Future Science Facilities and related campaigns relevant to polar science (CRISTALair, CIMRair, Altimetry)

Craig Donlon, CIMR Mission Scientist
Paolo Cipollini, CRISTAL Mission Scientist

Franck Borde, Jérôme Bouffard, Tânia Casal, Filomena Catapano, Alessandro Di Bella, Kristof Gantois, Valeria Gracheva, Günther March, Michele Scagliola, Martin Suess

Copernicus Polar Expansion Missions are **operational** missions, but with a strong **innovation** compon

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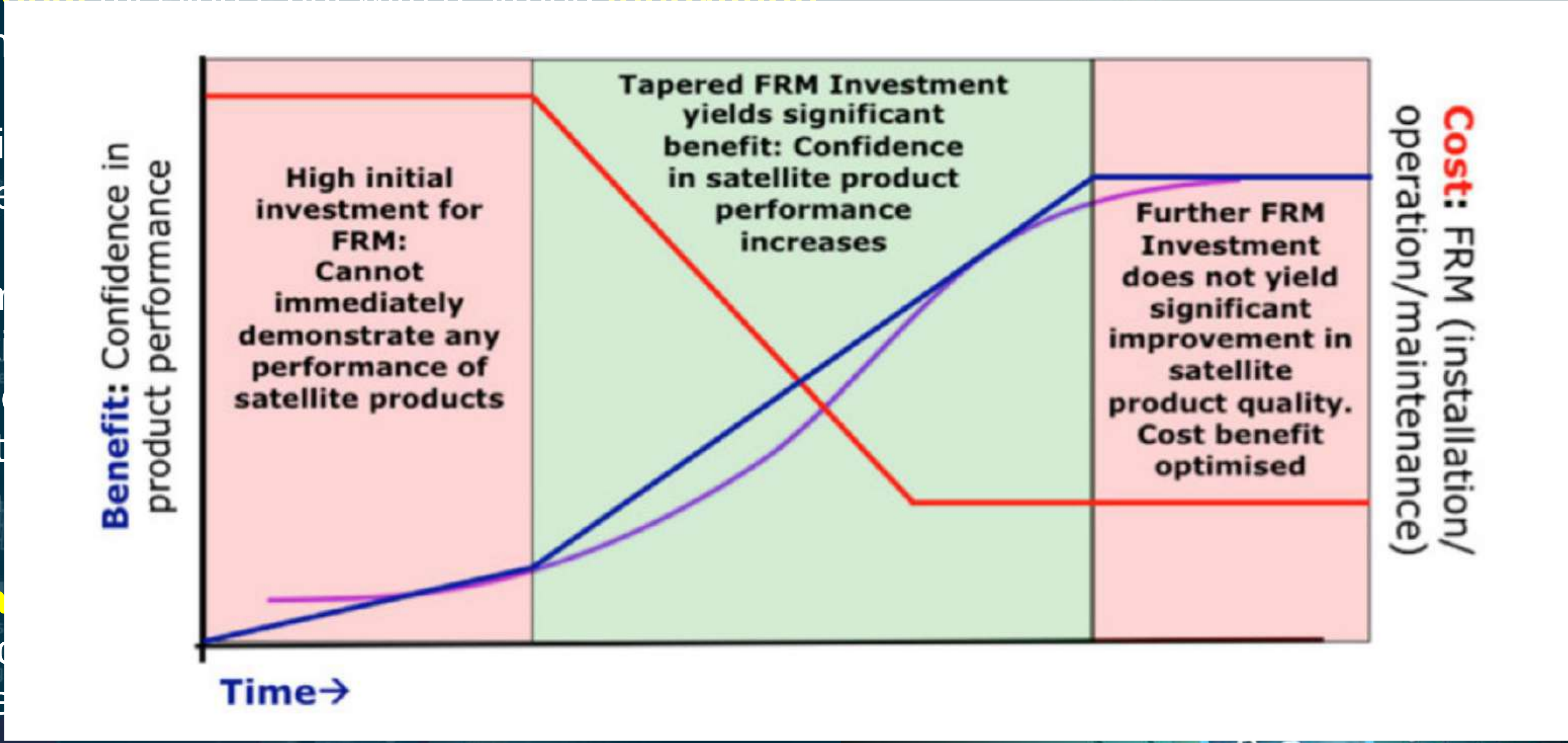

ROSE-L

CRISTAL
Copernicus Polar Ice and Snow Topography Altimeter

Fiducial Reference Measurements

Fiducial Reference Measurements (FRM) are

the suite of ***indepen*** ***pro*** ***Return On***
Investment for a *us* *s, in the form of*
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The defining mandat

Have **documen** a in onal-like
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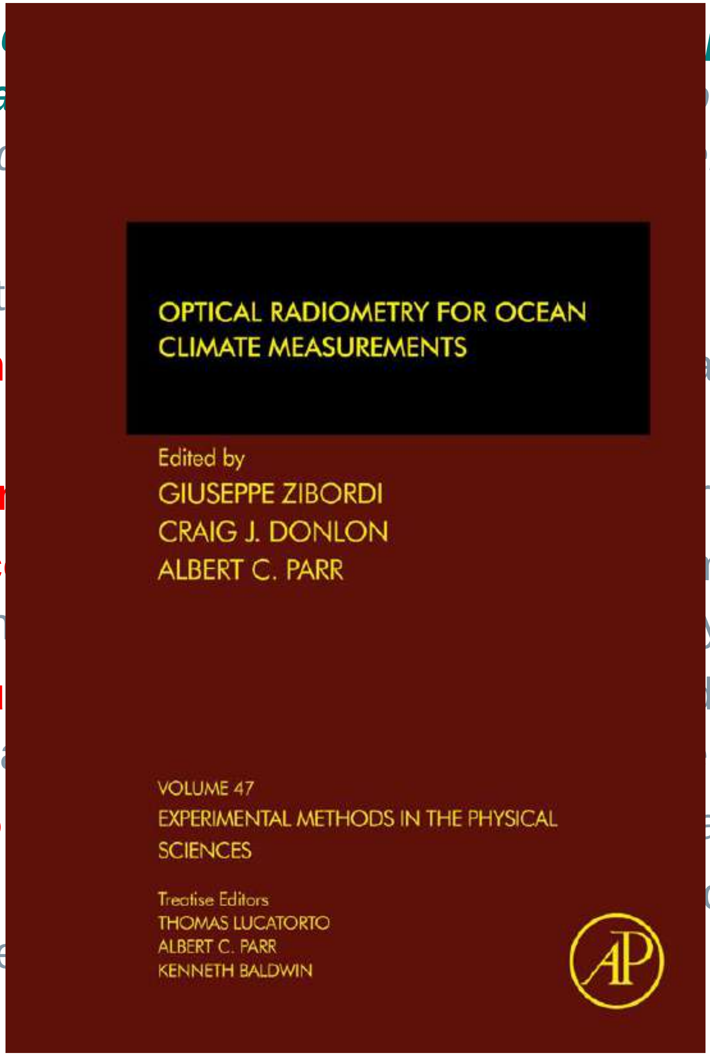

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Fiducial Reference Measurements (FRMs): What Are They?

by Philippe Goryl [1,*], Nigel Fox [2], Craig Donlon [3] and Paolo Castracane [4]

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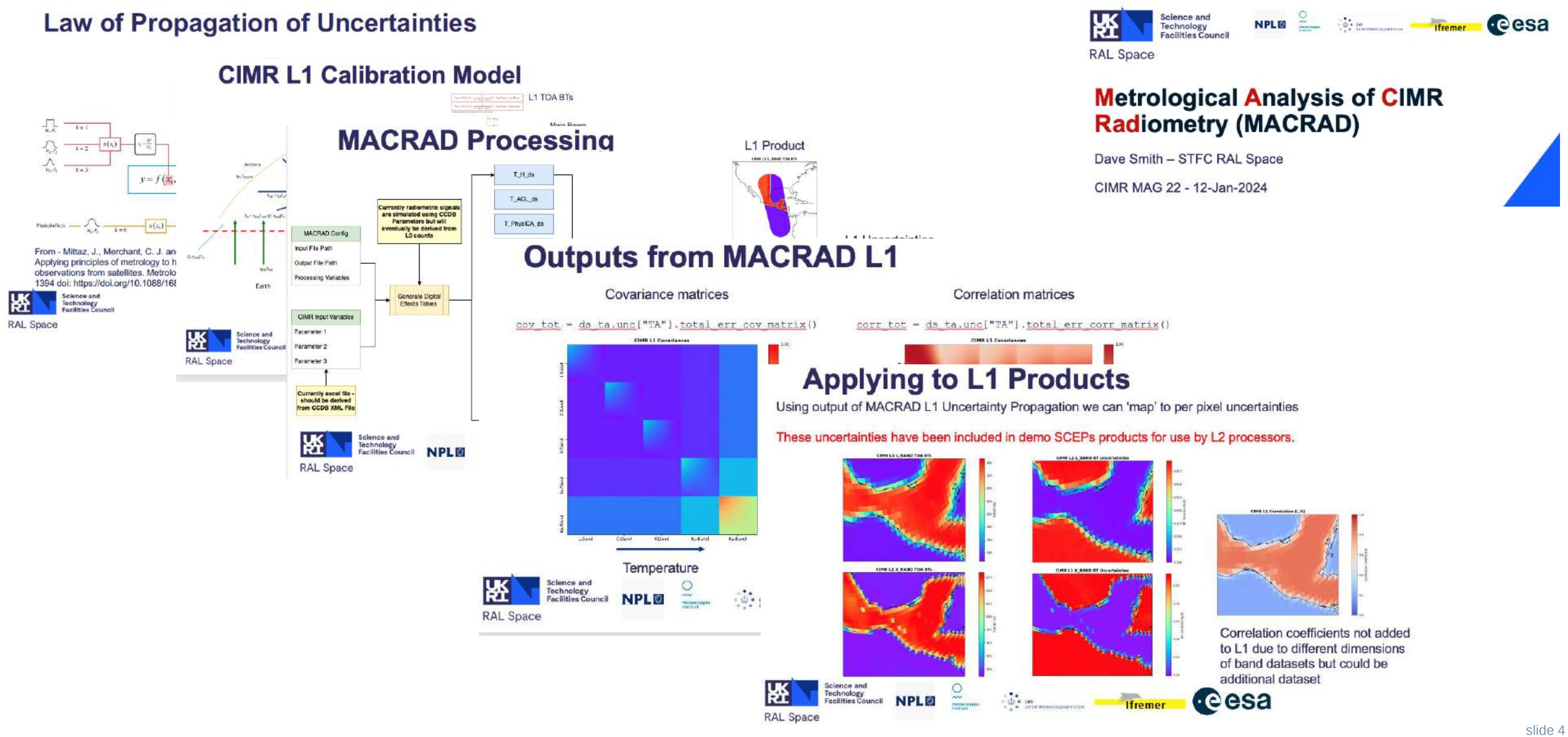
Abstract

In recent years, the concept of a Fiducial Reference Measurement (FRM) has been developed to highlight the need for precise and well-characterised measurements tailored explicitly to the post-launch calibration and validation (Cal/Val) of Earth observation satellite missions. The confidence that stems from robust, unambiguous uncertainty assessment of space observations is fundamental to assessing the changes in the Earth system and climate model prediction and delivering the essential evidence-based input for policy makers and society striving to mitigate and adapt to climate change. The underlying concept of an FRM has long been a core element of a Cal/Val program, providing a 'trustable' reference against which performance can be anchored or assessed. The 'FRM' label was created to embody into such a reference a set of key criteria. These criteria included the establishment of documented evidence of uncertainty with respect to a community-agreed reference (ideally SI-traceable) and specific tailoring to the needs of a satellite mission. It therefore facilitates comparison and interoperability between products and missions in a cost-efficient manner. Committee on Earth Observation Satellites (CEOS) Working Group Cal/Val (WGCV) is now putting in place a framework to assess the maturity and compliance of a 'Cal/Val reference measurement' in terms of a set of community-agreed criteria which define it to be of CEOS-FRM quality. The assessment process is based on a maturity matrix that provides a visual assessment of the state of any FRM against each of a set of given criteria, making visible where it is mature and where evolution and effort are still needed. This paper provides the overarching definition of what constitutes an FRM and introduces the new CEOS-FRM assessment framework.

