Recent Developments in Altimetry Measurements - Sentinel-6 Michael Freilich

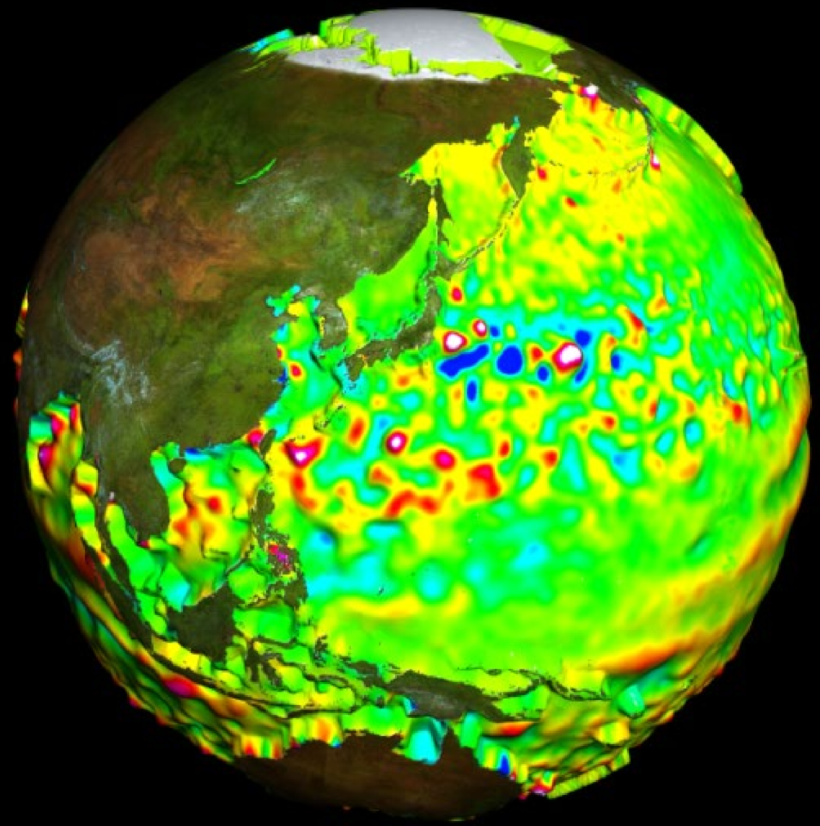
Vinca Rosmorduc, CLS
(with material from a number of agencies and altimetry users)

Short Course – 2022/09/29

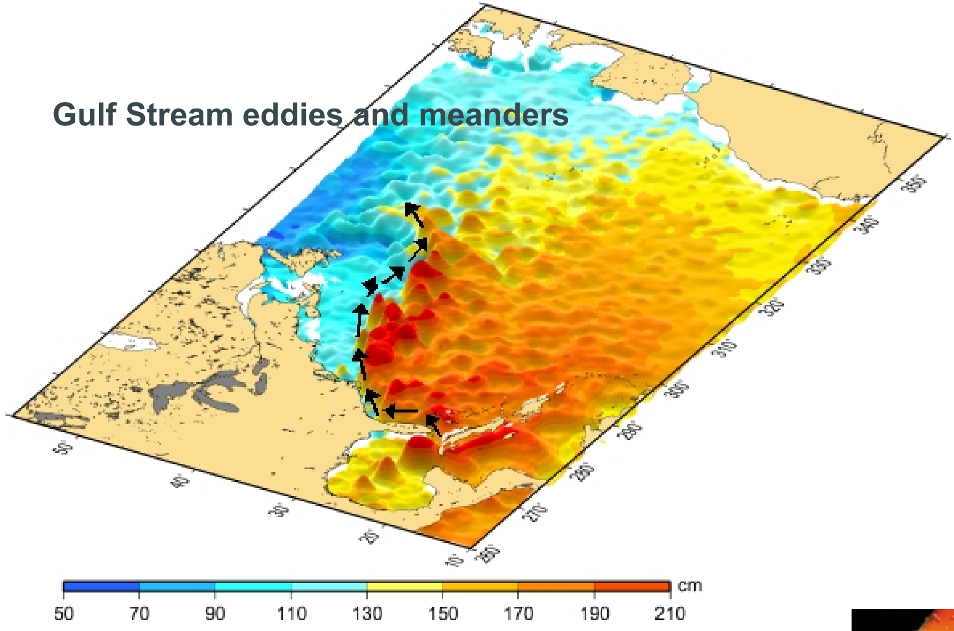
Radar altimetry data uses

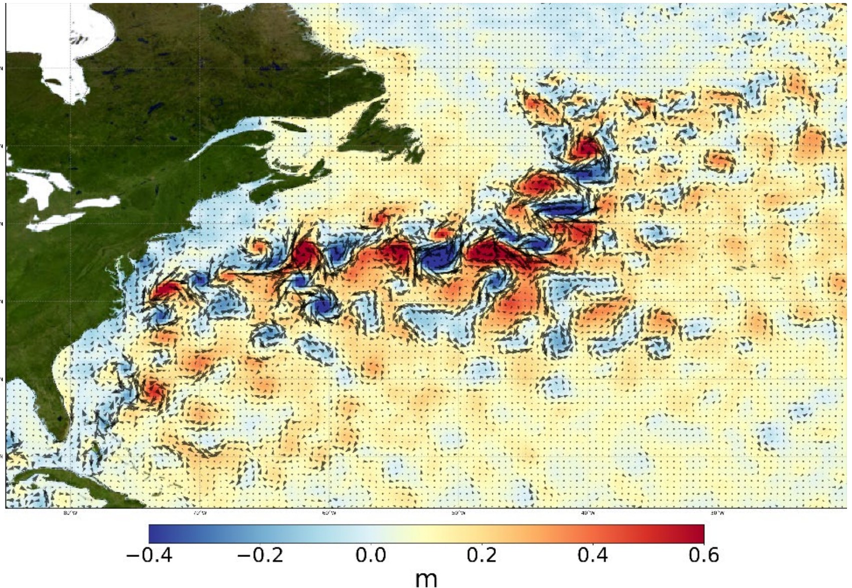
What can sea heights show? Eddies, gyres and meanders – variability in the ocean

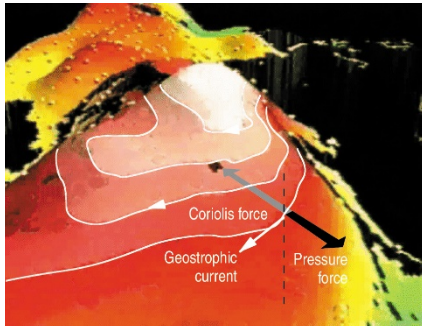
Eddies (turbulence) in a major current (Kuroshio)



Gulf Stream eddies and meanders







Gulf Stream eddies and associated currents

➔ forecast

What can sea heights show? Large-scale ocean-atmosphere coupled phenomena

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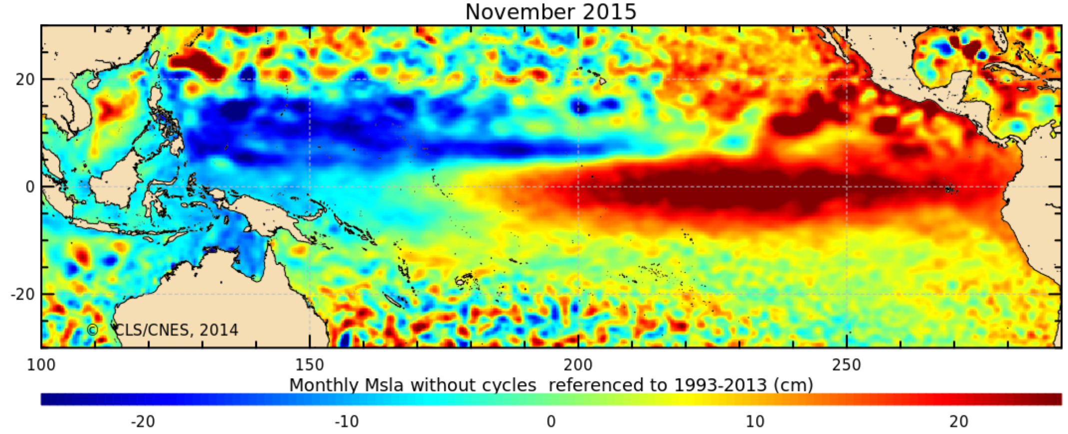
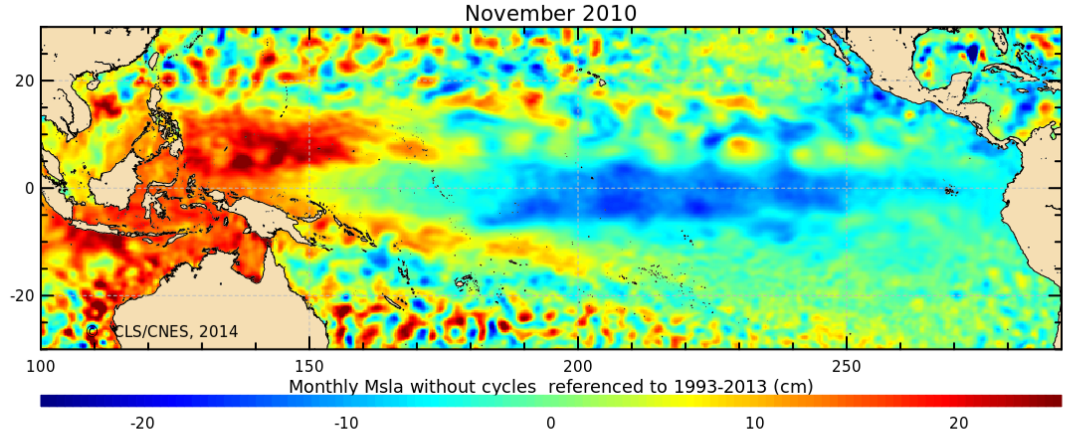
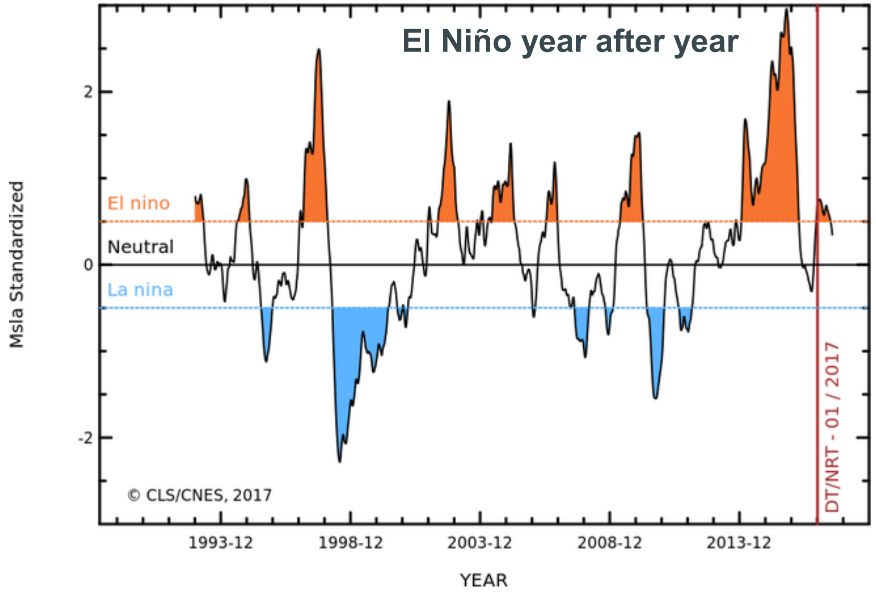
El Niño

