment of GNSS-based real-time navigation for the Sentinel-6 spacecraft

Oliver Montenbruck[1] · Florian Kunzi[1] · André Hauschild[1]

Received: 25 August 2021 / Accepted: 31 October 2021 / Published online: 15 November 2021
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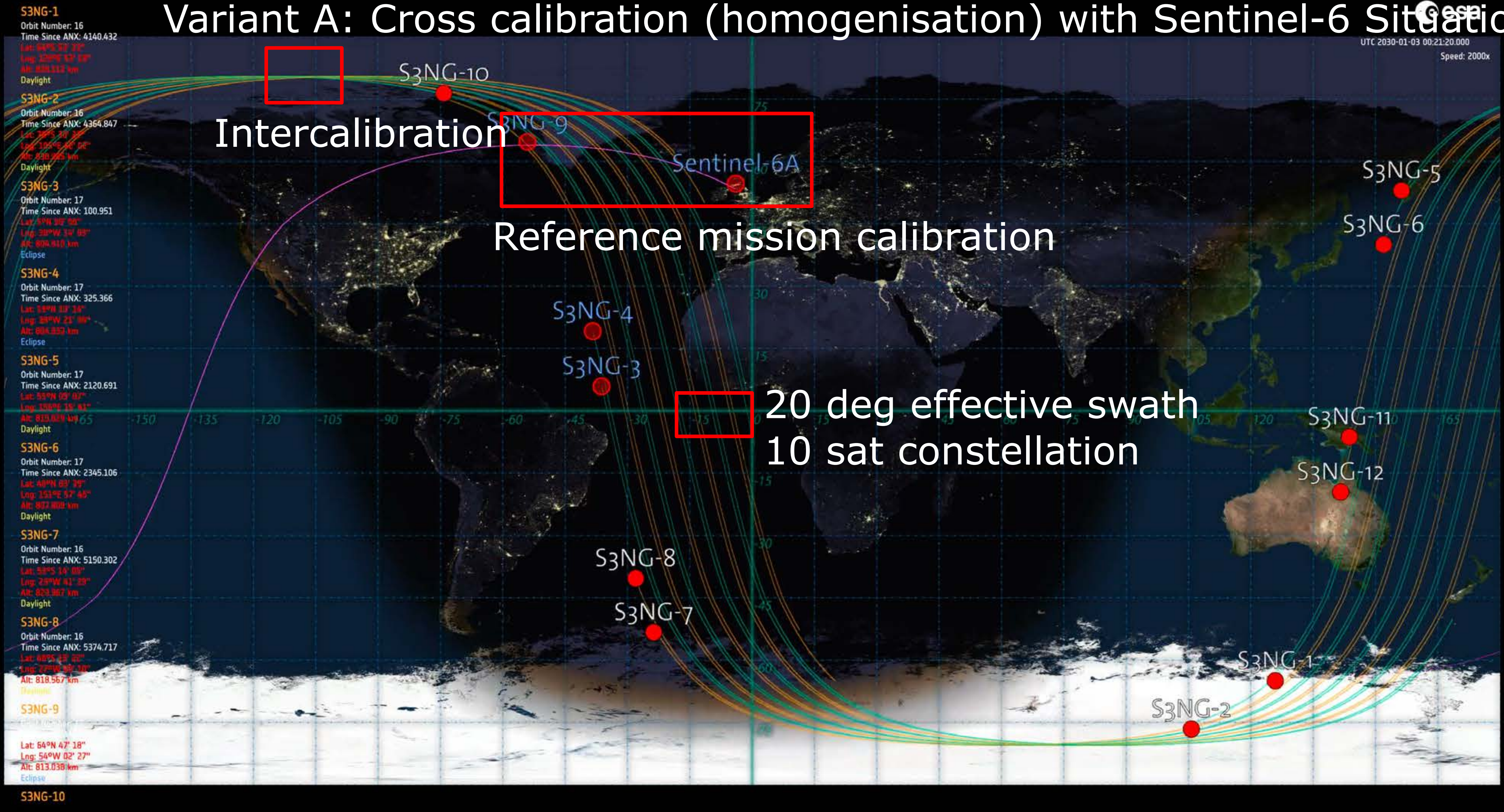
Abstract
The feasibility of precise real-time orbit determination of low earth orbit satellites using onboard GNSS observations is assessed using six months of flight data from the Sentinel-6A mission. Based on offline processing of dual-constellation pseudorange and carrier phase measurements as well as broadcast ephemerides in a sequential filter with a reduced dynamic force model, navigation solutions with a representative position error of 10 cm (3D RMS) are achieved. The overall performance is largely enabled by the superior quality of the Galileo broadcast ephemerides, which exhibits a two- to three-times smaller signal-in-space-range error than GPS and allows for geodetic-grade GNSS real-time orbit determination without a need for external correction services. Compared to GPS-only processing, a roughly two-times better navigation accuracy is achieved in a Galileo-only or mixed GPS/Galileo processing. On the other hand, GPS tracking offers a useful complement and additional robustness in view of a still incomplete Galileo constellation. Furthermore, it provides improved autonomy of the navigation process through the availability of earth orientation parameters in the new civil navigation message of the L2C signal. Overall, GNSS-based onboard orbit determination can now reach a similar performance as the DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) navigation system. It lends itself as a viable alternative for future remote sensing missions.