Keywords: earth observation; remote sensing; calibration; validation; fiducial reference measurements; CEOS

CIMR Uncertainty Modelling



ESA investments to ensure product quality

Science Facilities (Airborne Demonstrators – CRISTALair and CIMRair)

Essential for the consolidation of the retrieval algorithms during the implementation Phase, and then for in-flight calibration to complement FRM

Permanent facilities for calibration

Sizeable investment at the start, but essential for collecting the FRMs that are needed for post-launch validation. This supports the accurate delivery of level 1 and higher-level products, confirming expected performance including processors and any retrieval algorithms

al, 2015, Goryl et al, 202

Example: CRISTAL science data products support

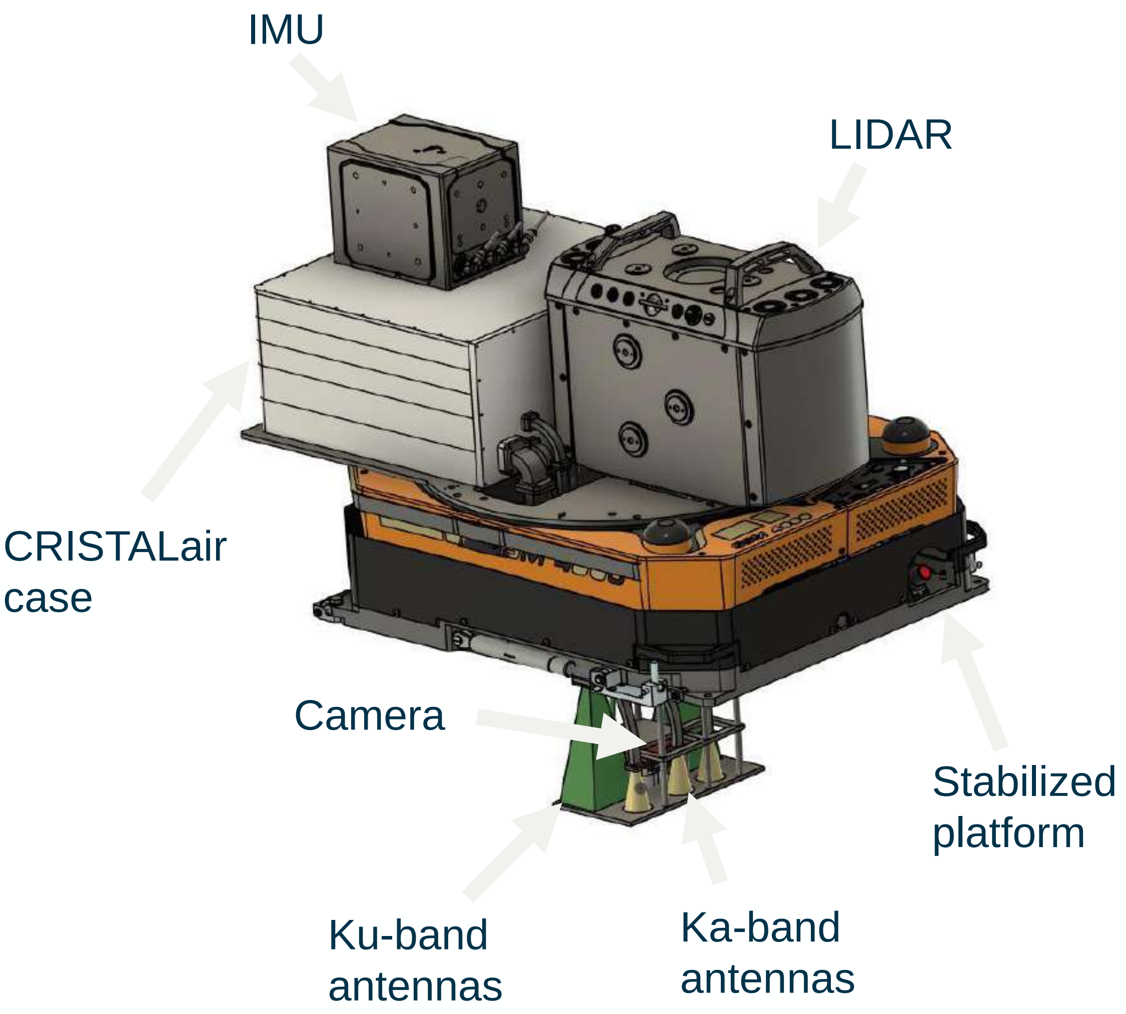
CRISTALair: the airborne demonstrator for CRISTAL

Ready early 2025

Interferometric Dual-Frequency Airborne Altimeter Instrument

- Interferometry in both Ku- **and** Ka-band
- 1 GHz bandwidth (sampling of full bandwidth)
- Range window: 300 m
- Altitude range: 1000 m – 4000 m (AGL)
- Currently optimized for Twin-Otter aircraft
  - We will also get it certified for Basler aircraft
- Included:
  - LIDAR (rented)
  - Colour infrared camera
  - Stabilized platform
  - Inertial Measurement Unit
  - GNSS receiver

CRISTALair



Courtesy: Metasensing

Corner Reflectors for CRISTALair
(*Triangular, Length 0.95 m, RCS: 38.4 dB, Elevation: 2 m AGL)*

CRISTALair proposed campaigns summary schedule

Campaign	Objectives	Time / Duration	SSP activities & Mission Obj.s
CRISTALair Functional Flight Campaign in the Arctic (includes a local/ European test ground/flight)	- Cal/sync flights - Radiometric / elevation accuracy / slope /point target response and other req verifications - Flights over corner reflectors - Antenna pointing verification - Performance evaluation over altitude - Verification of the CRISTALair Level1 ground processor	Feb 2025 / 4 days (~20 hours over 4 flights)	SP07, SP08
CRISTALair Functional Campaign add-on in the Arctic (Station Nord)	- Collocated snow measurements to validate snow depth - Drone/aircraft snow radar measurements	Feb 2025	SP03, SP07, SP08
CRISTALair for AWI	Certification of CRISTALair in AWI aircraft	TBD	
CRISTAL first Science Campaign in the Arctic (or Svalbard)	- Snow, sea/land ice measurements to develop & consolidate snow depth measurements - Characterize radar return at both frequencies - Validate snow retrievals	TBD (2025)	SP06, SP07, SP08
The joint Copernicus Expansion Missions CIMR, CRISTAL and ROSE-L sea ice experiment (CEMSIE)	Collocated measurements of CRISTALair, CIMRair, snow radar, radiometer (airborne) with ground measurements	Spring 2026	SP06, SP07, SP08
CRISTAL Science Campaign in Antarctica	Additional measurements for developing retrieval methods based on Antarctica snow conditions which differ considerably from Arctic snow	Dec 2026	SP01, SP02,SP06 SP08

First Arctic Campaign and CEMSIE

First Arctic Campaign

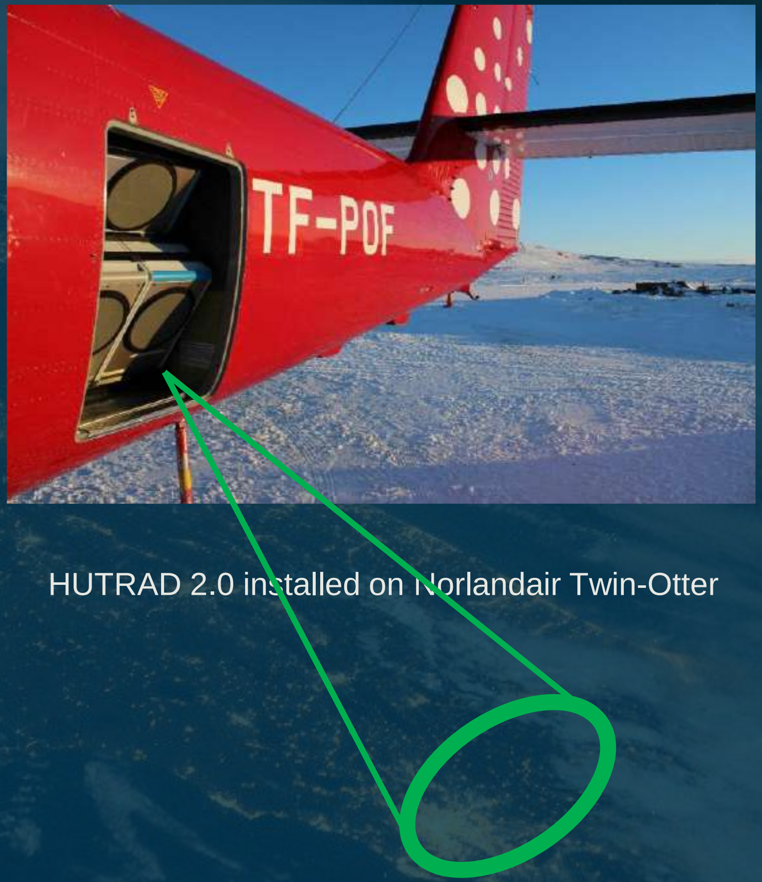
- Objective 1: develop and consolidate snow depth measurement retrievals
- Objective 2: verify the across-track collocation of the radar return at both frequencies
- Expected outcome: Collect sufficient airborne Ka/Ku/La + snow radar and in situ data to validate the snow retrievals
- Study how snow depth measurements vary with the spatial scale observed and snow conditions
- Place TBD <81.5° (Svalbard)? Time possibly 2025, airborne+drones+in situ

CEMSIE

- CIMR, CRISTAL and ROSE-L Sea Ice Experiment, proposed by John Yackel (Univ. Calgary) and Rasmus Tonboe (DTU)
- To reduce uncertainties and improve retrievals for Sea Ice concentration/thickness, Snow Depth
- Cambridge Bay (First-Year Ice), Spring 2026
- Extensive set of in-situ instrumentation
- Excellent opportunity for NASA/JPL participation

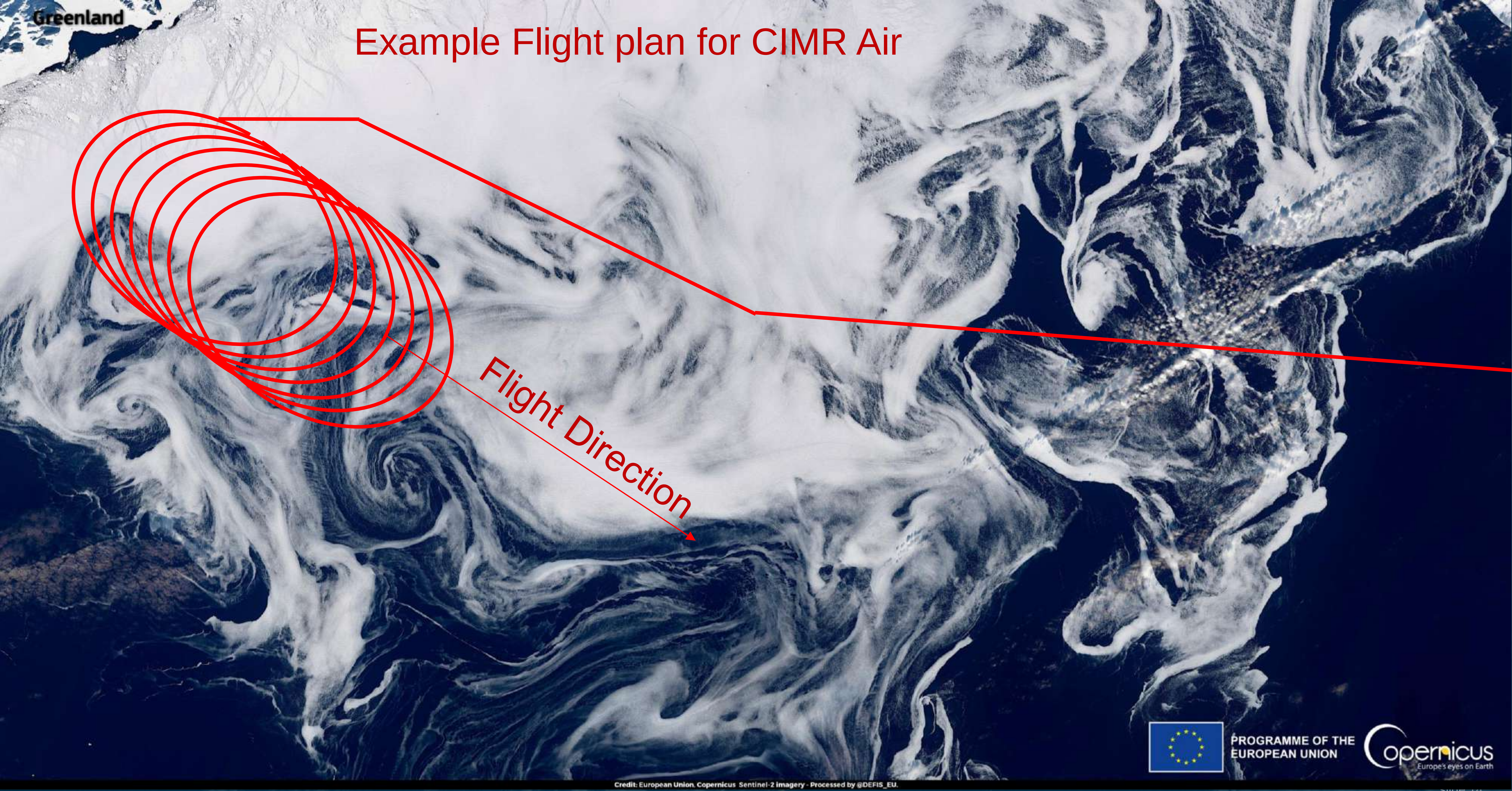
CIMRair - High Level Requirements

- Airborne Radiometer with 5 frequency bands (L-, C-, X-, K-, Ka-band)
- Acquire measurements with two channels in vertical linear (V) and horizontal linear (H) polarisation
- Measuring the full stokes vector for each frequency band
- Side-looking configuration with one fixed beam per band with an OZA ~55 deg
- Maximum operational altitude > 3000 m above sea level
- Reference altitude for instrument performance is 1000 m above ground
- Fixed footprint measurement from all aspect angles by using circular flight pattern
- The development activity includes
    - Certification of the instrument for the baseline aircraft
    - One initial Functional Flight Campaign in the arctic environment to demonstrate the function and performance of the instrument