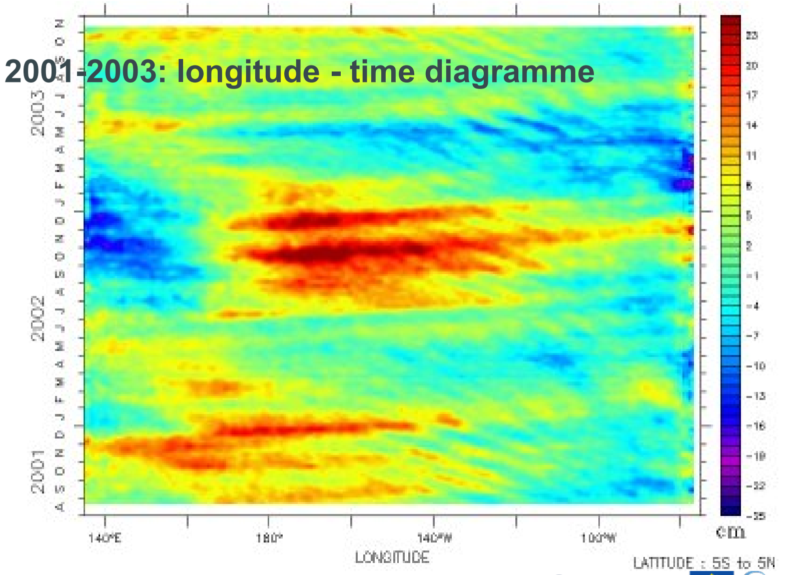


La Niña





El Niño 2001-2003: longitude - time diagramme



➔ forecast

Ocean altimetry: not “only” sea surface height

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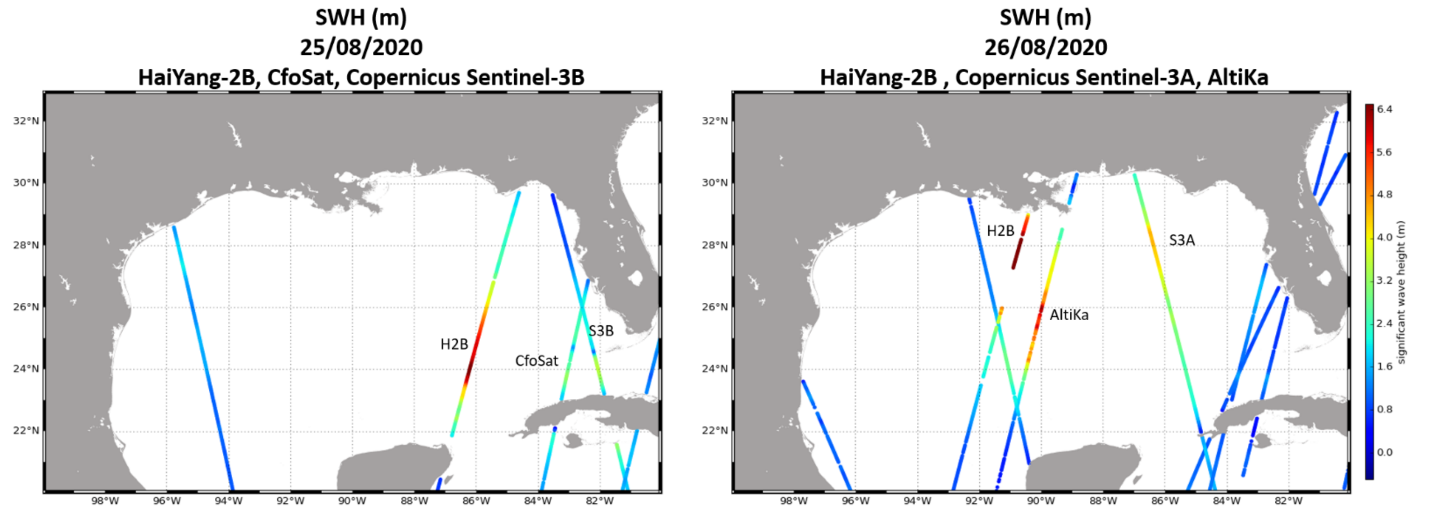
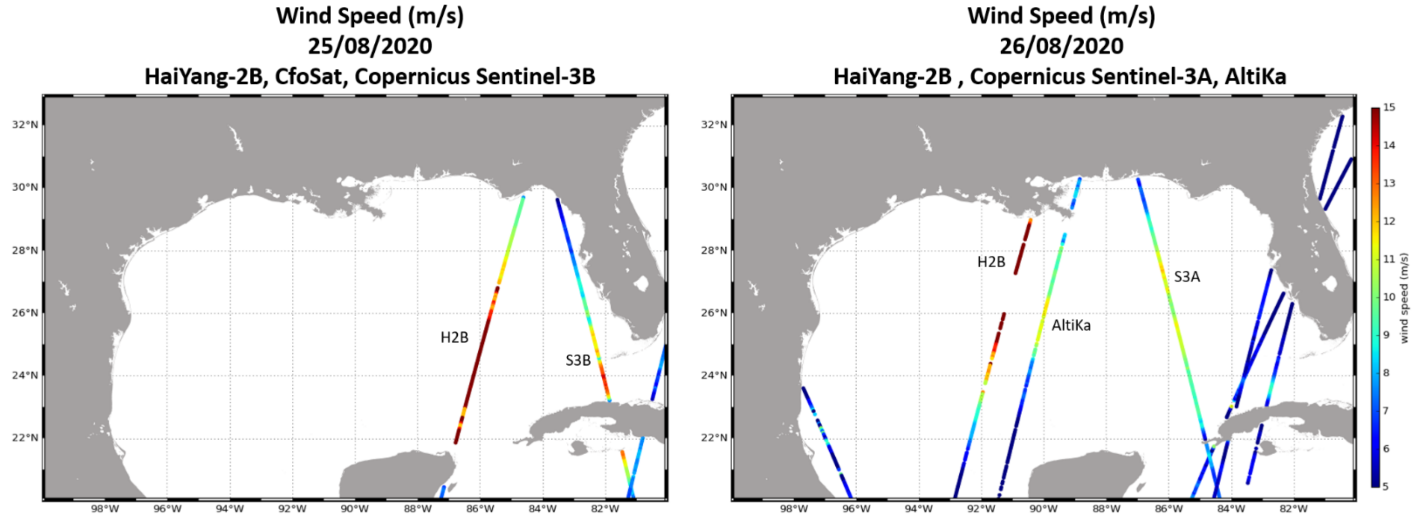
Significant wave height (SWH)

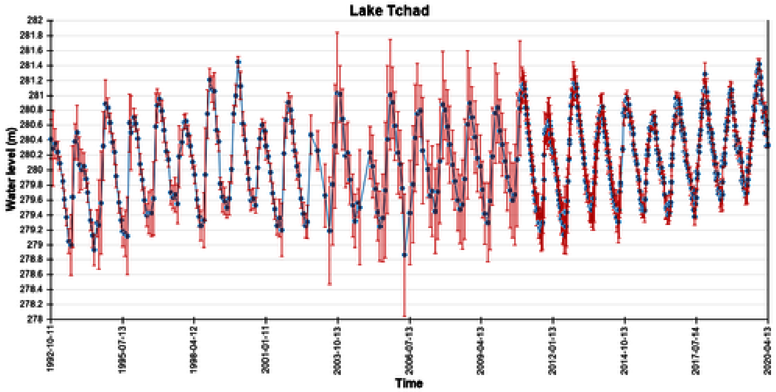


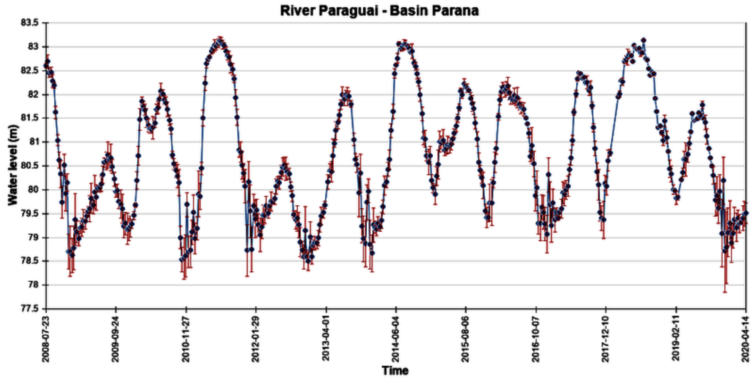
Wind speed (modulus)



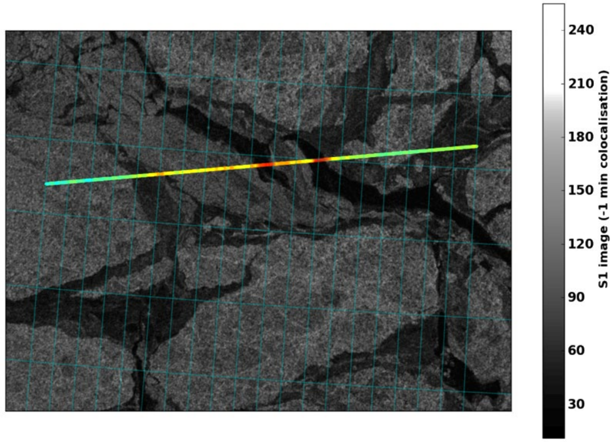
Altimetry: not only sea surface height & significant wave heights

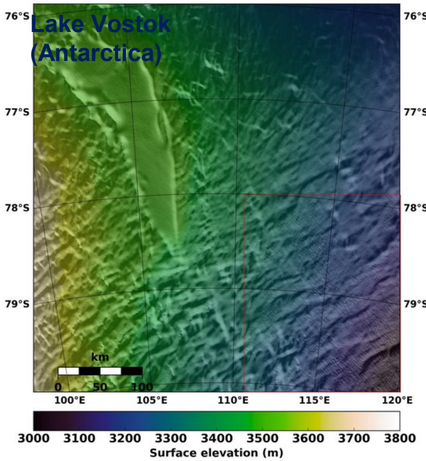
Other water bodies' level (**lakes, rivers**…)

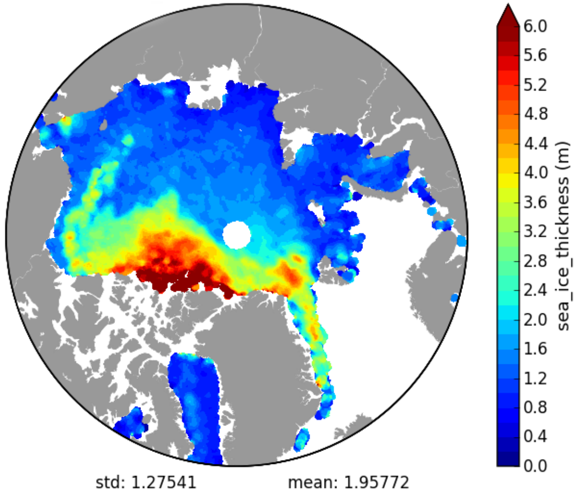




Ice topography, including leads and fractures (**sea ice** or **ice sheets**)



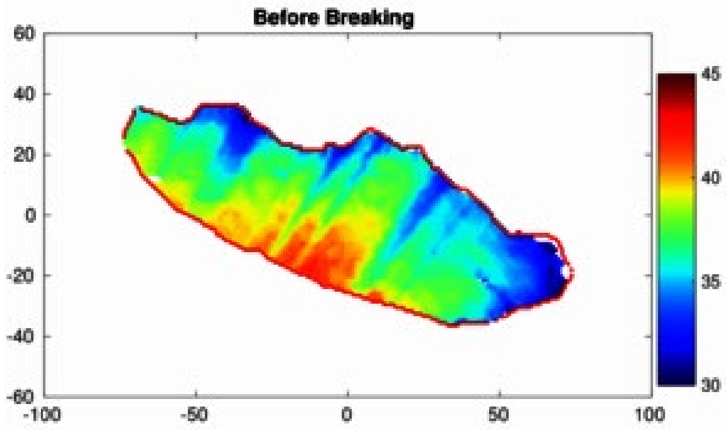


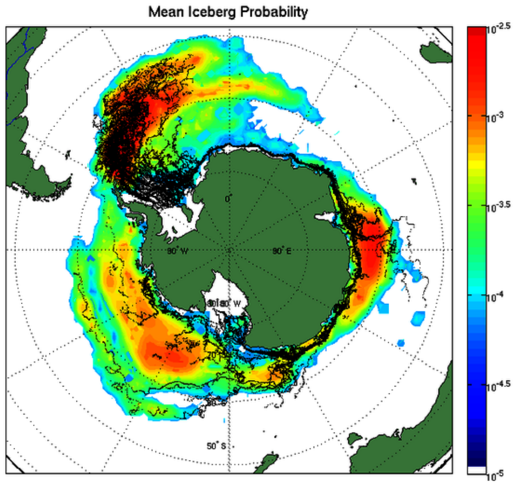


(provided at least one satellite flies over them)

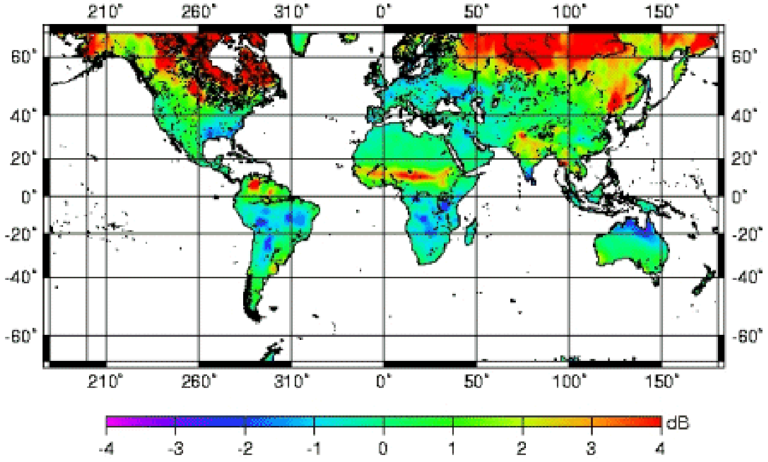
Altimetry: not only sea surface height & significant wave heights