Keywords Orbit determination · Broadcast ephemerides · LEO satellites · Galileo · Sentinel-6 · DORIS

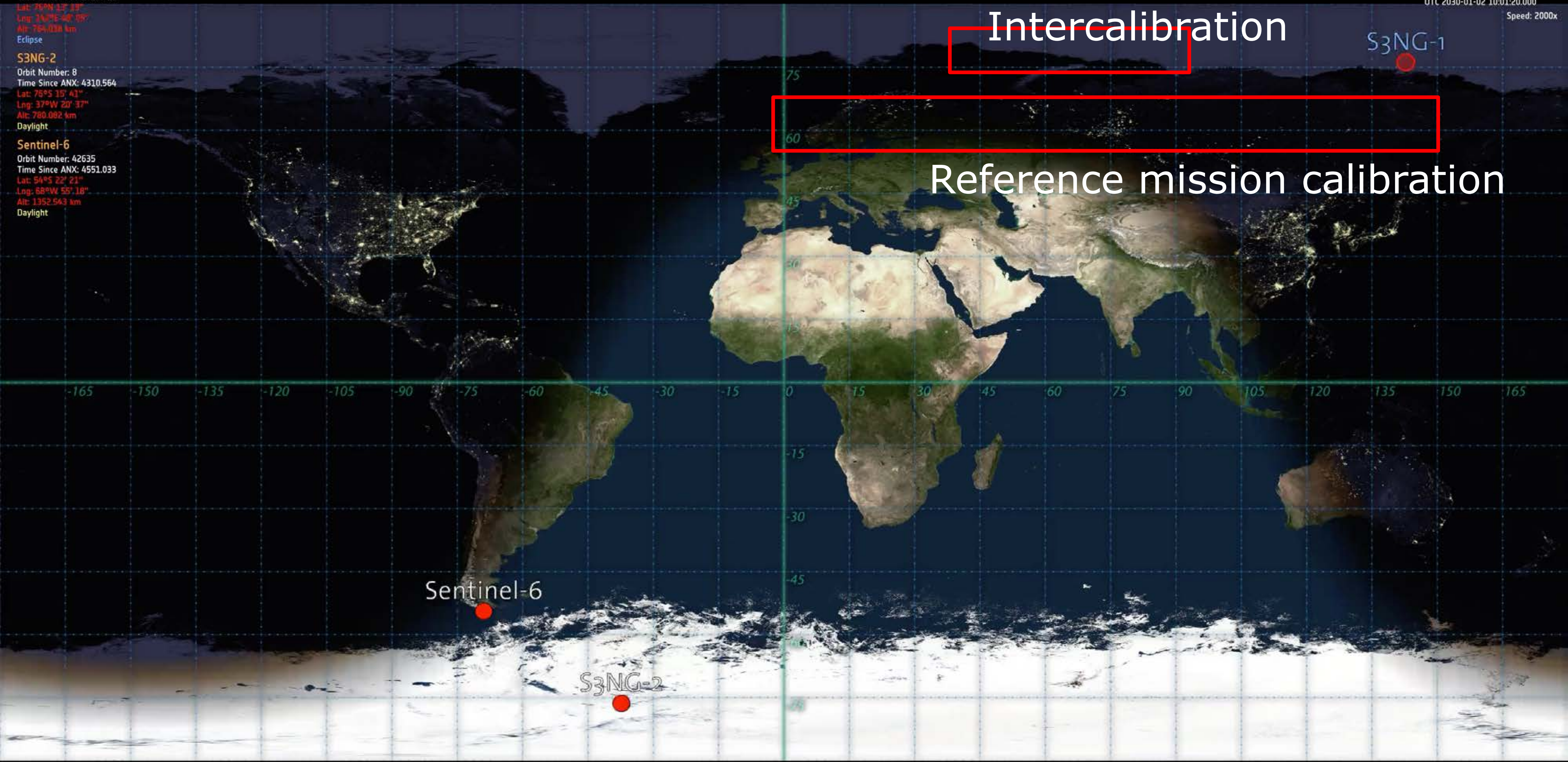
European GNSS Service

EUSPA European Union Agency for the Space Programme

Variant A: Cross calibration (homogenisation) with Sentinel-6 Situatio



Variant B: Cross calibration (homogenisation) with Sentinel-6 Situatio



Variant B (swath) and Variant C (with Swath) require vicarious calibration

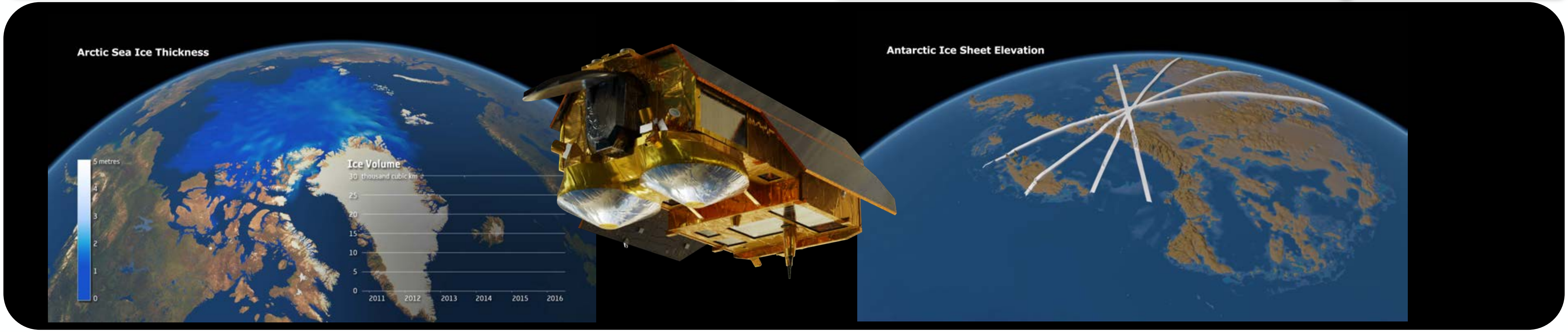
- The Interferometric measurement is extremely sensitive to Roll knowledge errors, new unproven approaches are needed.
  - Extremely high performance roll attitude knowledge is required (~1 cm over 50 km = **0.04 arcsec**). To attain such performance, extremely demanding technical solutions are required (not available today)
  - If not corrected this will induce slope errors in the retrieved Sea Surface Height measurements.
  - Alternative use of vicarious calibration based on ocean surface crossover points which have not yet been demonstrated in flight for a swath altimeter

- Thus, continuity of Sentinel-3 can only be **guaranteed** for measurements derived from a dedicated Ku-band nadir altimeter that is also part of the swath concept, augmented by Sentinel-6 and CRISTAL altimeters.

CRISTAL Mission

The **Arctic's fragile environment** is a direct and key **indicator of climate change**

Mass loss from **Antarctic and Greenland ice sheets and glaciers** is responsible for about half of the current sea level change.



CRISTAL will provide (Primary mission objectives):

- ❑ high resolution **sea ice thickness** and **snow depth** measurements in polar regions
- ❑ high resolution **land ice elevation** measurements of glaciers, ice caps and of the Antarctic and Greenland ice sheets

CRISTAL Mission

Based on CryoSat-2 heritage but with significant improvements

Instrument suite improvements:

- Ku-band Interferometric Synthetic Aperture Radar Altimeter with **Ka-Band channel for snow depth** retrieval
- Addition of **Passive Microwave Radiometer** for
  - wet troposphere correction (secondary mission objective)
  - potential contribution to ice and snow classification (primary mission objective)

Performance & operation improvements:

- **36% improvement of Sea ice freeboard measurement** resolution, by increasing bandwidth to 500MHz (CryoSat 320MHz)
- **Improved interferometric measurements** with **50%** improvement on elevation error
- **Higher precision monitoring of icebergs, ice lead discrimination** etc. with very high along-track resolution (up to **0.5m** with fully-focused SAR processing)
- **Tracking of glaciers** with added Open Loop operational mode