HUTRAD 2.0 installed on Norlandair Twin-Otter

Example Flight plan for CIMR Air



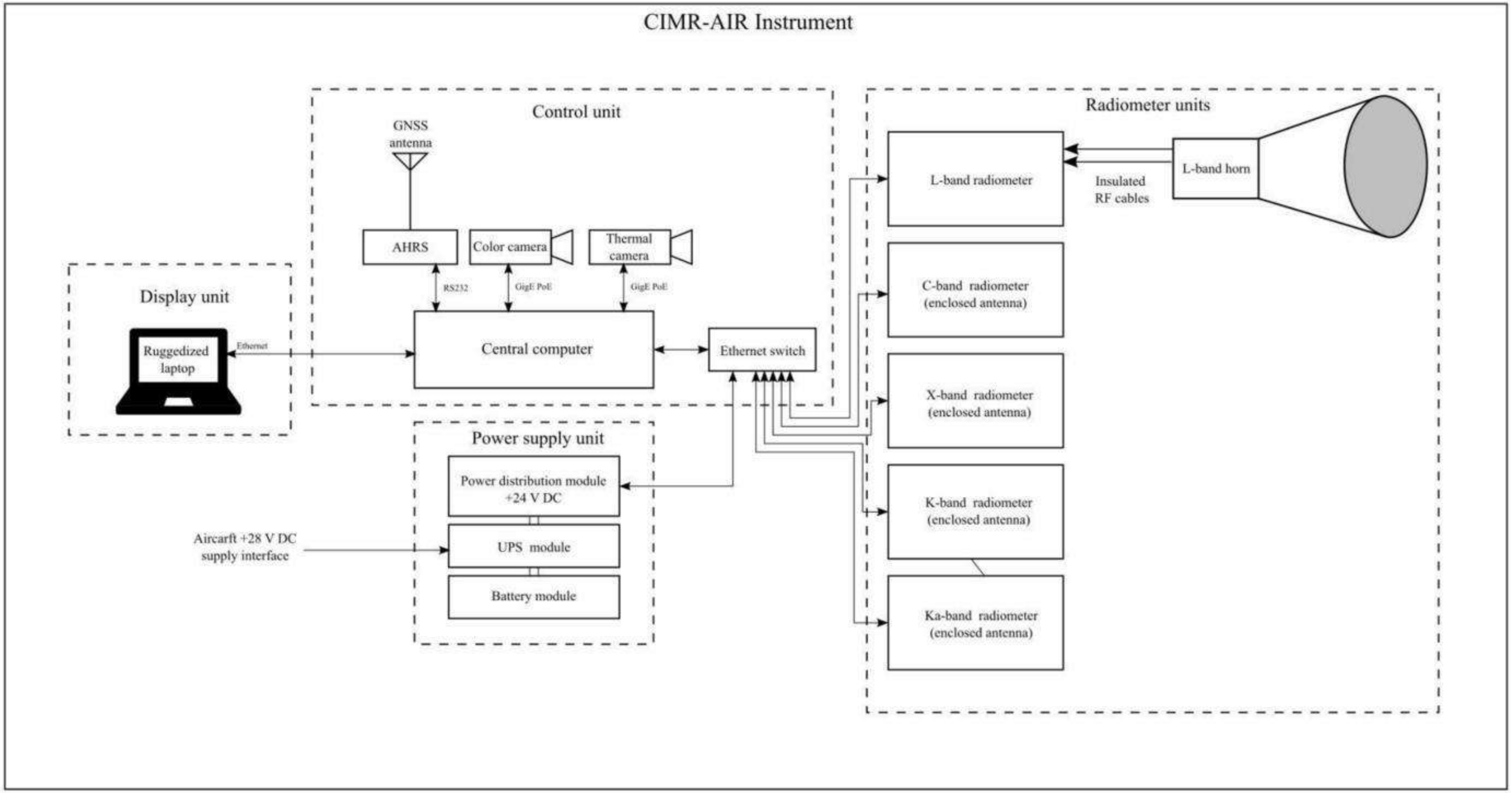
Aircraft Selection

- The Norlandair Twin-Otter has been confirmed as the baseline aircraft
- The custom door cover with antenna feed through and radomes will be designed and flight certified for this specific aircraft
- The compatibility with the DO228 as secondary aircraft will be assessed and should maintained during the design
- However, this compatibility shall not compromise the instrument performance

Confirmed Baseline: Norlandair Twin-Otter

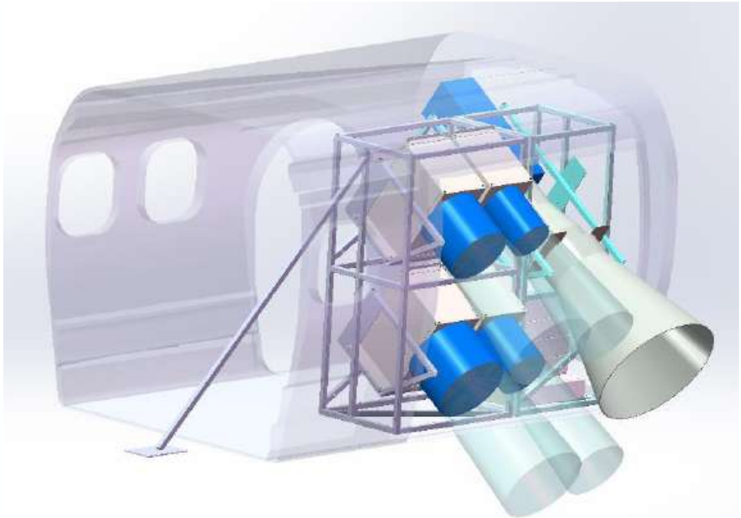
Lufttransport Do-228 in Svalbard

CIMR-AIR Instrument Overview

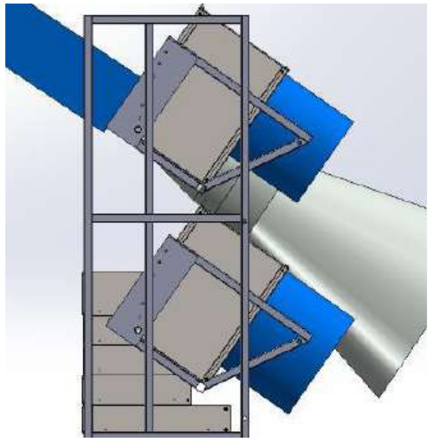


Instrument configuration

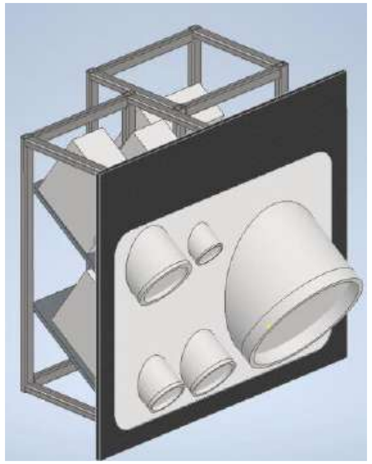
- The radiometer will be mounted behind the cargo door opening
- The door will be closed with a cover including radomes
- The L-band antenna may cover directly the horn opening
- The odd-nadir angle can be adjusted in steps of 5 degree
- This enables antenna angle adjustment for circular flights for multi aspect angle measurements
- The pivot point as close to the radome as possible
- Horn antennas are considered as antenna baseline



Visualisation of instrument inside the aircraft



Radiometer carrier



Door cover radome

Colour and Thermal Cameras

- Selected CIRM-AIR cameras
  - Baumer VCXG-15C.I.XT (colour)
  - Infratec HDx 675 (thermal)
- The field of view can be adapted by changing the (C-Mount) optics
- Recorded frame rate specified < 10 fps

Parameter	Value
Camera type	**Baumer VCXG-15C.I.XT (optical)**
Image size	1440 x 1080
8 mm focal length - field of view	33° x 25°
Projected pixel size	1.7 m
4 mm focal length - field of view	63.8° x 50.1°
Projected pixel size	3.4 m
Dimension	40 x 40 x 50.8 mm
Mass	137 g

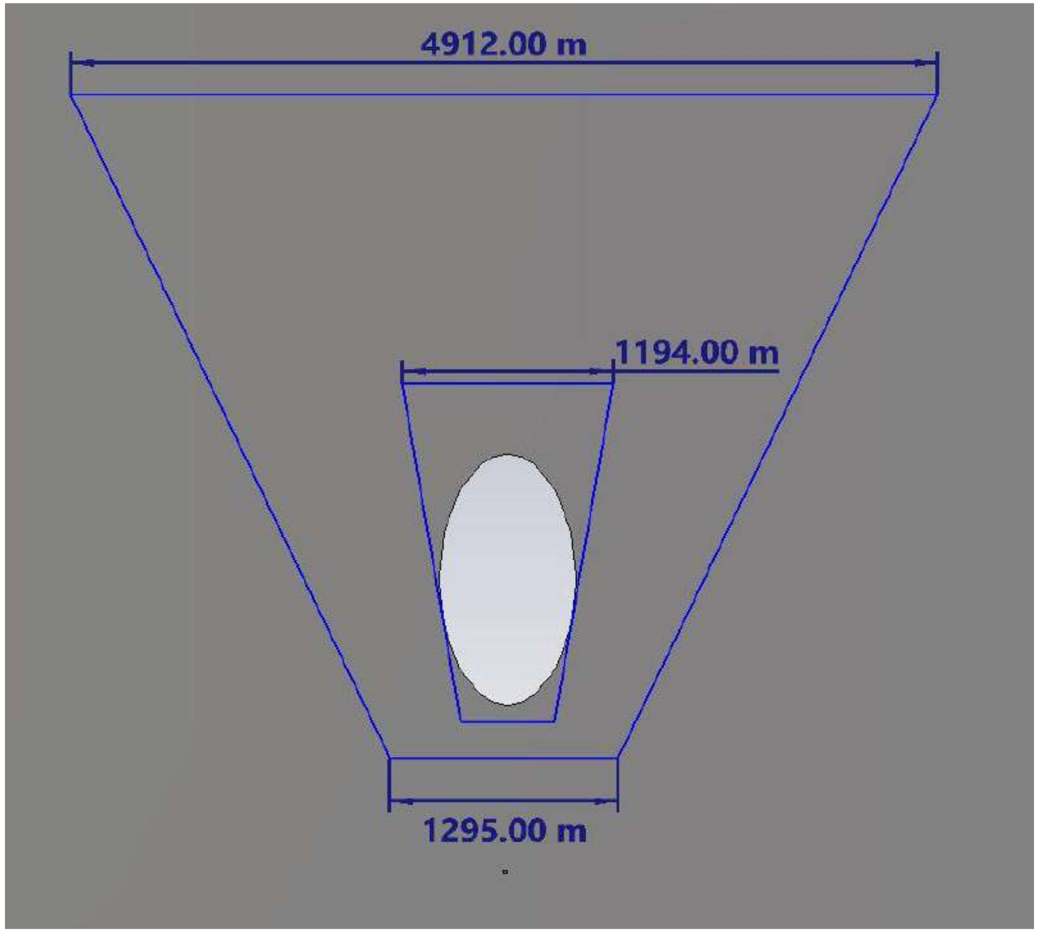
Baumer VCXG-15C.I.XT

Infratec HDx 675

Parameter	Value
Camera type	**Infratec HDx 675 (thermal)**
Spectral range	7.5 … 14 µm
Thermal reslution	40 mK
Image size	640 x 480
20 mm focal length - field of view	30.0° x 23.1°
Projected pixel size	4.9 m
10 mm focal length - field of view	57.1° x 44.4°
Projected pixel size	7.4 m
Dimension	90 x 94 x 190 mm
Mass	1150 g

Cameras Field of View

- Comparison of cameras field of view with L-band antenna footprint (~24 deg)
- The image should not only cover the -3dB contour but rather the main beam (~ factor 2.5)
- This ensures that all significant contributors are covered
- This leads to reduced resolution and less detailed images



Thermal camera - field of view projections for 10mm (outer) and 20mm (inner) focal lengths.