Icebergs and some other reflectors on the ocean





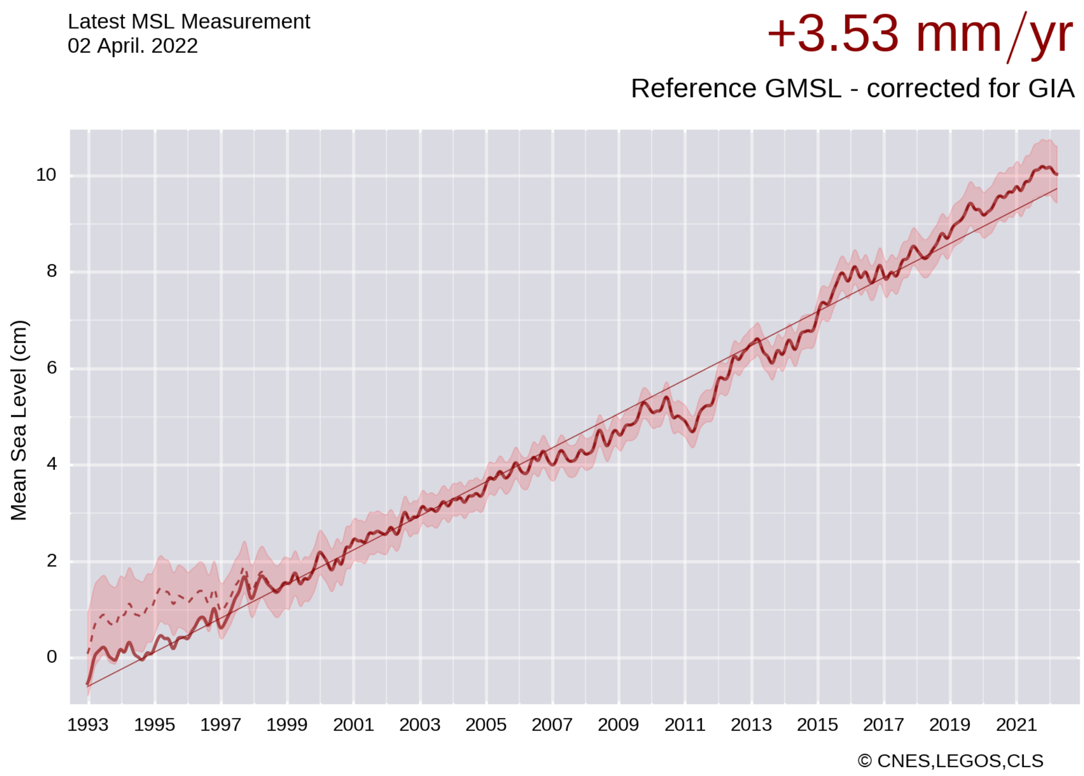
Some “solid land” (deserts, snow-covered areas) through the backscattered radar wave power (➔ waveform power)



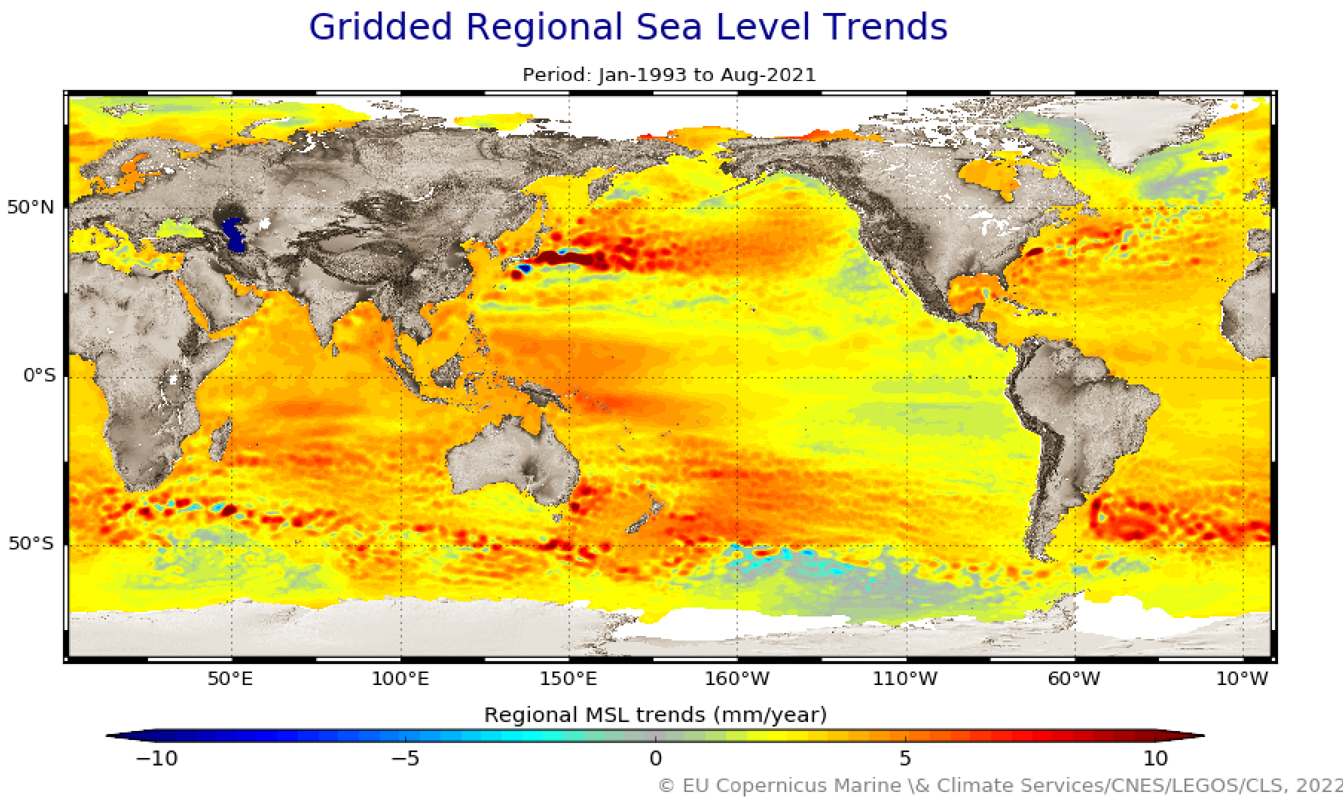
…

What can sea heights show? Long-term global-averaged variations

Global Mean Sea Level



& its geographical variations



- Questions? → go to Slido.com – event code: #EUMSC33

Surface Height & Significant wave height measurements

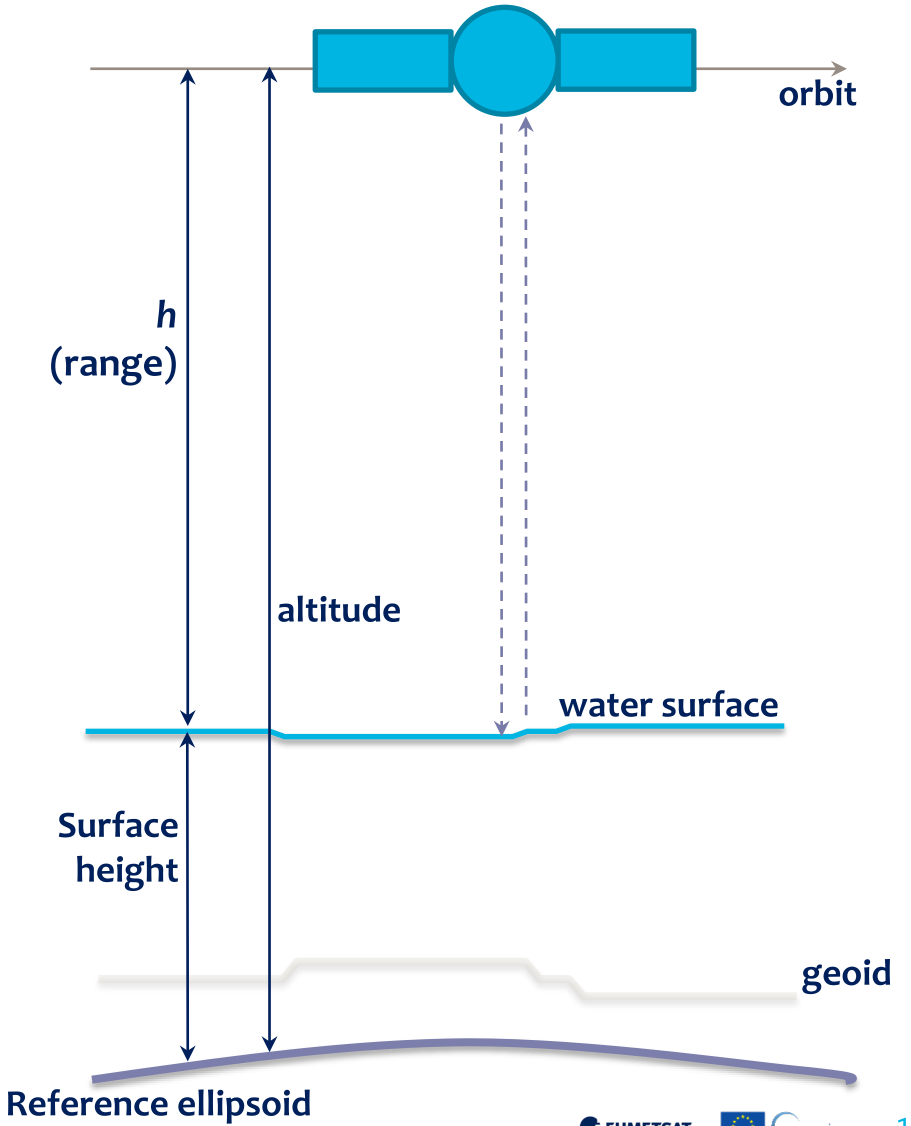
How it works? (very) simplified

- Measure travel time **2T** from emit to return of the radar pulse
- Speed of the radar pulse is light's celerity ($c \approx 3\mathrm{x}10^8$ m/s)
- The range h is deduced:

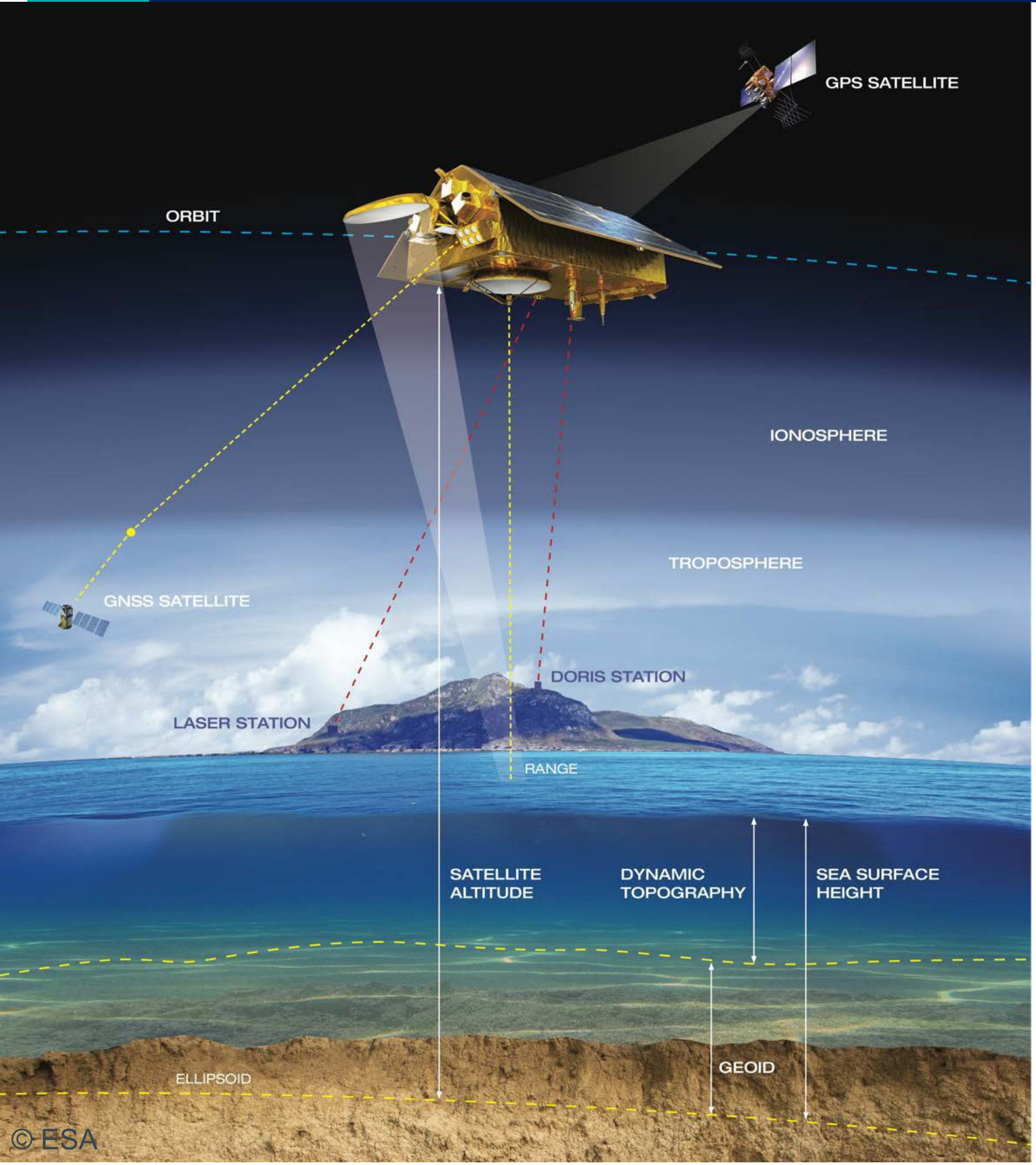
$$h = T \times c$$

- The altitude of the satellite is also very precisely measured;
water level is the difference:

Surface height = altitude - range



How it works (slightly more realistic)



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SSH_{corr} = Altitude – Range – Corrections

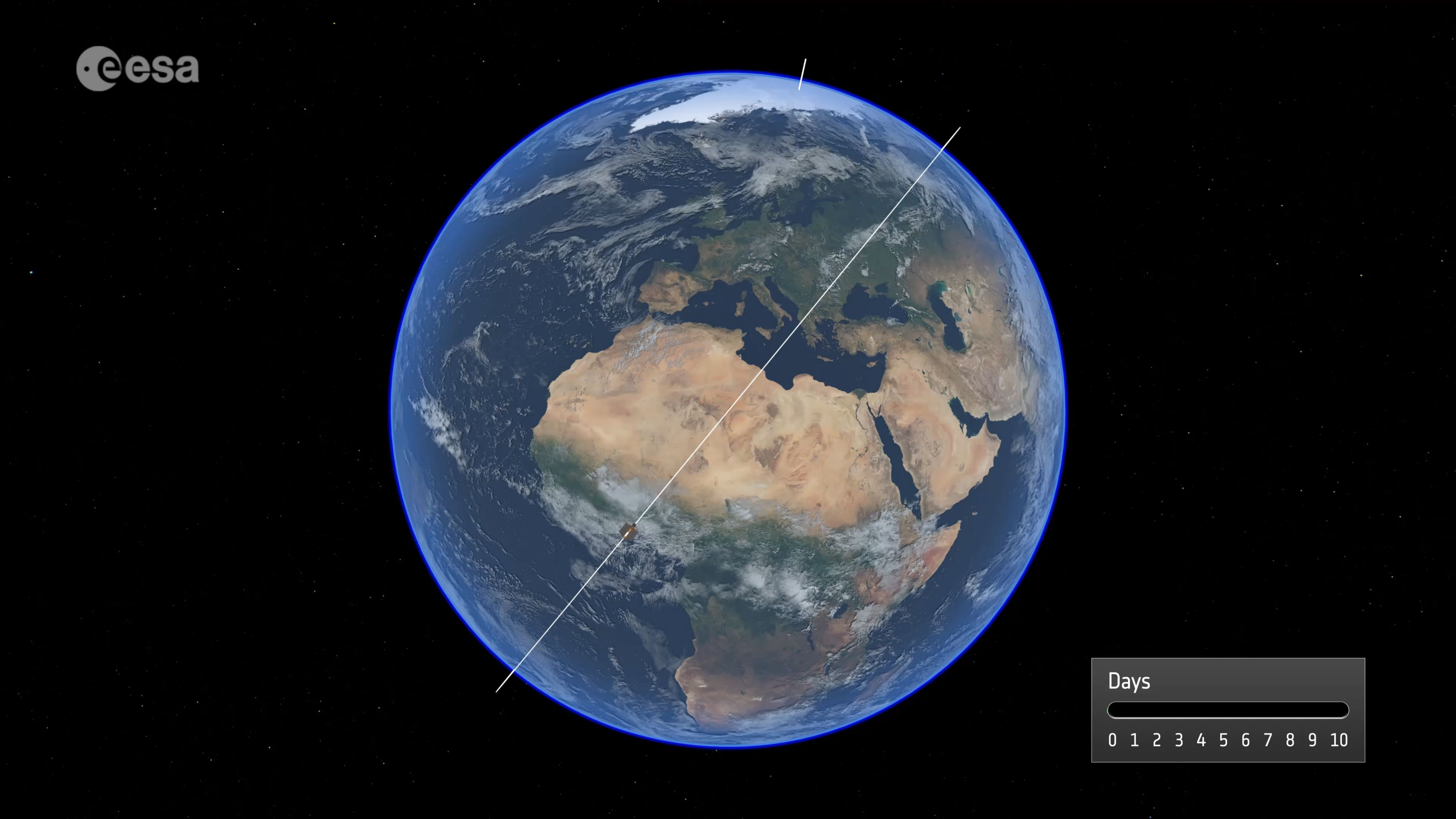
Range = satellite-to-surface distance

Altitude from the onboard instruments

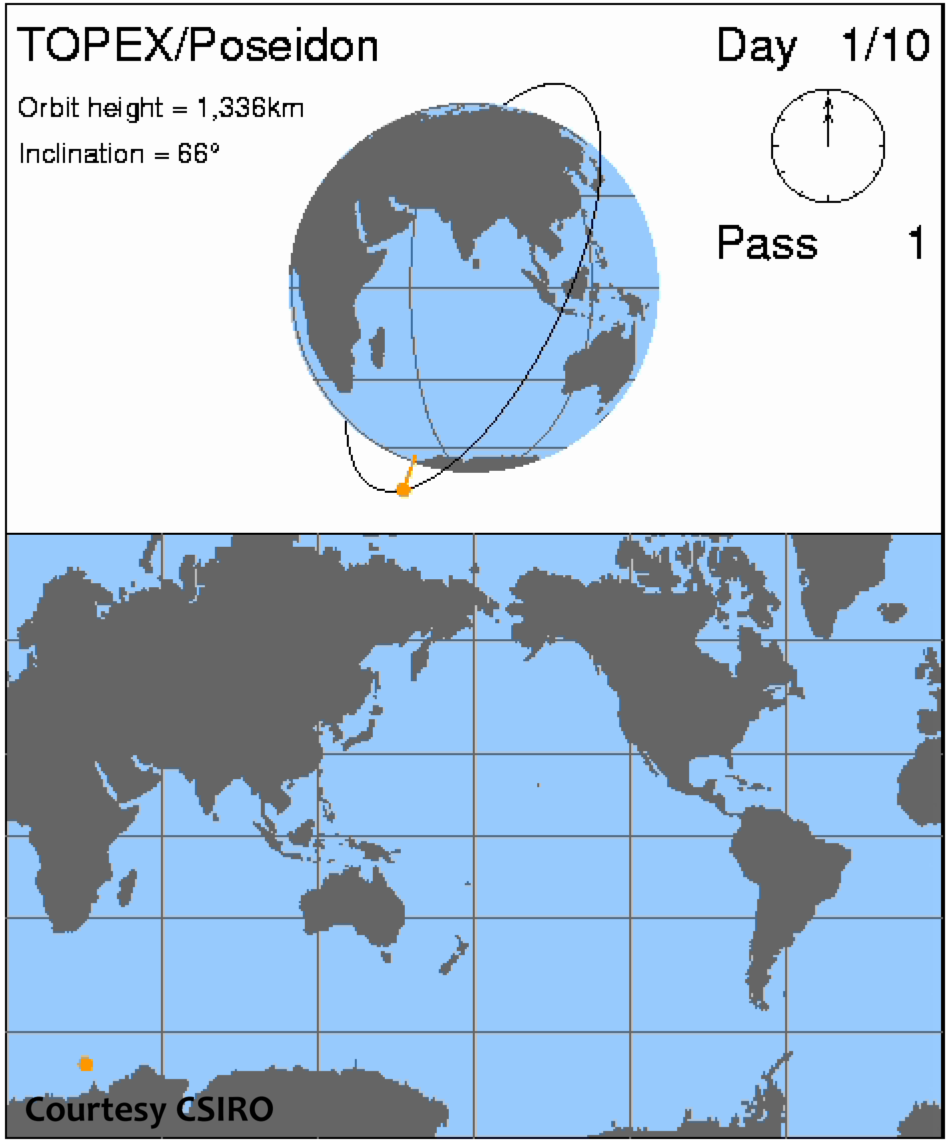
Corrections applied:

- water in the troposphere ("wet tropo")
- electrons in the ionosphere
- dry gases in the atmosphere ("dry tropo")
- atmospheric pressure ("inverse barometer")
- sea state bias (wave crests reflect radar beam less than troughs)
- tides (ocean, solid Earth, pole)

(All corrections are **subtracted** from the rough SSH)


Days
0 1 2 3 4 5 6 7 8 9 10

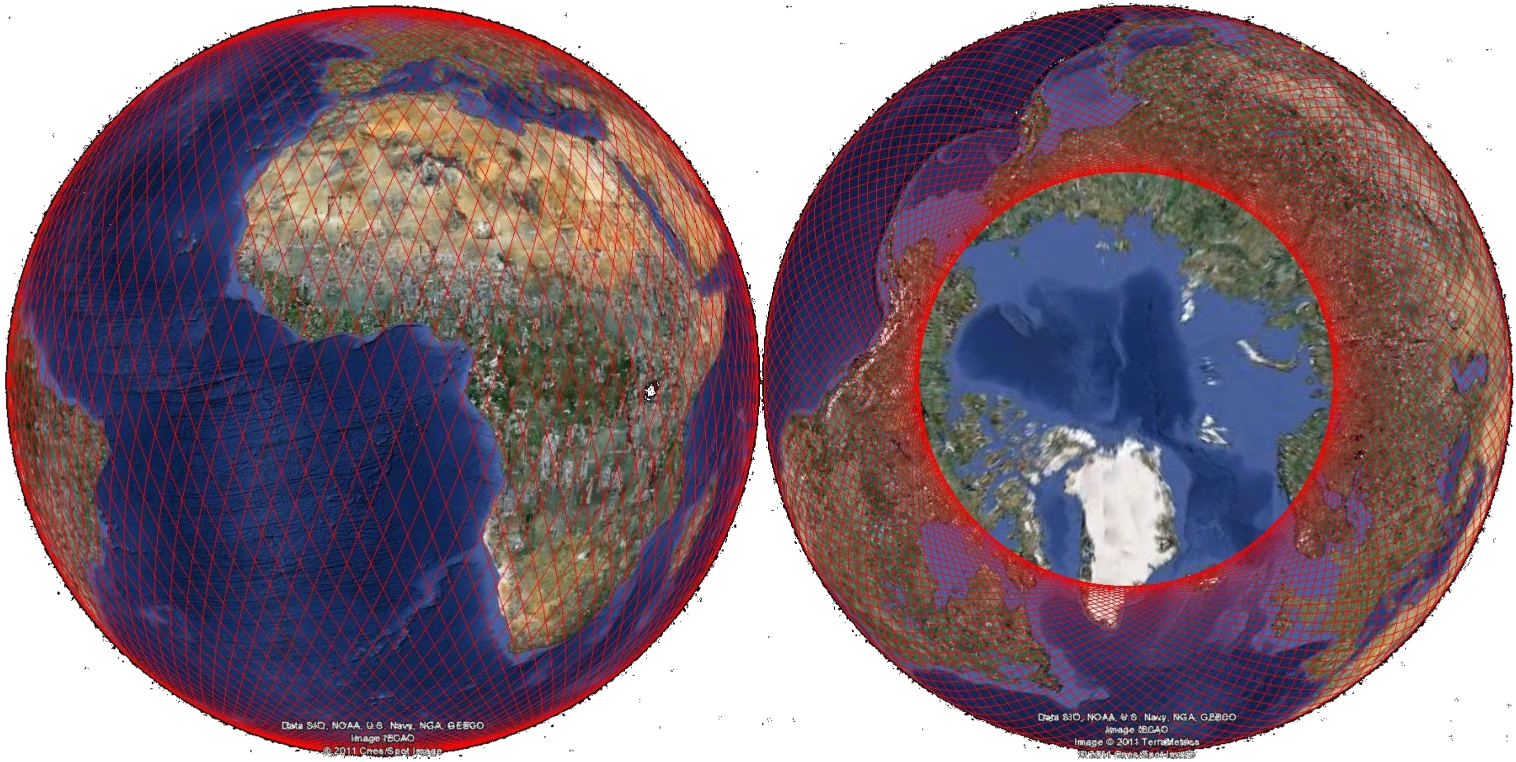
!! Altimetry is not imagery... (for now)



NB. altimetry data = a narrow thread of measurements just beneath the satellite.

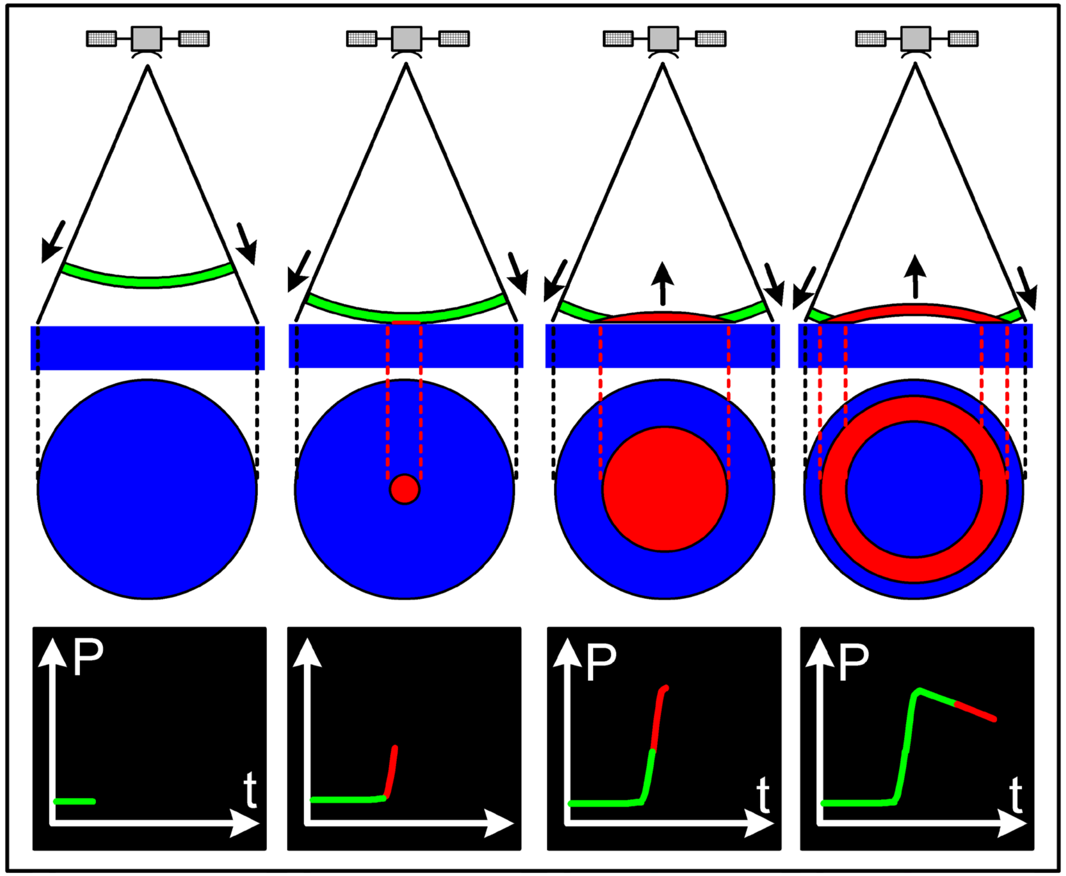
"along-track" data

Sentinel-6:
10-day track revisit



Sentinel-6 Michael Freilich coverage (formerly Topex/Poseidon, Jason-1, Jason-2 & Jason-3)