Instrument Performance Figures

- **Radiometer Channels are largely aligned with CIMR**

	L-band	C-band	X-band	K-band	Ka-band
Centre Frequency [GHz]	1.4135	6.925	10.65	18.7	36.5
Bandwidth [MHz]	50	400	100	200	300
Band [MHz]	1.4-1.45	6.675-7.075	10.6-10.7	18.6-18.8	36.35-36.65

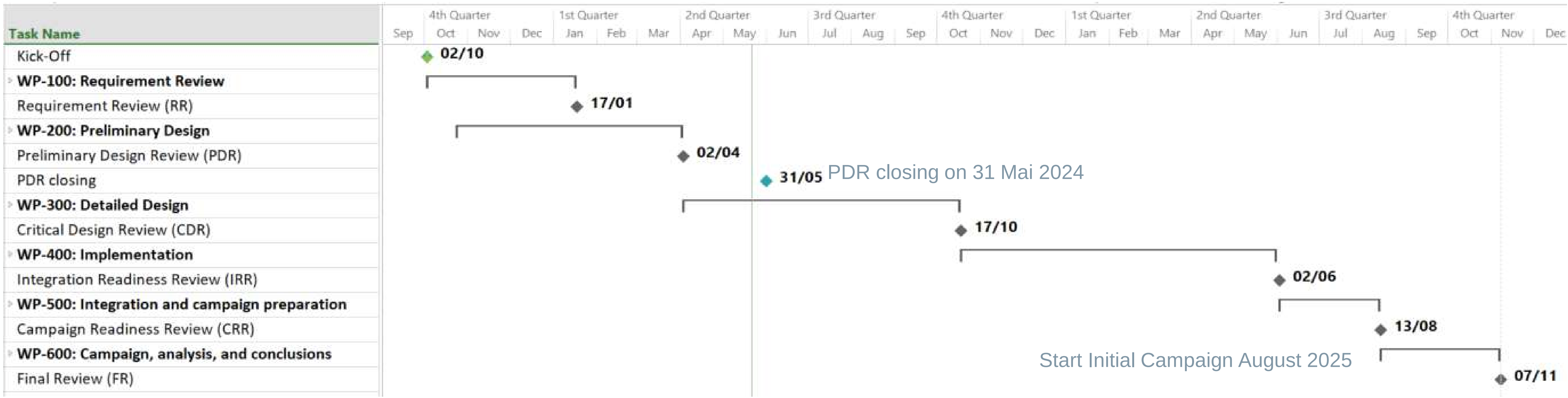
- **Footprint size at reference altitude**

Reference Altitude [m]	1000	1000	1000	1000	1000
Incidence angle [deg]	55	55	55	55	55
Footprint_size Requirement [m]	< 1000	< 500	< 500	< 200	< 200
Prelimininary Footprint size [m]	1170	439	445	213	147

- **Total standard uncertainty budget**

Total standard uncertainty requirement [K]	0.5	0.5	0.5	0.6	0.8
NEDT [K]	0.04	0.04	0.08	0.11	0.09
Stability requirement [K]	0.2	0.15	0.1	0.2	0.2
Remaining Error budget for calibration errors [K]	0.46	0.48	0.48	0.56	0.77

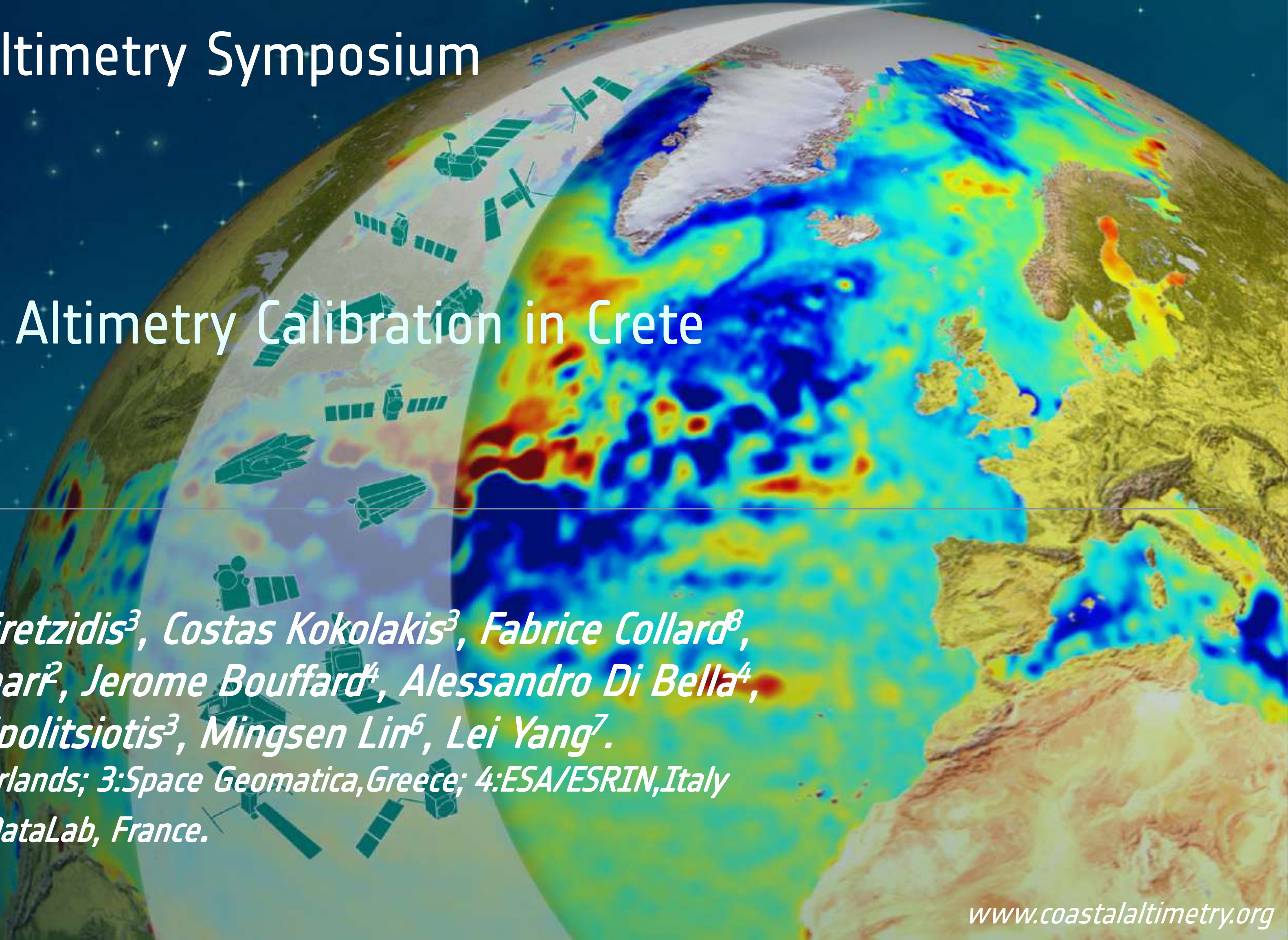
Schedule



- Compared to the previous schedule the Final Review is delayed by 5 weeks

30 Years of Progress in Radar Altimetry Symposium
2-7 September 2024 | Montpellier, France

The ESA Permanent Facility for Altimetry Calibration in Crete



Stelios Mertikas[1], Craig Donlon[2], Dimitrios Piretzidis[3], Costas Kokolakis[3], Fabrice Collard[8], Robert Cullen[2], Pierre Femenias[4], Marco Fornari[2], Jerome Bouffard[4], Alessandro Di Bella[4], Francois Boy[5], Xenofon Frantzis[1], Achilles Tripolitsiotis[3], Mingsen Lin[6], Lei Yang[7].

1:Technical University of Crete; 2:ESA/ESTEC, The Netherlands; 3:Space Geomatica,Greece; 4:ESA/ESRIN,Italy 5:CNES, France; 6:NSOAS, China; 7:FIO, China, 8: OceanDataLab, France.

ESA Permanent Facility for Altimetry Calibration

Calibrate radar satellite altimeters:

- ESA Permanent Facility for Altimetry Calibration in Crete, Greece;
-Transponders, Corner Reflectors, Sea-Surface, and Sea-State Optical Techniques.

Results of Calibration to FRM Standards:

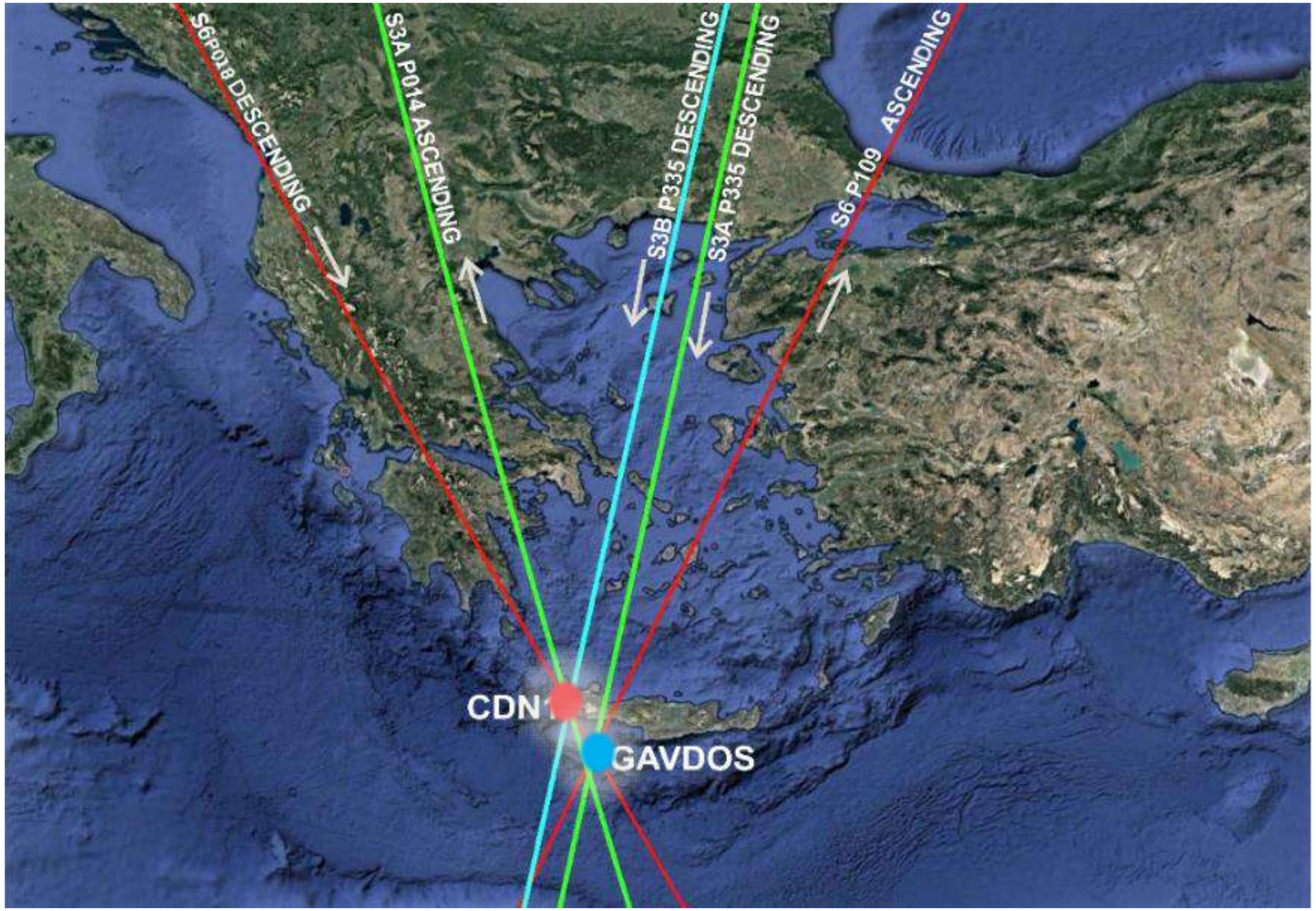
- To absolute reference signals,
- Traceable to SI-standards,
- Different & redundant techniques (sea & land),
- Various processes, diverse instrumentation, settings, locations, etc.

Report FRM Uncertainty for Satellite Cal/Val Results

Analyse Performance.