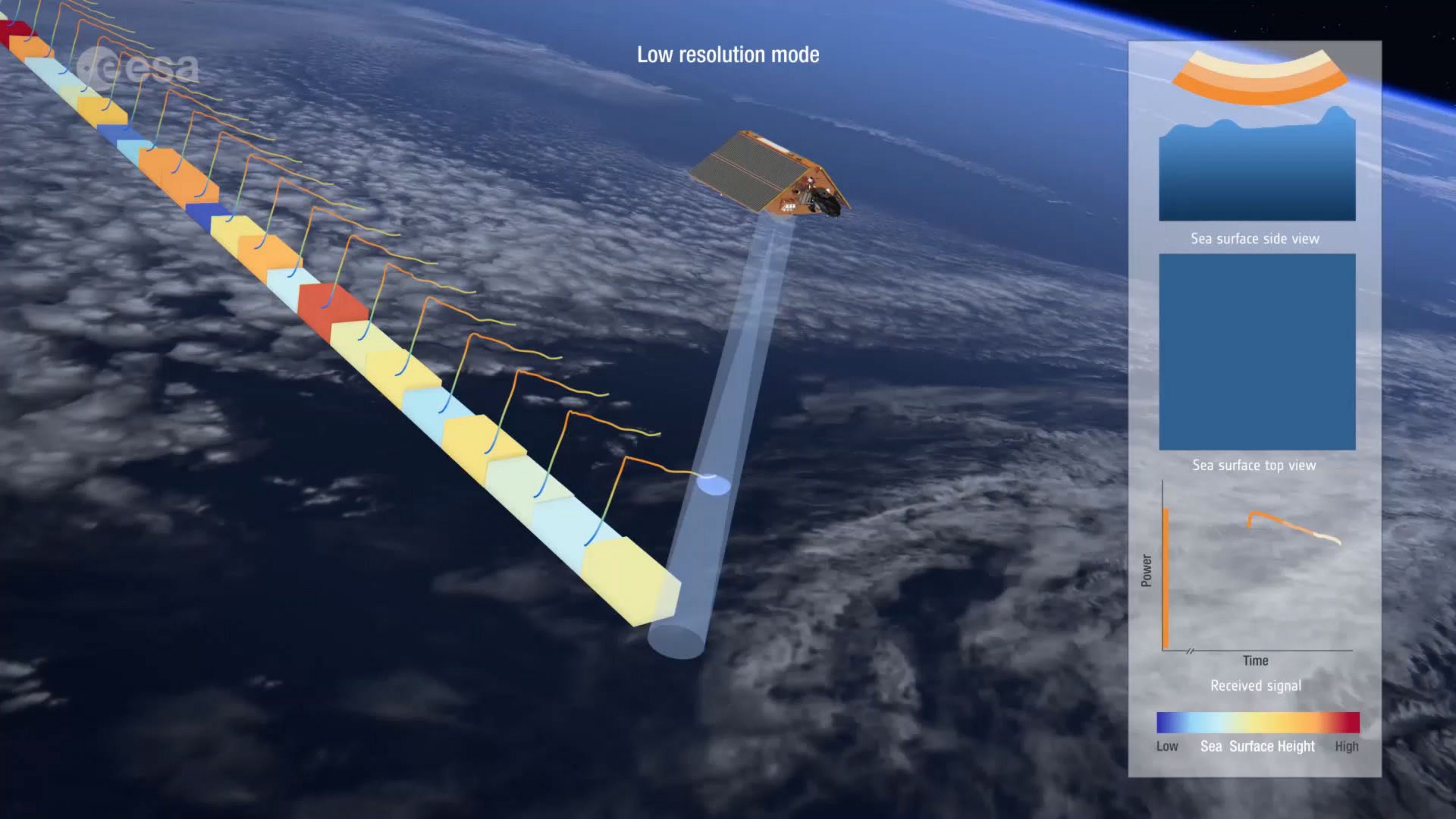
In practice: analysis of radar (averaged) “echoes”: waveforms



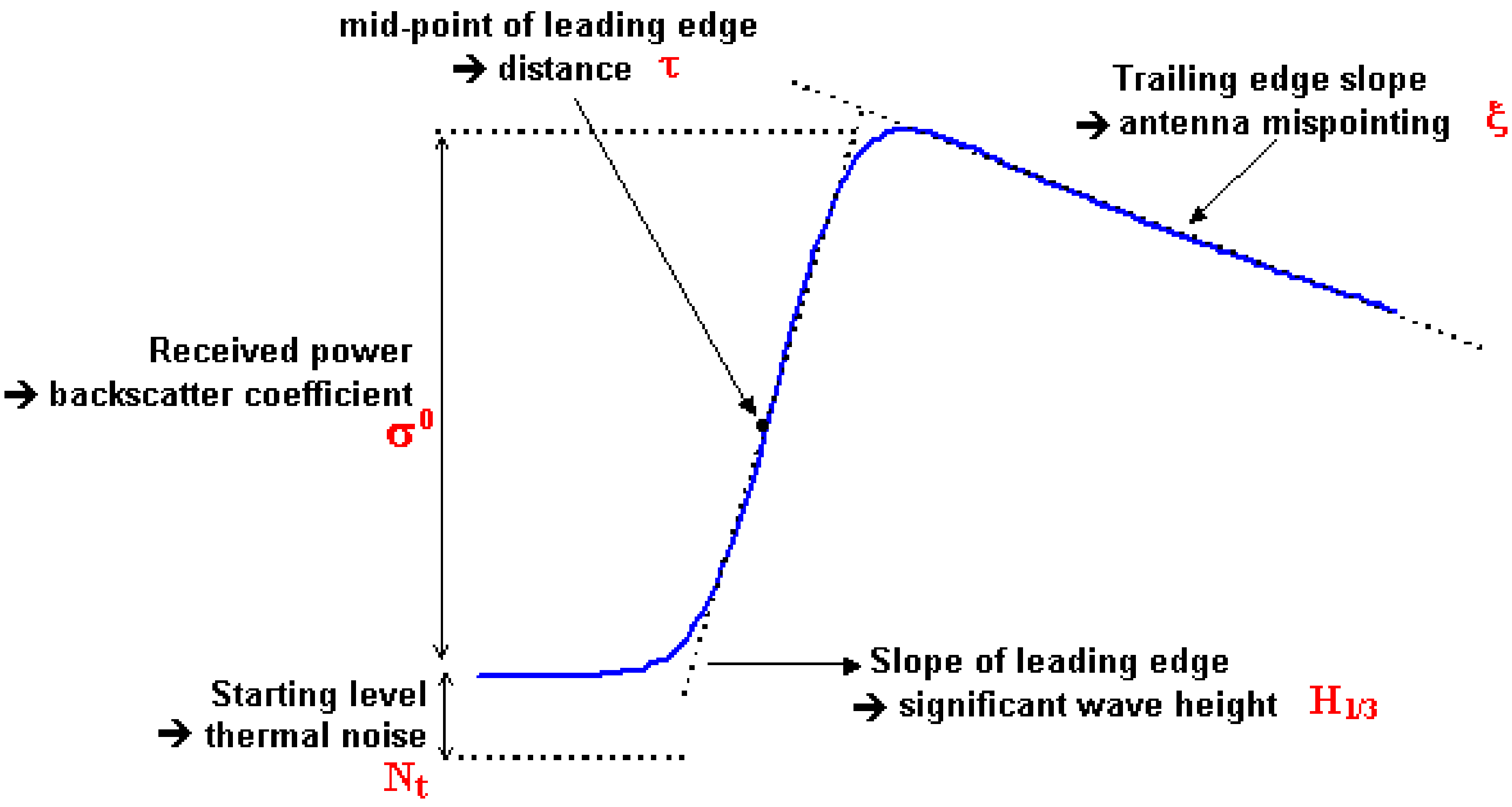
How an echo is “built”

Classical altimeter
Calm sea

- The satellite-to-surface distance (aka “range”) is retrieved from averaged echoes.


Low resolution mode
esa
Sea surface side view
Sea surface top view
Power
Time
Received signal
Low
Sea Surface Height
High

In real life: analysis of radar (averaged) “echoes”: waveforms



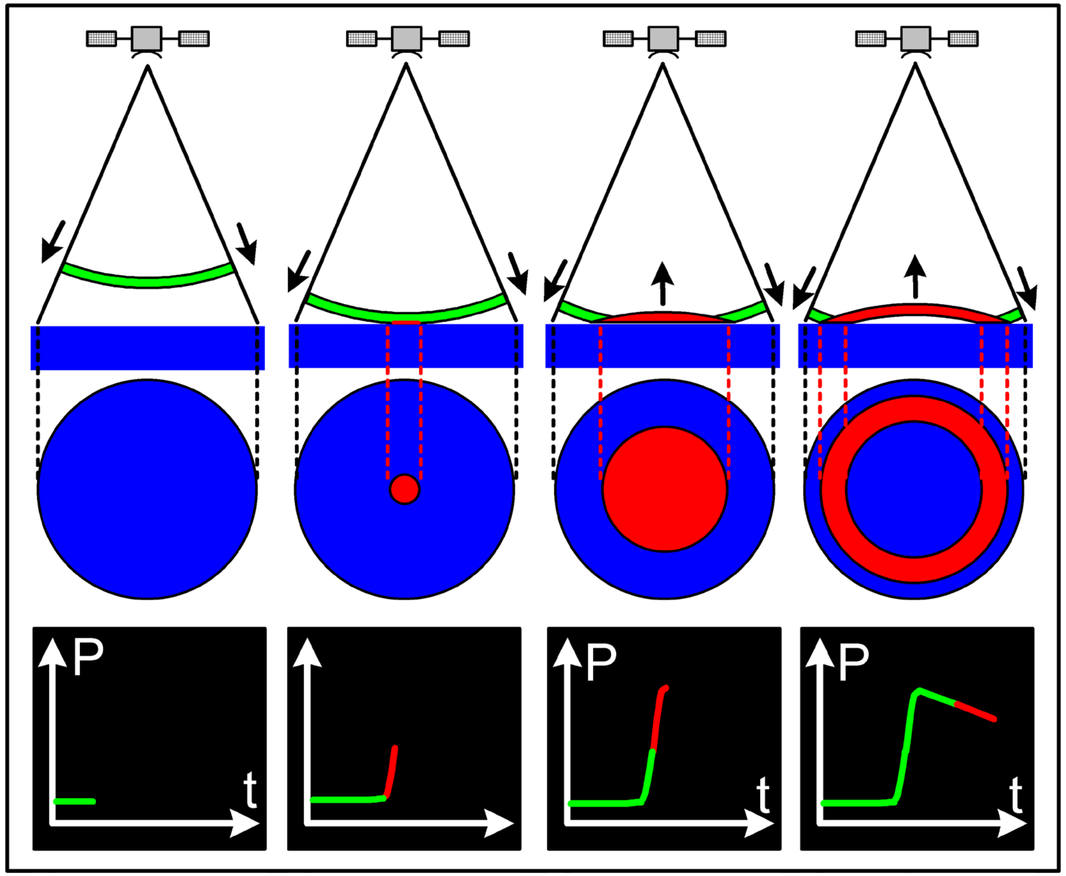
Theoretical waveform and parameters extracted “**Brown model**” (Open ocean, Classical altimetry)

Epoch at mid-height→ time → range

Leading edge slope → SWH

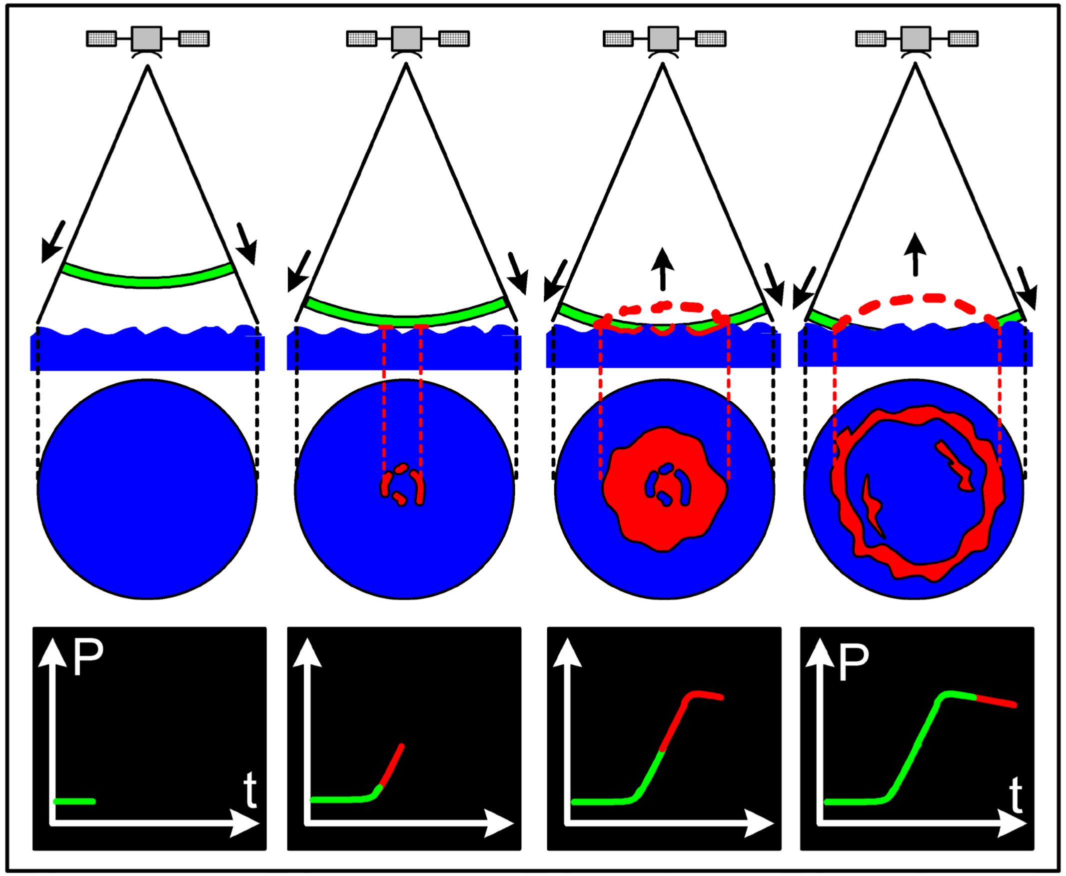
Received Power
→ backscatter coefficient
wind speed