ESA Permanent Facility for Altimetry Calibration

Transponders at ESA PFAC, Crete



-Multiple Cross-over (S3A, S3B, JA3, S6, CryoSat-2, SWOT),
-Low clutter,
-Cross-calibration,
-Crystal clear signal of satellites

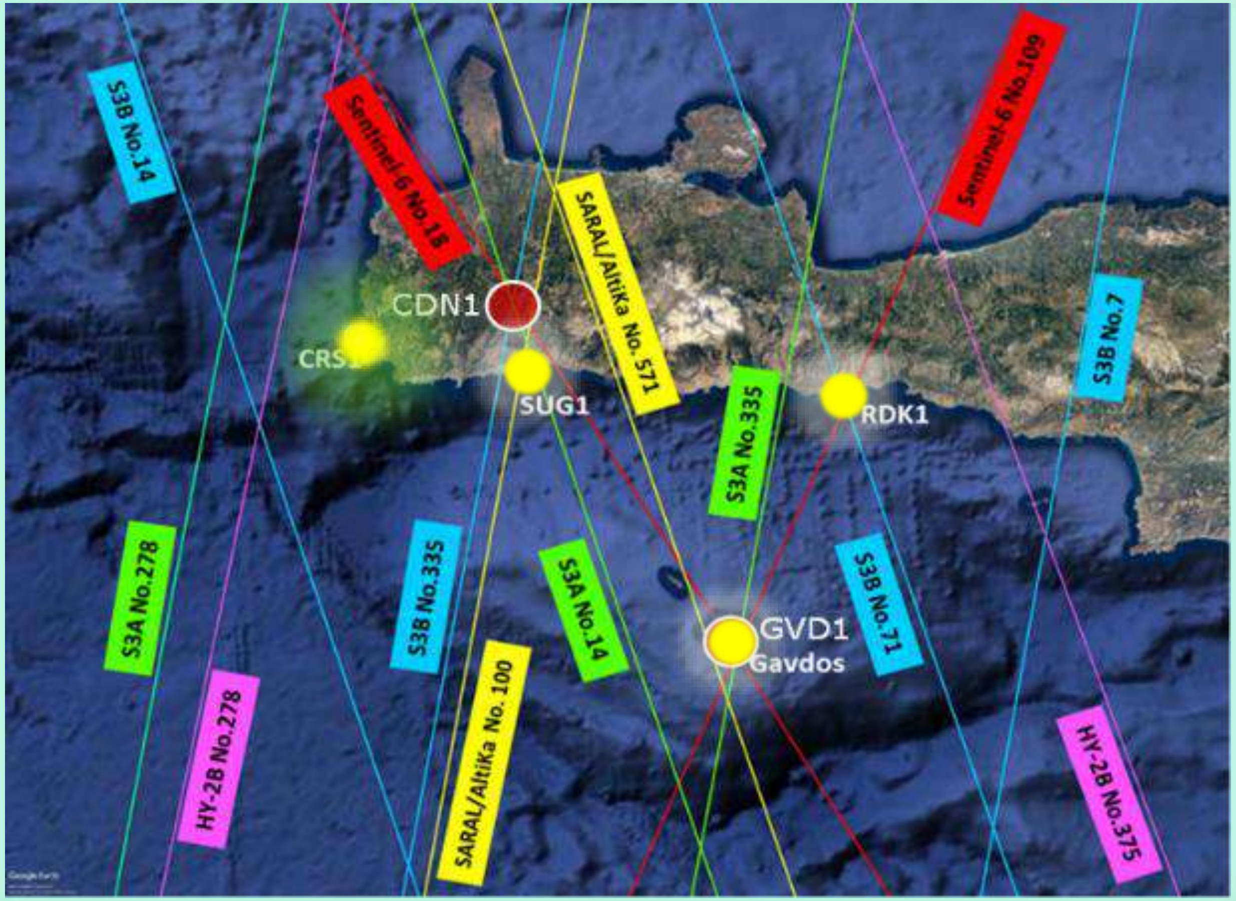
Gavdos (GVD1 Transponder)

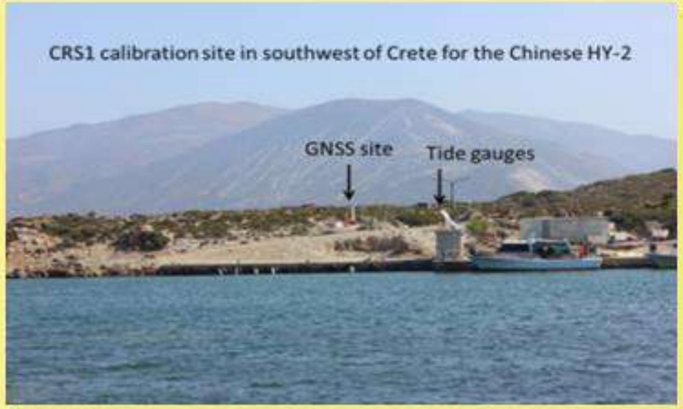
S3A, Sentinel-6 (A109 & D18), CryoSat-2
Sea-Surface Cal/Val

24

ESA Permanent Facility for Altimetry Calibration

Sea-surface infrastructure, Crete





CRS1 Cal/Val site (West Crete)

SUG1 Cal/Val site (West Crete)

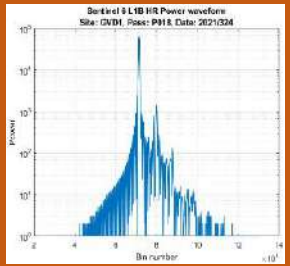
Gavdos Cal/Val site

RDK1 Cal/Val site (South Crete)

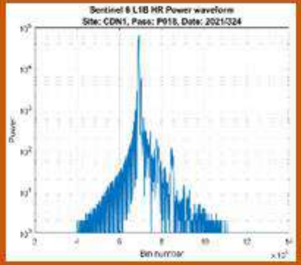
ESA Permanent Facility for Altimetry Calibration