In practice: analysis of radar (averaged) "echoes": waveforms



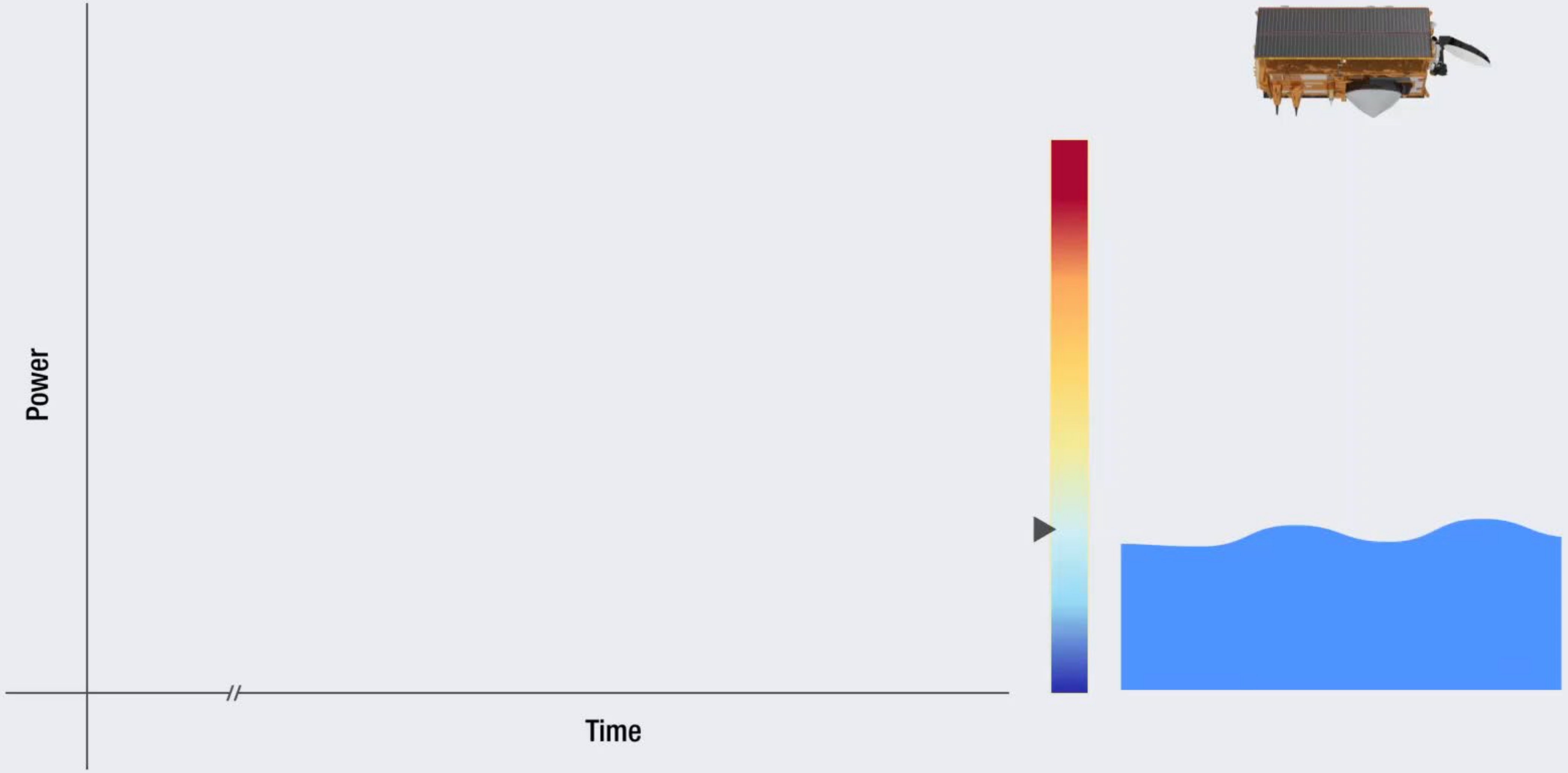
How an echo is "built"

Classical altimeter
Calm sea



How an echo is "built"

Classical altimeter
Rough sea



ESA

- Questions? → go to Slido.com – event code: #EUMSC33

Sentinel-6 Michael Freilich inheritance & future

Altimetry early years

- Geos-3, Skylab as test bed (1973-75)
- Seasat the 1st "real" altimeter flying (1978)
- Geosat (US Navy) 1984-89
- Nasa, Cnes both had plans for a mission in the 1980s; they merged them into
  Topex (US altimeter, with legacy from Geosat) **/ Poseidon** (French altimeter), launched 10 Aug. 1992
- NB. In the meantime, ESA launched ERS-1 with an altimeter – among other sensors (1991).
- Topex/Poseidon follow-on was Jason-1 (launched 2001), with only the Poseidon-2 altimeter onboard, then Jason-2 (2008), & 3 (2016) with Eumetsat and Noaa joining.

Calibration & cross-calibration phase

- if possible, an altimetry satellite is launched to follow/precede closely its predecessor for at least 6 months
  - cross-calibration with the previous mission (Jason-3 for Sentinel-6 Michael Freilich).
  - calibration using *in situ*, statistics… of the mission (true for all EO satellites)

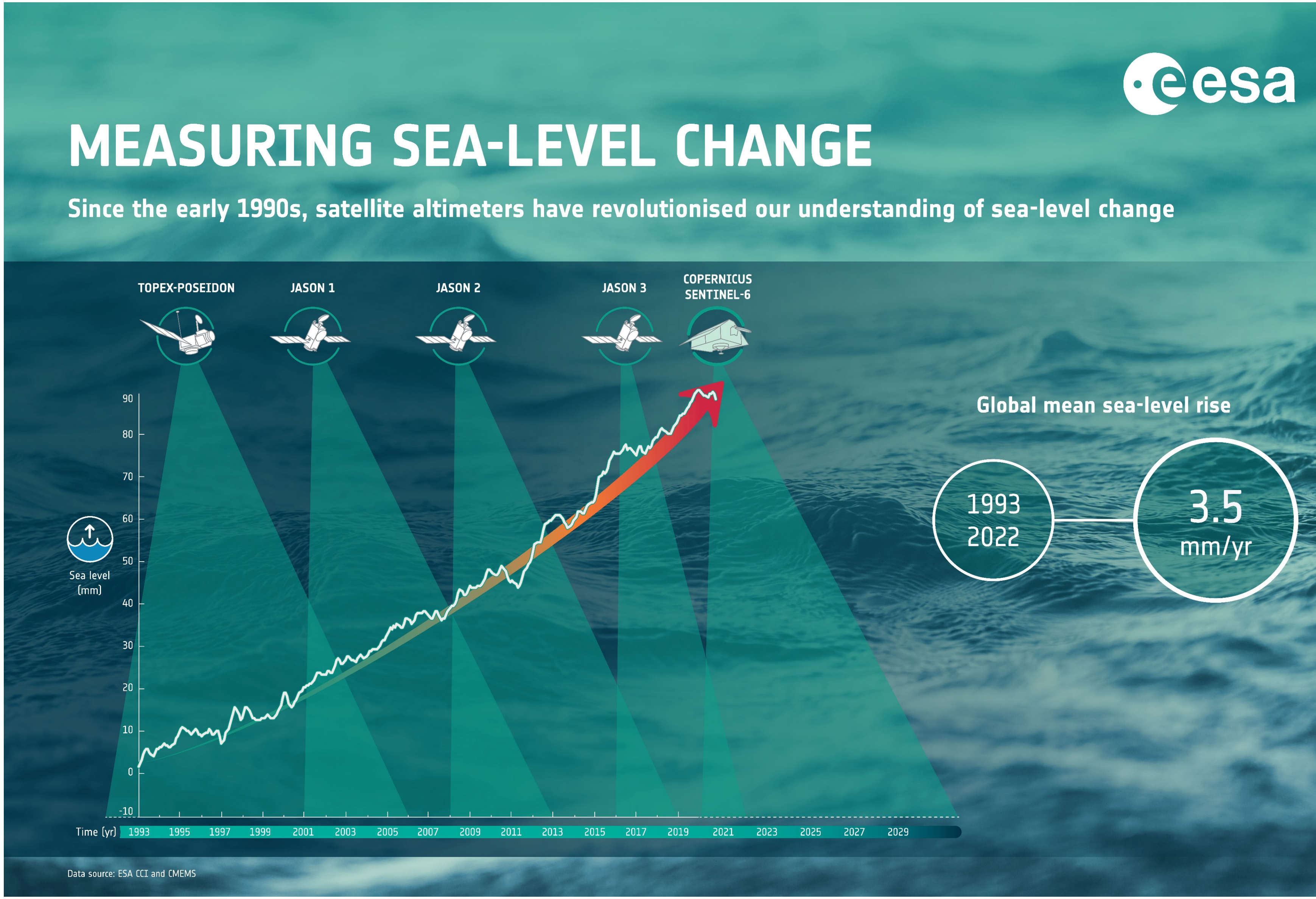
Calibration & cross-calibration phase

- There was more than 6 months of calibration phase for Sentinel-6 Michael Freilich, to also intercalibrate the redundant altimeter onboard (and because it was a brand new satellite).

- Sentinel-6 Michael Freilich declared fit for duty in **March 2022**

"Reference" altimetry missions

- Topex/Poseidon - Jason series: highest accuracy, cross-calibrated series
  → "reference" mission for the Mean Sea Level variation measurements



Sentinel-6A (Jason-CS A) / Michael Freilich

- Altimetry-**dedicated** mission, non sun-synchronous (**<u>not</u>** in phase with tides)
- Launched on **21st Nov 2020**
- To take over Jason-3 for at least 5.5 years

➔ continuous, intercalibrated, measurements on this orbit since Oct. 1992 (30 years soon!)

- **Sentinel-6B** (clone): launch planned in Nov. 2025

Onboard Sentinel-6A (Jason-CS A) / Michael Freilich

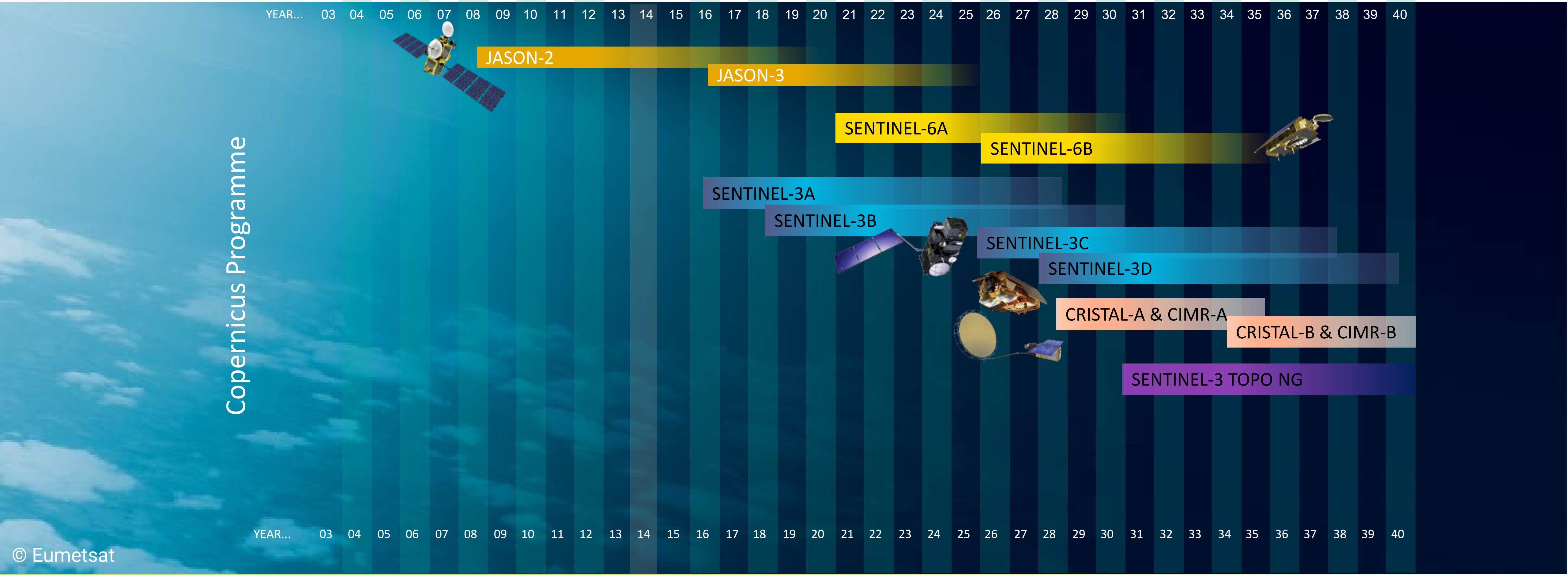
- Poseidon-4 Altimeter:
  - descending from Poseidon onboard Topex/Poseidon & the Poseidon altimeters onboard the Jasons
  - instrument & processing close to Sentinel-3's (except emission / reception pattern)