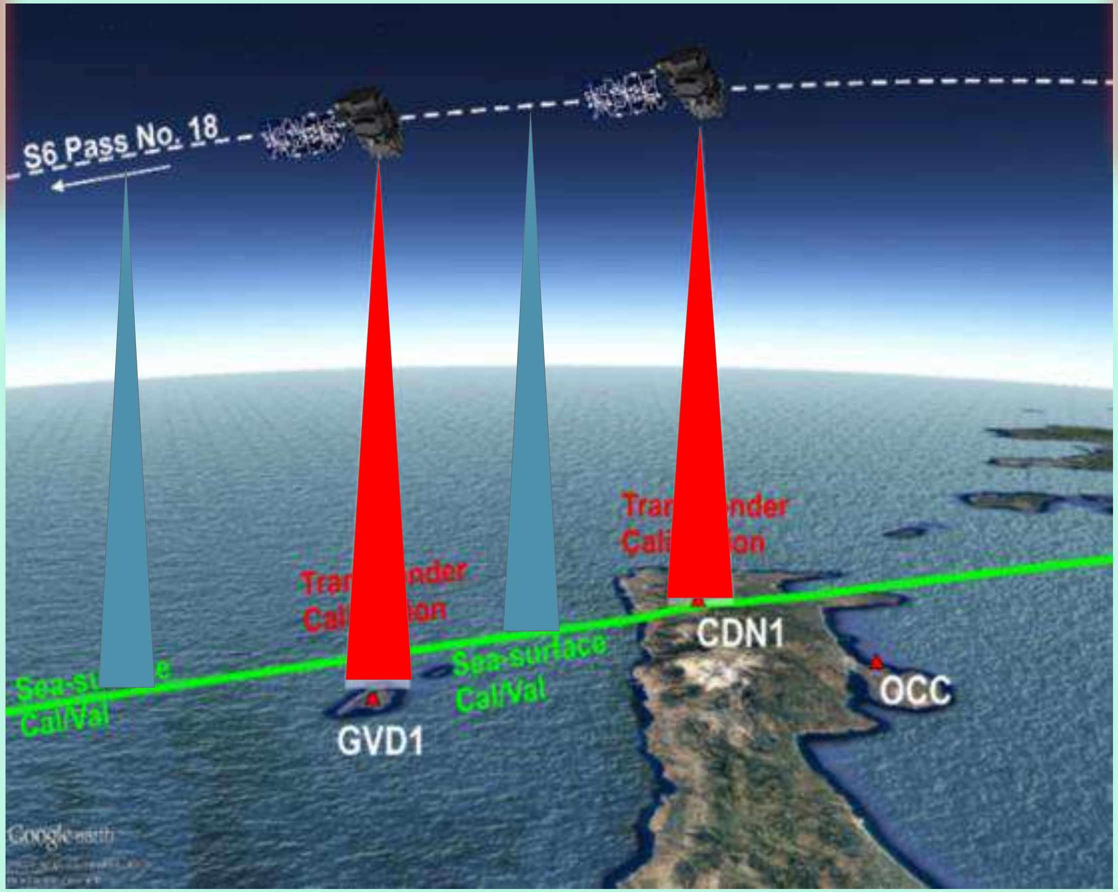
“Simultaneous” Cal/Val: Descend

GVD1 Transponder

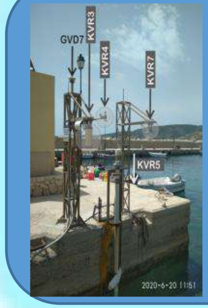


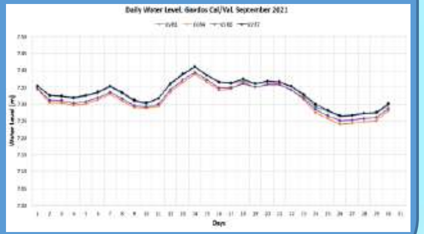
CDN1 Transponder



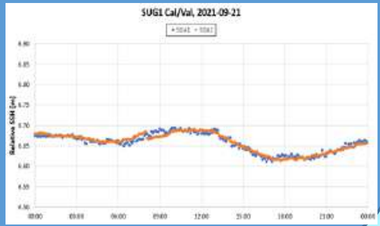


Gavdos sea-surface





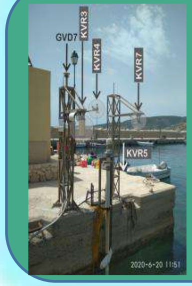
SUG1 sea-surface

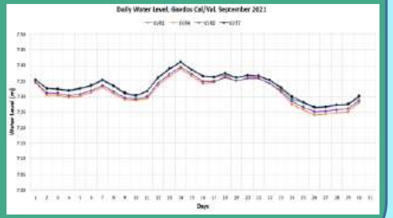


ESA Permanent Facility for Altimetry Calibration

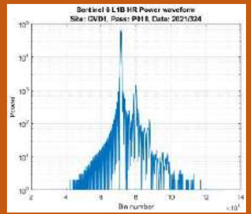
“Simultaneous” Cal/Val: Ascending

Gavdos sea-surface

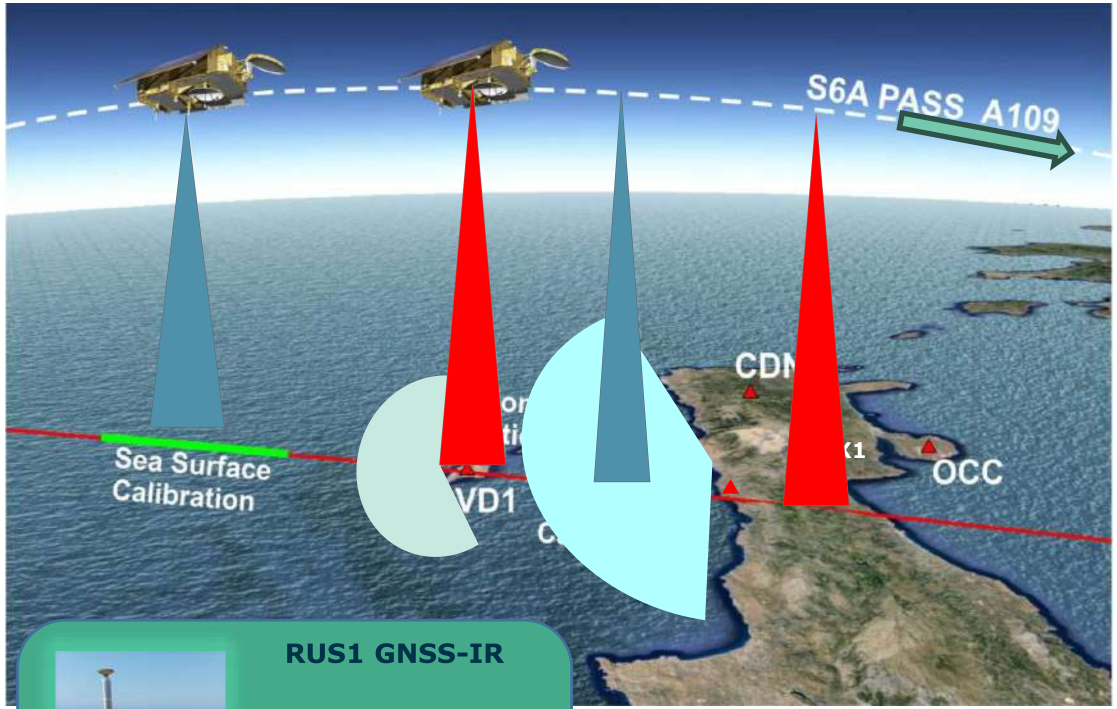




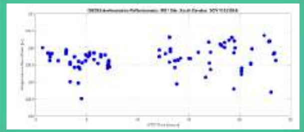
GVD1 Transponder



SUG1 sea-surface



RUS1 GNSS-IR



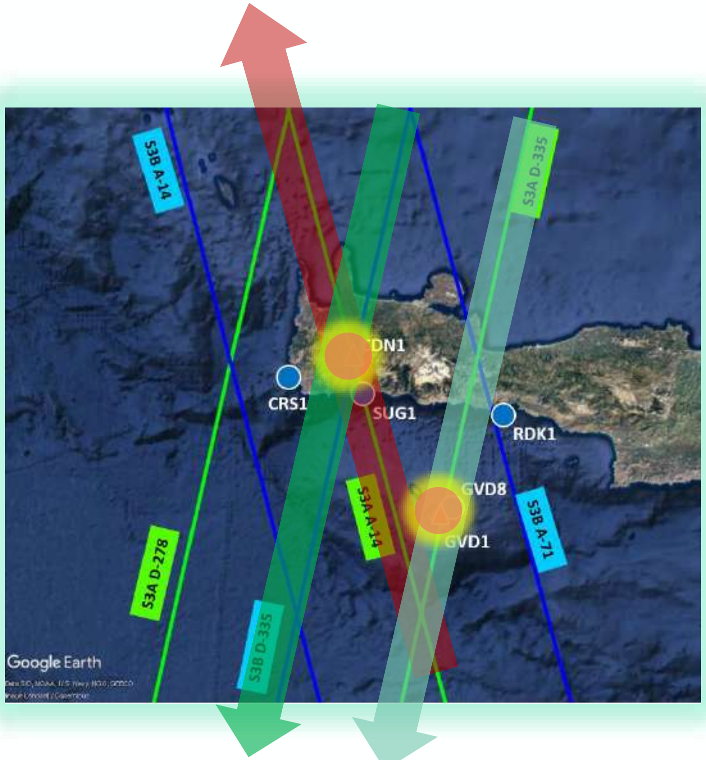
Sea-State Optical

ALX1 Corner Reflector

ALX2 Corner Reflector

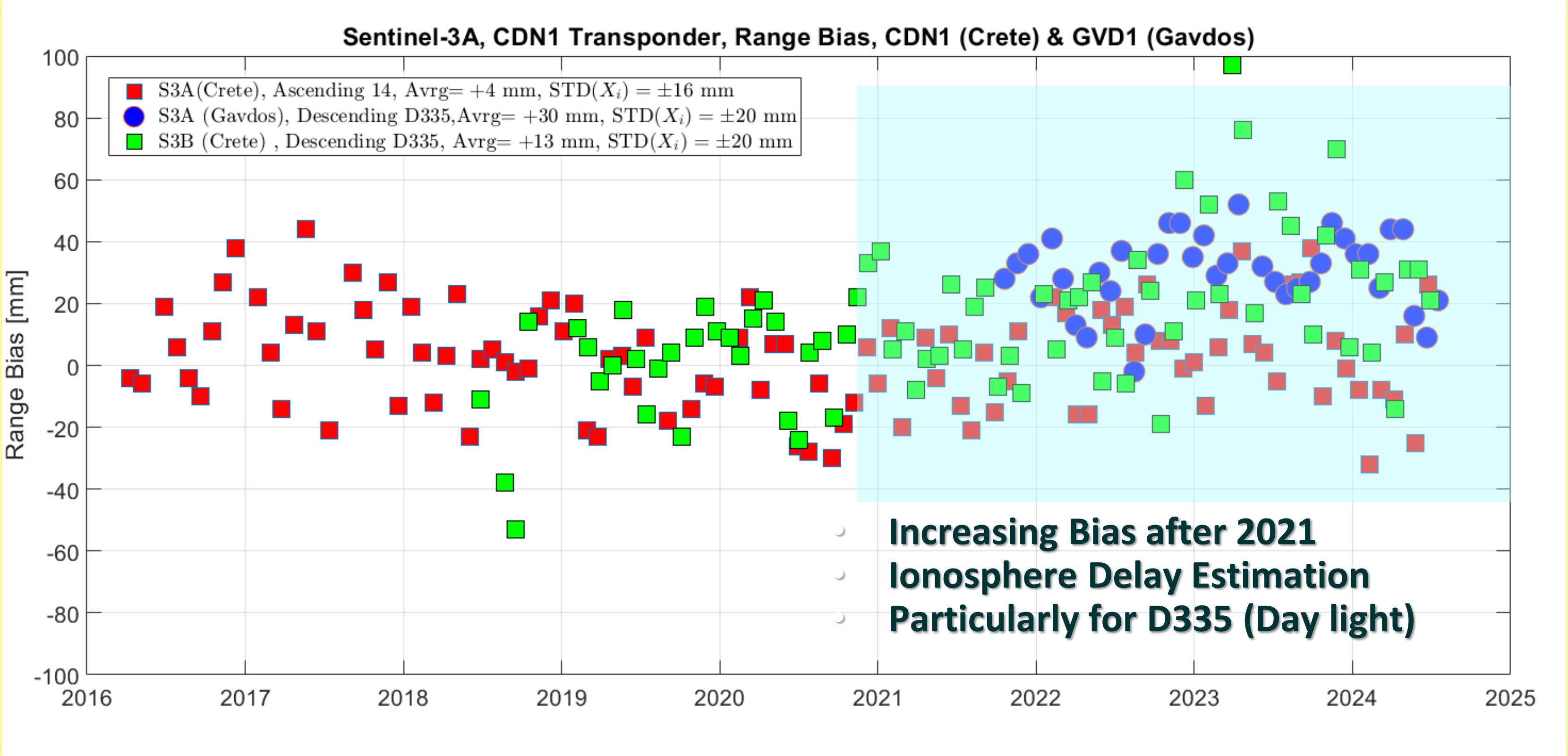
Sentinel-3A & -3B Transponder Range Bias [Delay-Doppler]

S 3A
A14



S-3B
D335

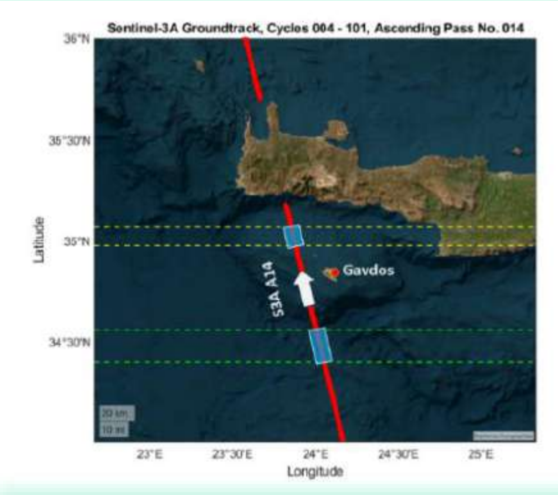
S-3A
D335

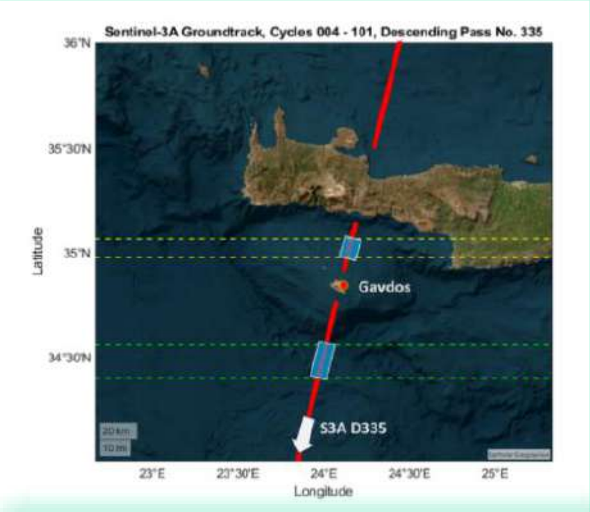


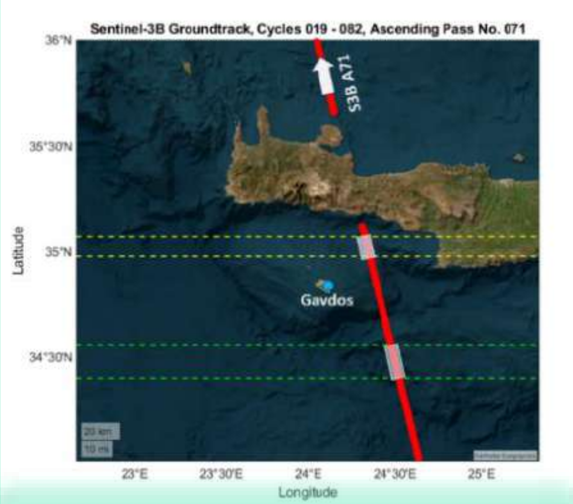
- S3A Range Bias (Crete) = +4 mm ± 16 mm, Ascend A14; [U(FRM)= ± 30mm]
- S3A Range Bias (Gavdos) = +30 mm ± 12 mm, Descending D335, (Day light pass)
- S3B Range Bias (Crete) = +20 mm ± 16mm, Descending D335, (Day light pass)