- Similar complement of
  - a radiometer

  and
  - 3 precise (independent) orbit determination instruments

Copernicus Programme in altimetry for the years to come…

copernicus.eumetsat.int

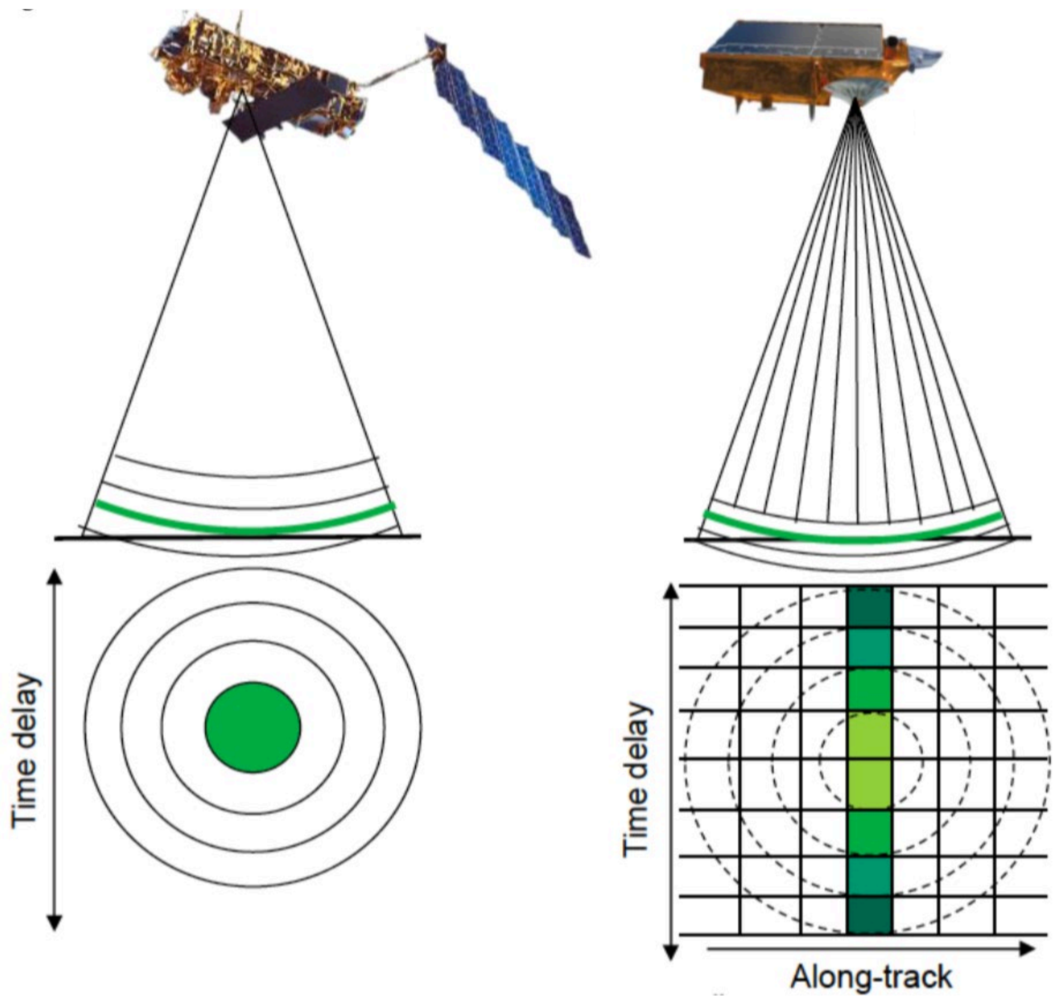


All above-listed missions controlled, processed and distributed by EUMETSAT

The follow-on of Sentinel-6B is currently under study

Sentinel-6 Michael Freilich improvements in altimetry

“SAR-Mode” on Sentinel-6 (also Cryosat2, Sentinel-3)



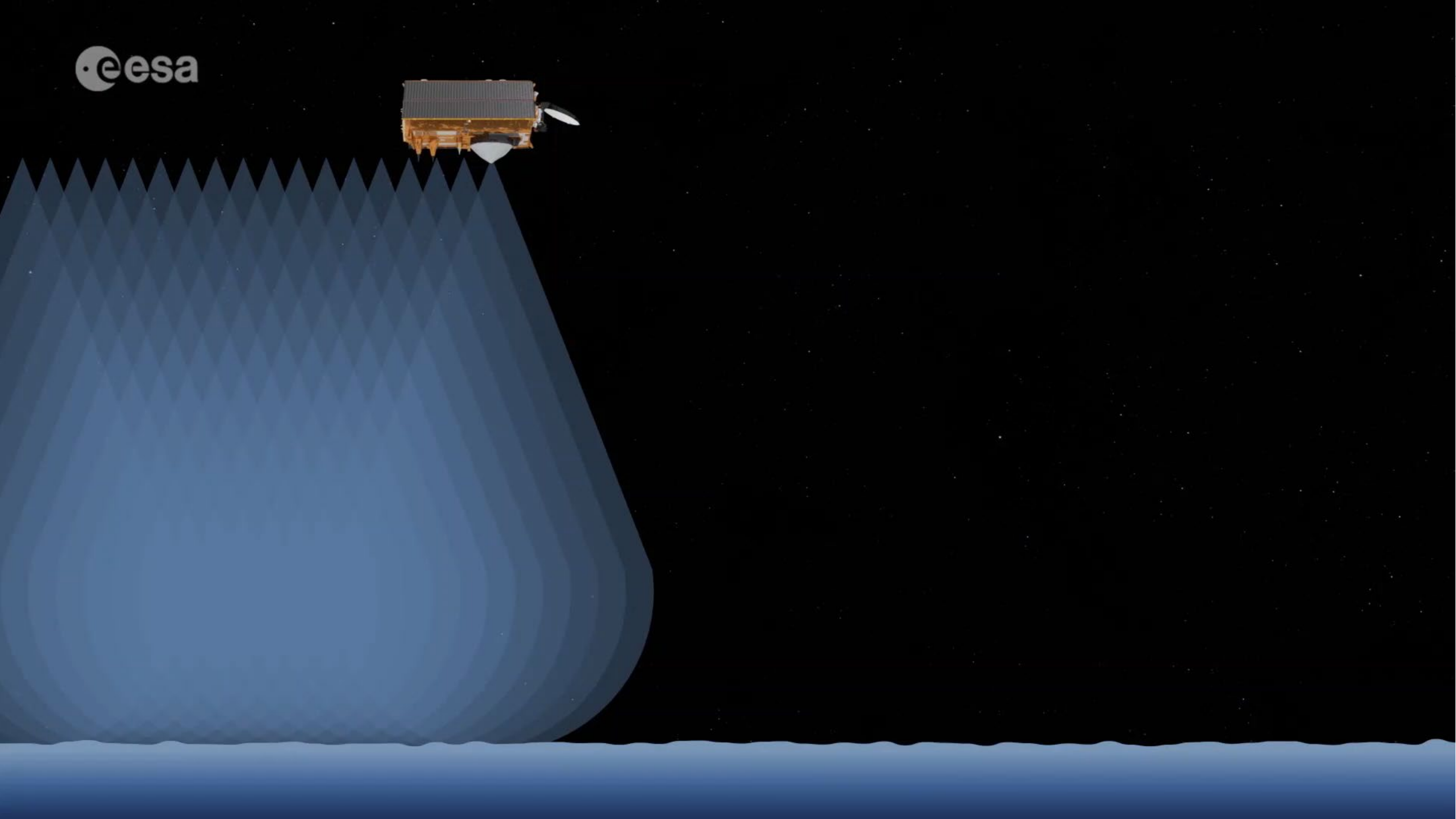
Classical altimeter (or Low Resolution Mode)

SAR mode

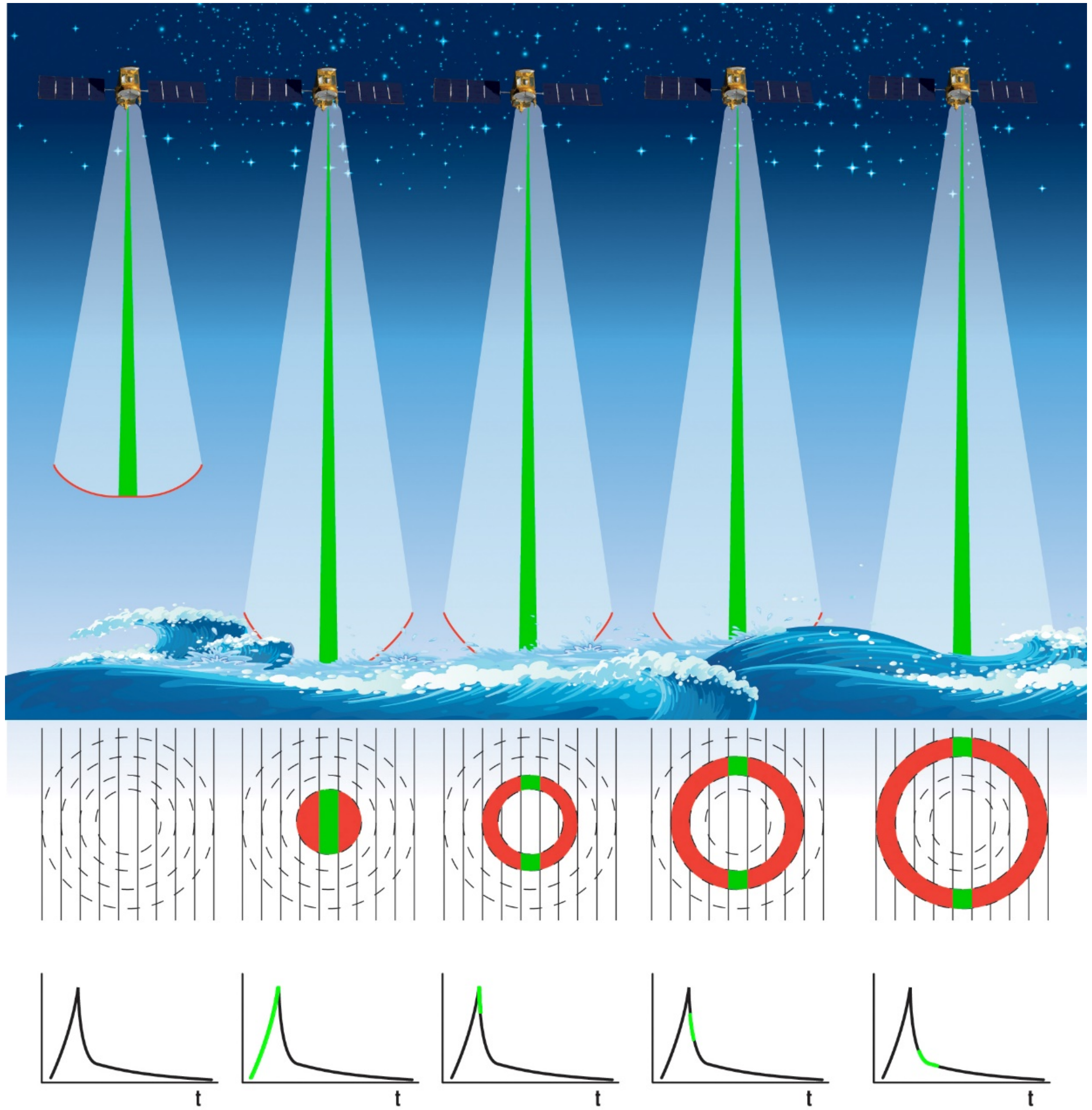
- Higher emission rate than previous (classical) altimeters
- Frequency received used to compute direction of the beam (Doppler shift)
- Coherence of the signal sent for about 2.5 s

➔ Split radar footprints in “slices”, data over each slice averaged using different satellite positions

➔better along-track resolution.