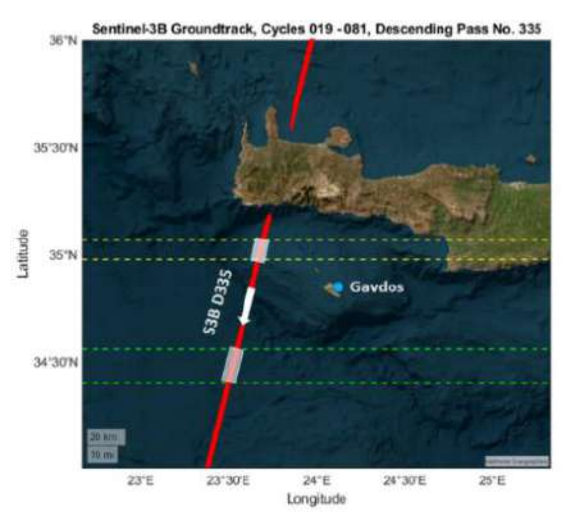
→ THE EUROPEAN SPACE AGENCY

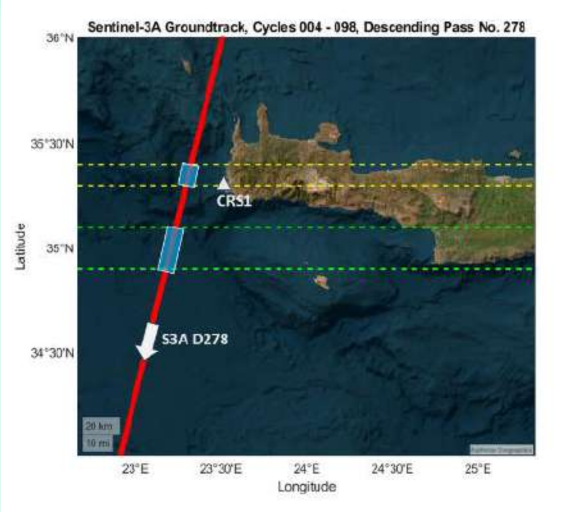
Sentinel-3: Sea-Surface Cal/Val Regions

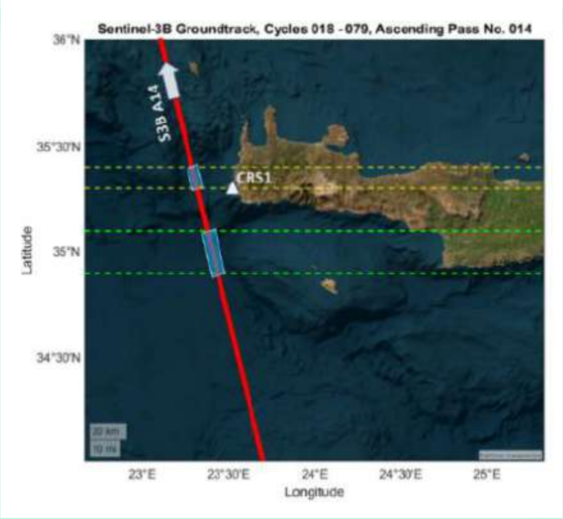




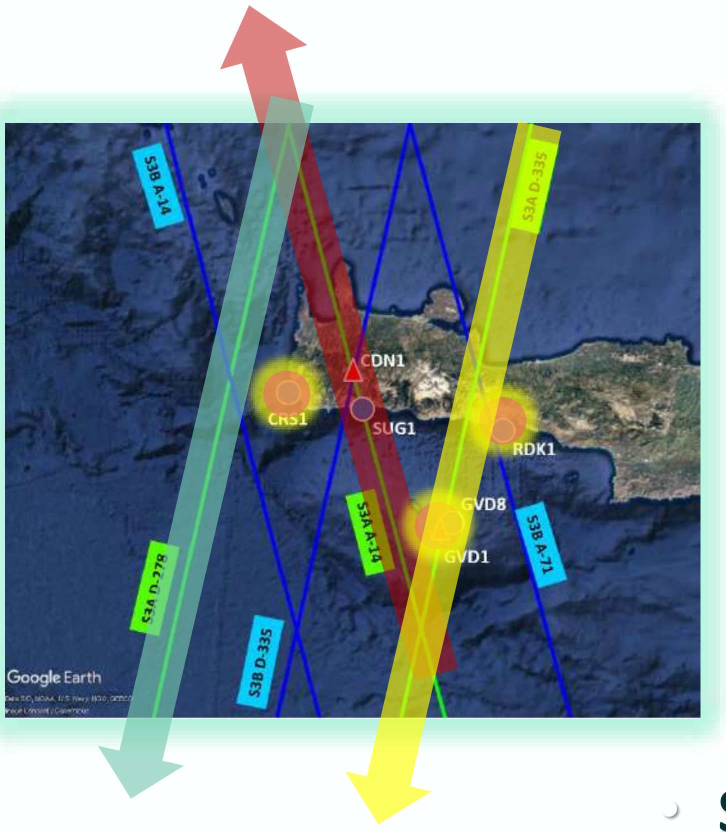


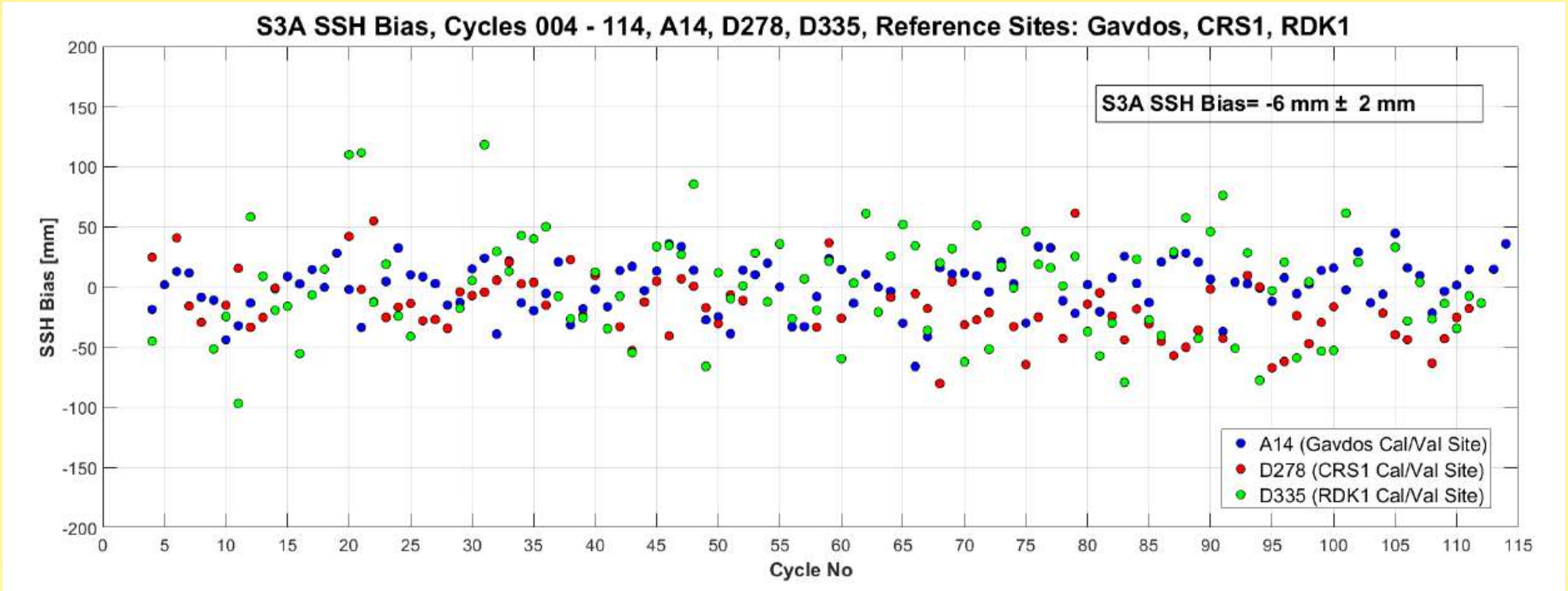






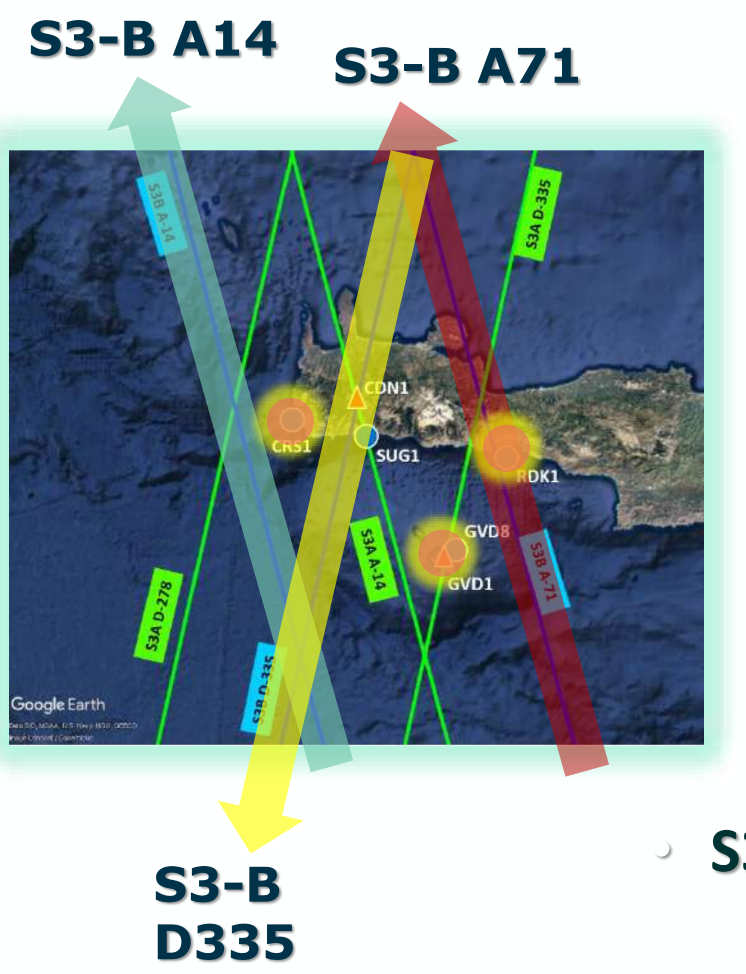
Sentinel-3A: Sea-Surface Cal/Val Results

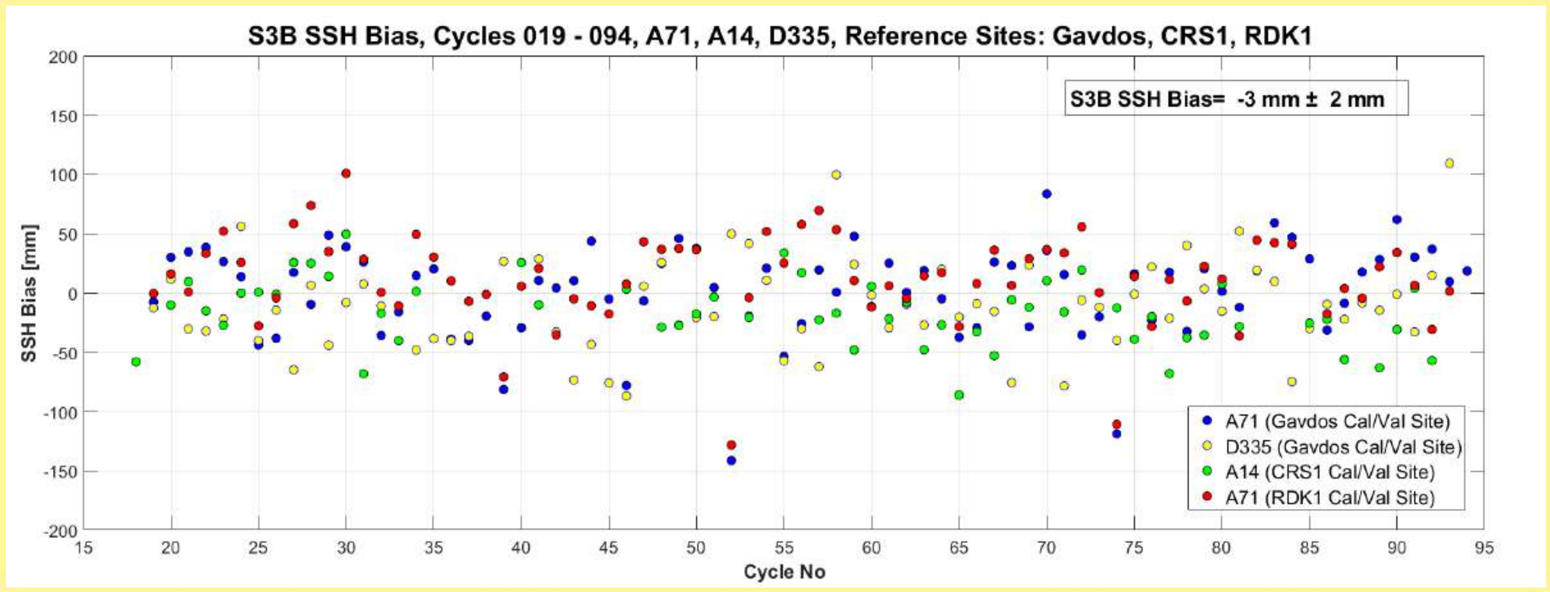




- **S3A SSH Bias (Crete) = –6 mm ± 2 mm, [U(FRM)= ± 50mm]**

Sentinel-3B: Sea-Surface Cal/Val Results

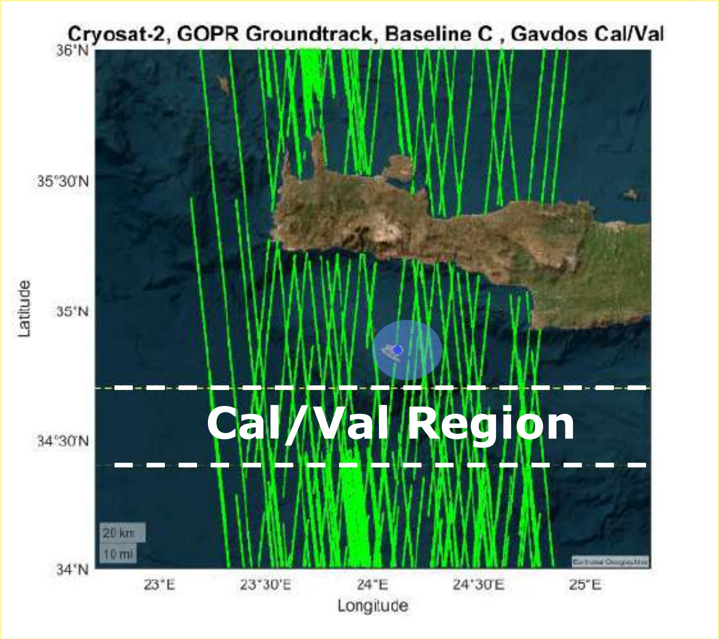


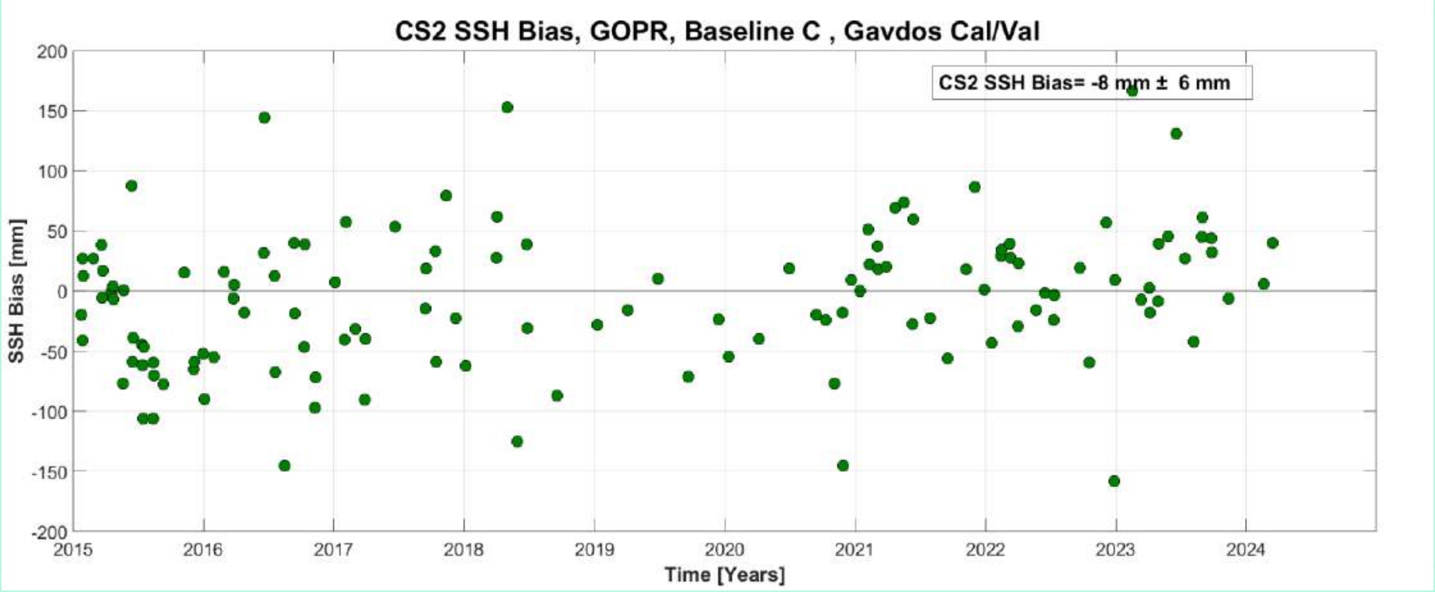


- S3A SSH Bias (Crete) = – 3 mm ± 2 mm, [U(FRM)= ± 50mm]

CryoSat-2 Sea-surface Cal/Val: SAR Observations

Geophysical Ocean Products-SAR, Baseline-C,
23-Jan-2015 till 6-May-2024 (N=132)
Gavdos Cal/Val Reference site

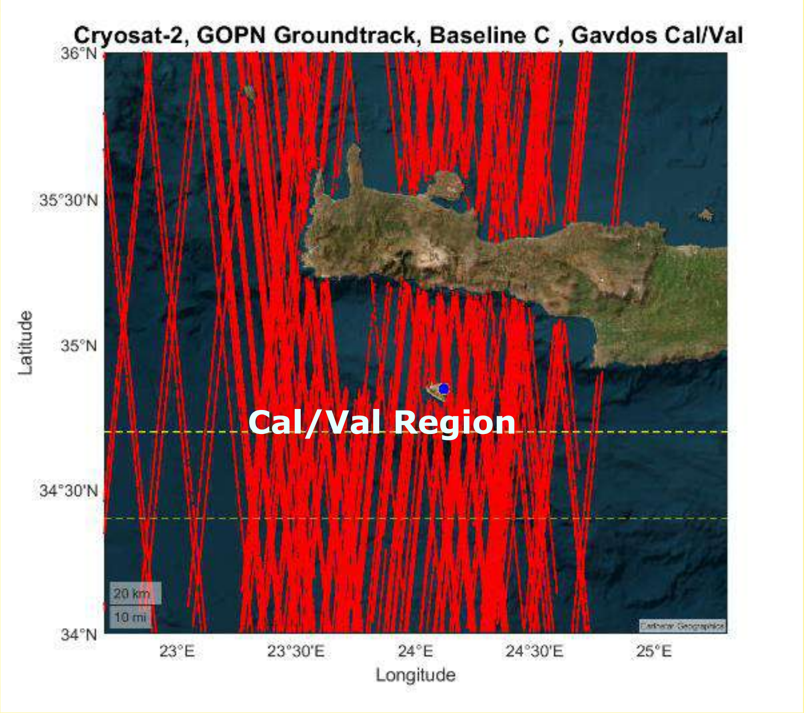


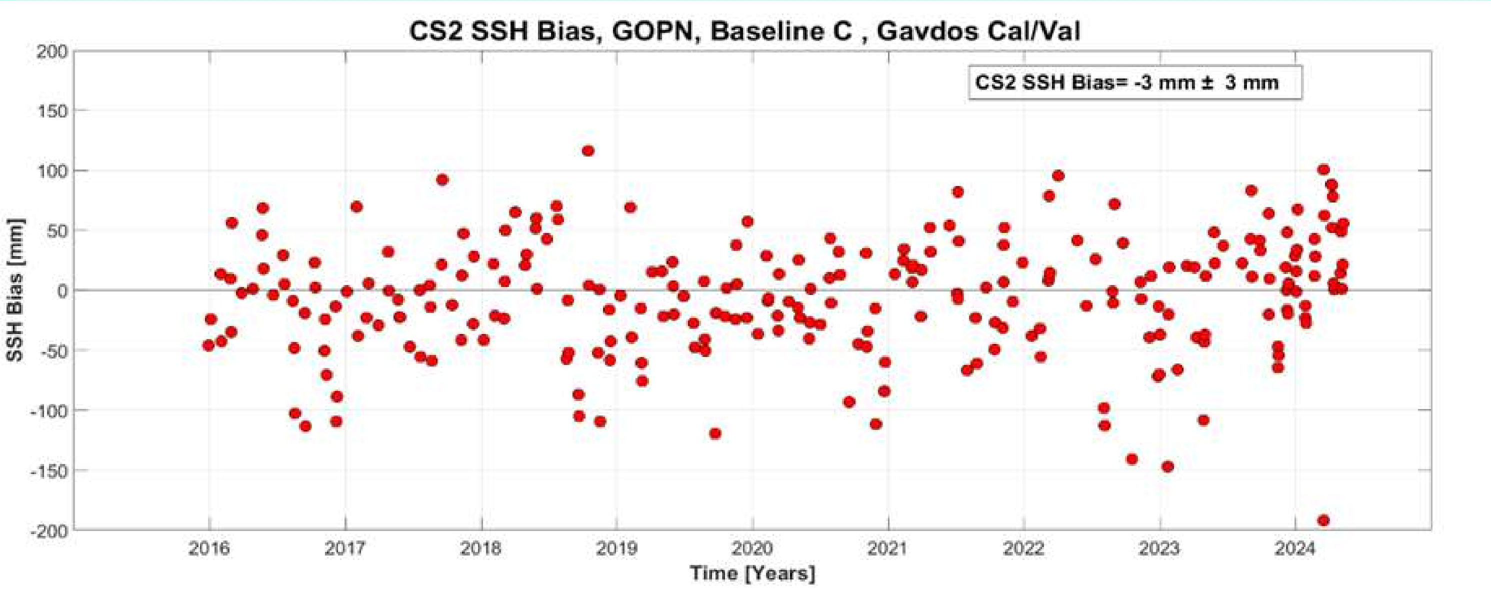


SSH Bias = −8 mm ± 6 mm, [U(FRM)= ± 50mm]

CryoSat-2 Sea-surface Cal/Val: SARIn Observations

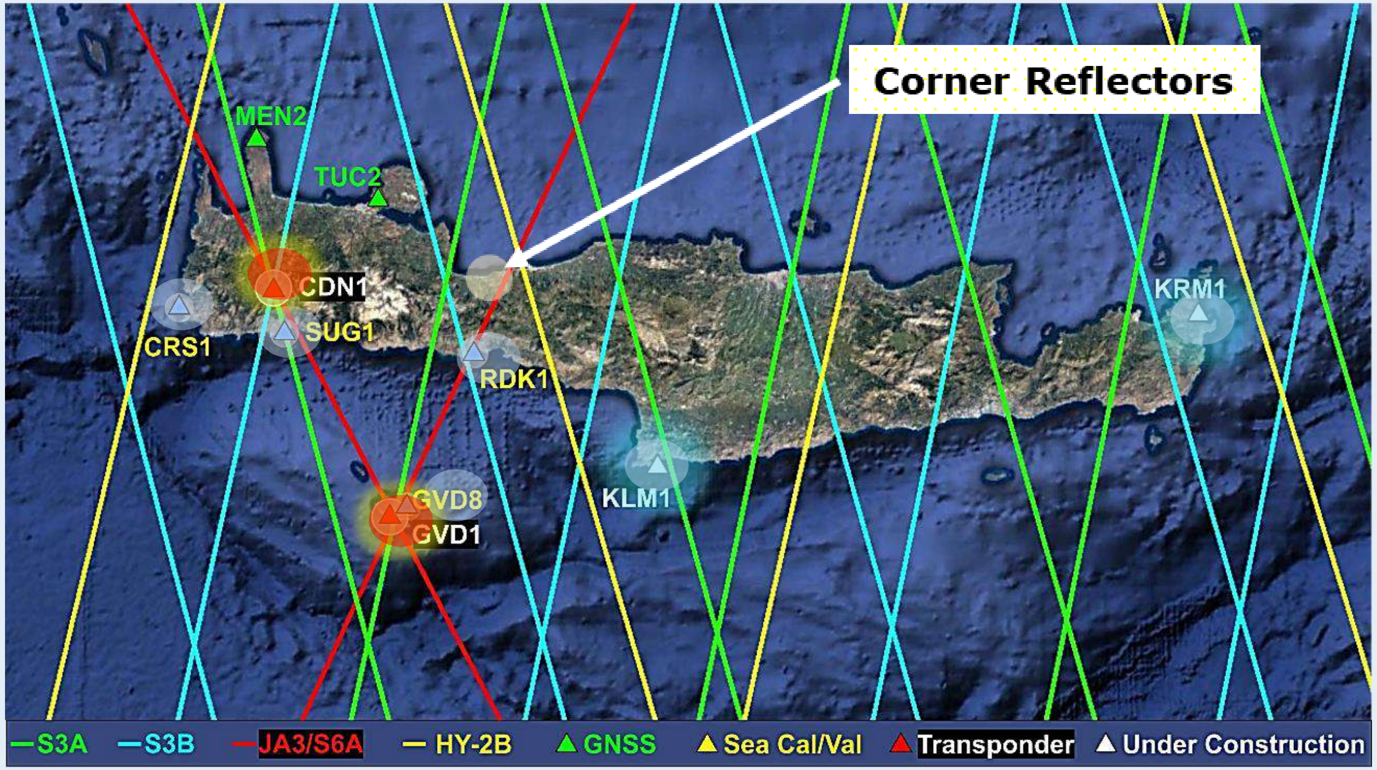
Geophysical Ocean Products: SARIn, Baseline-C, 28-Dec-2015 till 8-May-2024 (N=247), Gavdos Cal/Val Reference site.





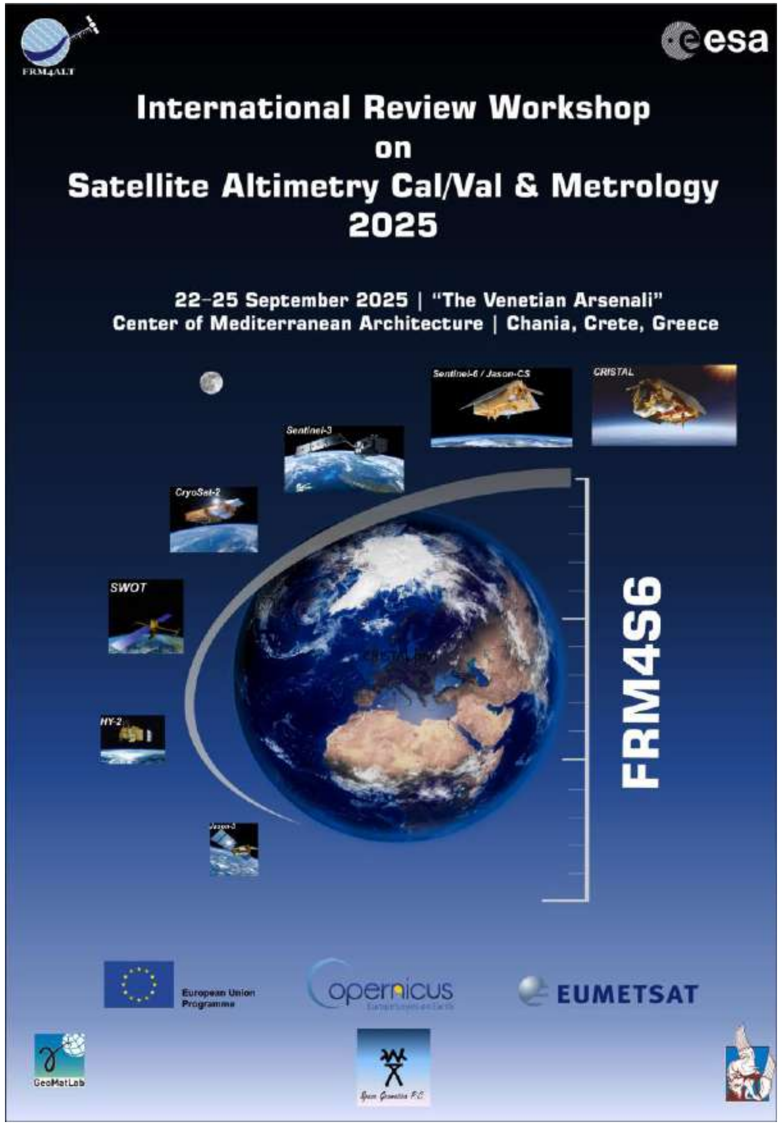
SSH Bias = –3 mm ± 3 mm, [U(FRM)= ± 50mm]

Future of ESA Permanent Facility for Altimetry Calibration



- Ground infrastructure covering 260 km (E-W),
- Diverse Instrumentation, Techniques, Locations,
- FRM strategy fully followed,
- LRM, SAR, FF-SAR, SWH, Sigma0,
- Gavdos Transponder tied to absolute time,
- Ascend & Descend orbits (Directional Errors),
- Different sats & Results are cross-examined,
- Data & Results screened for quality;
- Confidence on results built up;
- Patterns & structures can be understood;
- Uncertainty Budget in FRM Standards.

September 2025: Altimetry Cal/Val Review meeting



Thank you Any Questions?

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