In practice: analysis of radar “echoes”: SAR waveforms



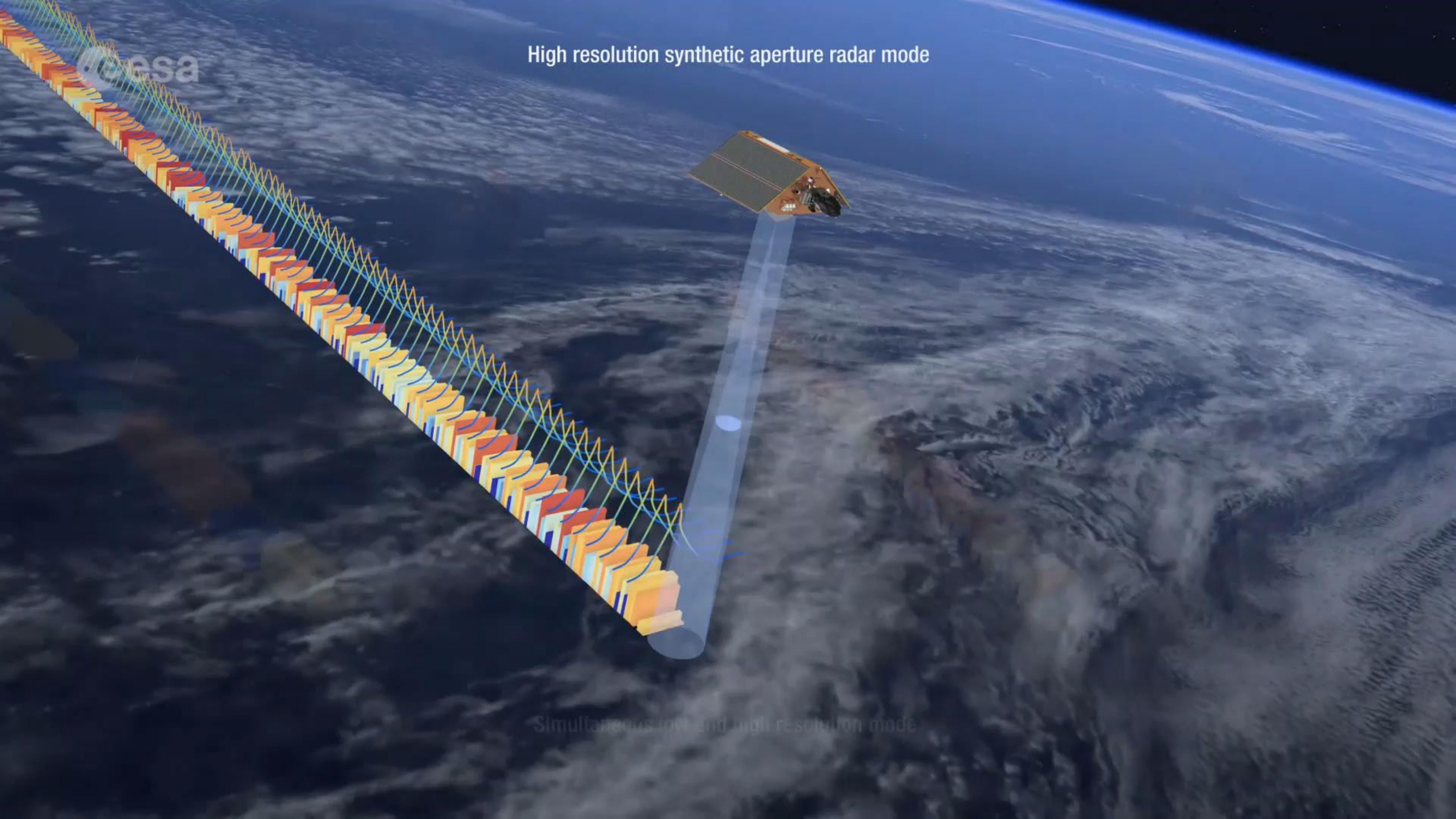
How an echo is “built”

Satellite

Radar beam

Radar signal as seen from above the surface

Shape of the power as received back by the onboard radar with respect to time (“waveform”)


High resolution synthetic aperture radar mode

Delay-Doppler (or SAR-) altimetry advantages

Improvements wrt conventional altimetry:

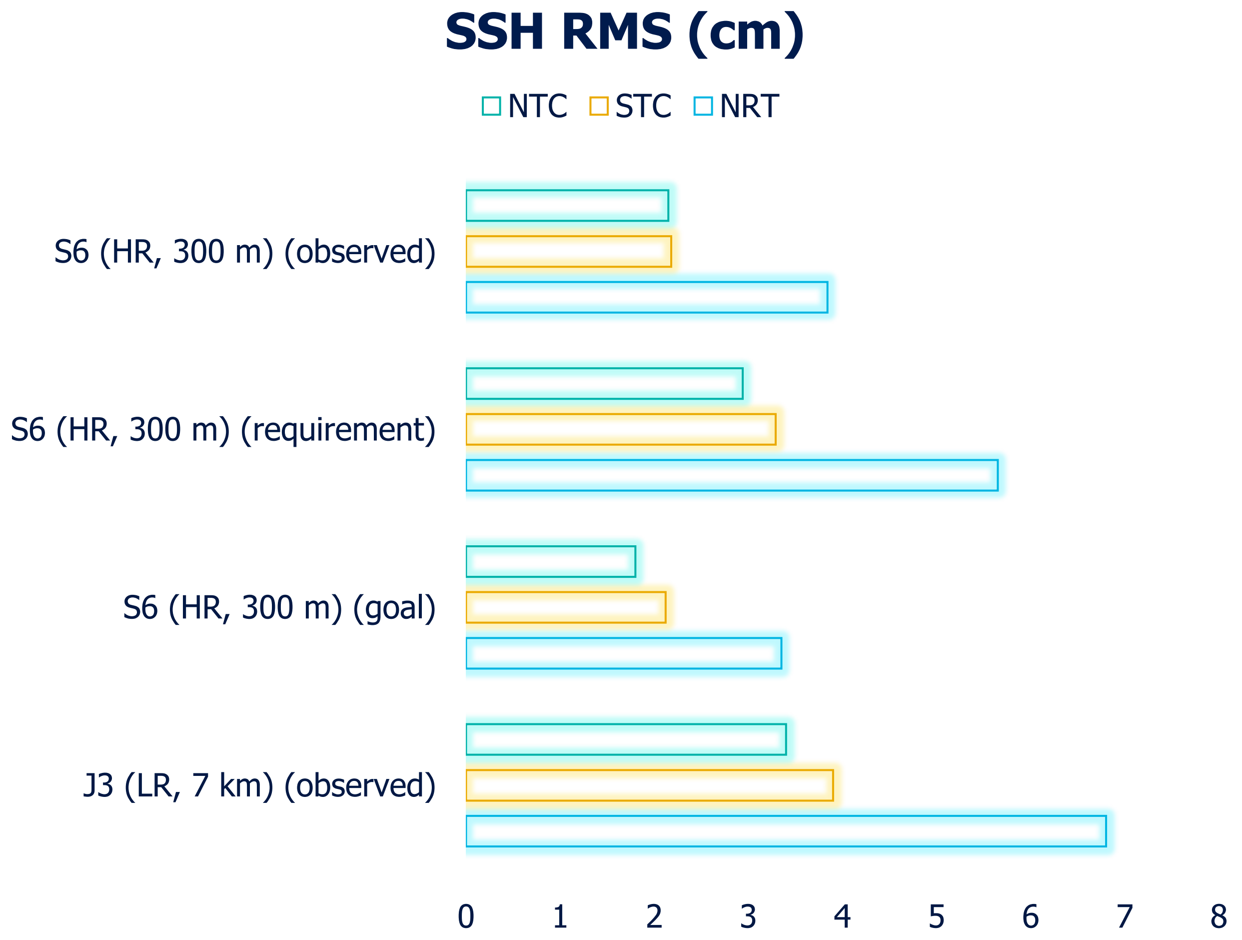
- More observations of a same “slice” (also called stack data) to be averaged
  → lower noise → more accurate ranges
  with the finer along-track spatial resolution provided
  (~ 300 meters along-track, aka 20 Hz data)
- Less ambiguity about what surface is observed close to land
  → more-coastal altimetry

Sentinel-6 in High-Resolution (HR) over most Earth up to 66°N & S (ocean, ice, and land waters)

Performances (NRT/STC/NTC)

Range noise

- S6 (HR, 300 m) (observed, low SWH): 0.62 cm
- S6 (HR, 300 m) requirement: 0.8 cm
- S6 (HR, 300 m) goal: 0.5 cm
- J3 (LR, 7 km): 1.8 cm



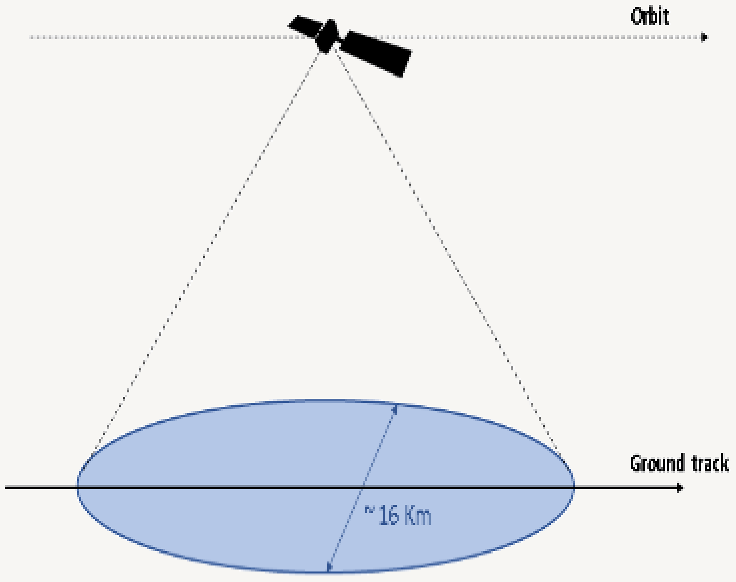
Delay-Doppler (or SAR-) altimetry – current developments

- A new capability: “fully-focused SAR” : processing the synthetic aperture using the longest possible integration time
  ➔ 50 cm along-track resolution *possible* with specific processing of Level-1A data

- Outputs of this processing not currently in operational nor standard products
- Several studies ongoing, including swell-wave spectra, small water bodies, rivers, coastal ocean features, etc.

From Conventional to FF-SAR Altimeter processing

Conventional Altimetry (LR mode)



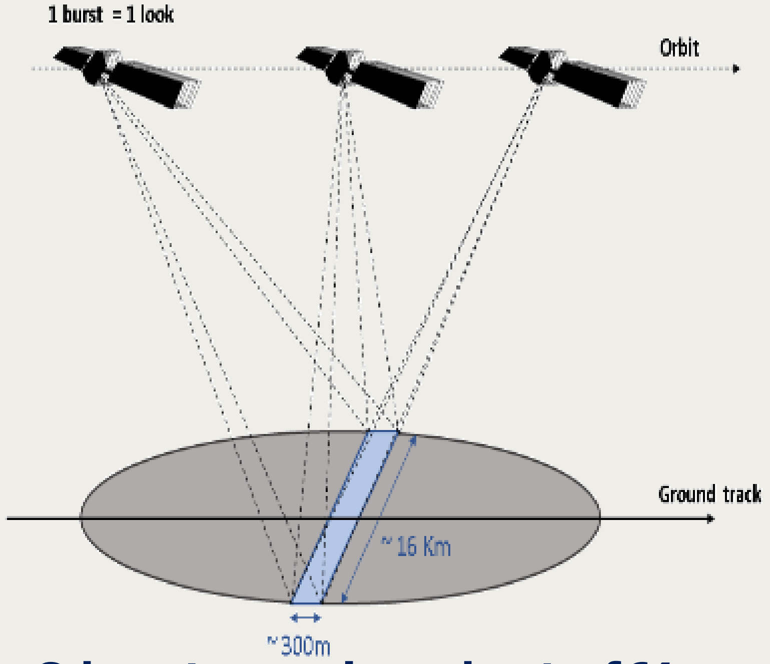
- No coherent processing (Phase not exploited)

➔ Footprint diameter = 16 km

T/P, ERS, Jason, Envisat, Saral…

Unfocused SAR (HR mode)

[Raney, 1998]



- Coherent processing on bursts of 64 emissions

➔ Along-track resolution ~ 300 m

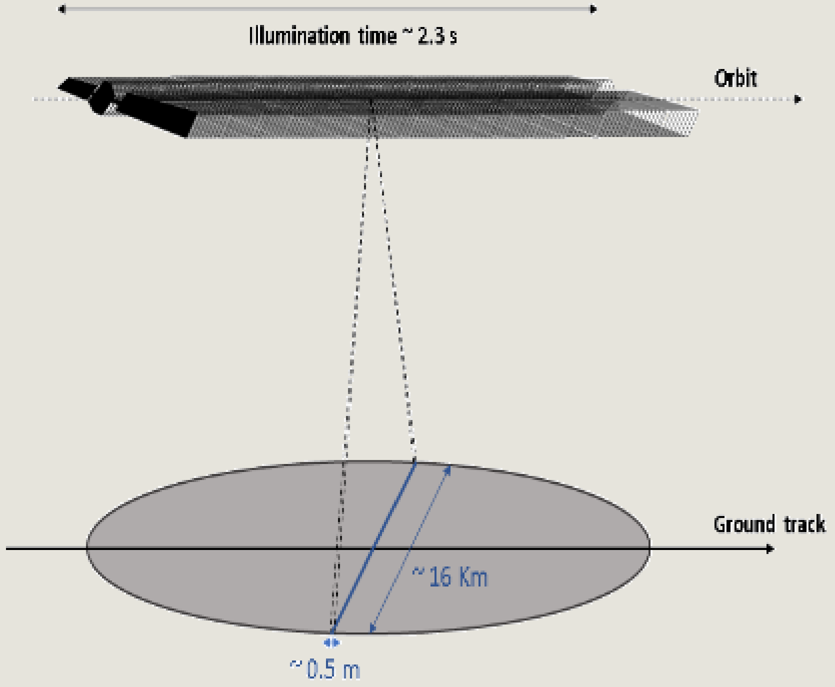
- Multi-looking (sum of independent looks)

➔ Noise level reduction

Cryosat-2 and Sentinel-3
Sentinel-6 standard processing

Fully-Focused SAR (FF-SAR)

[Egido & Smith, 2017]

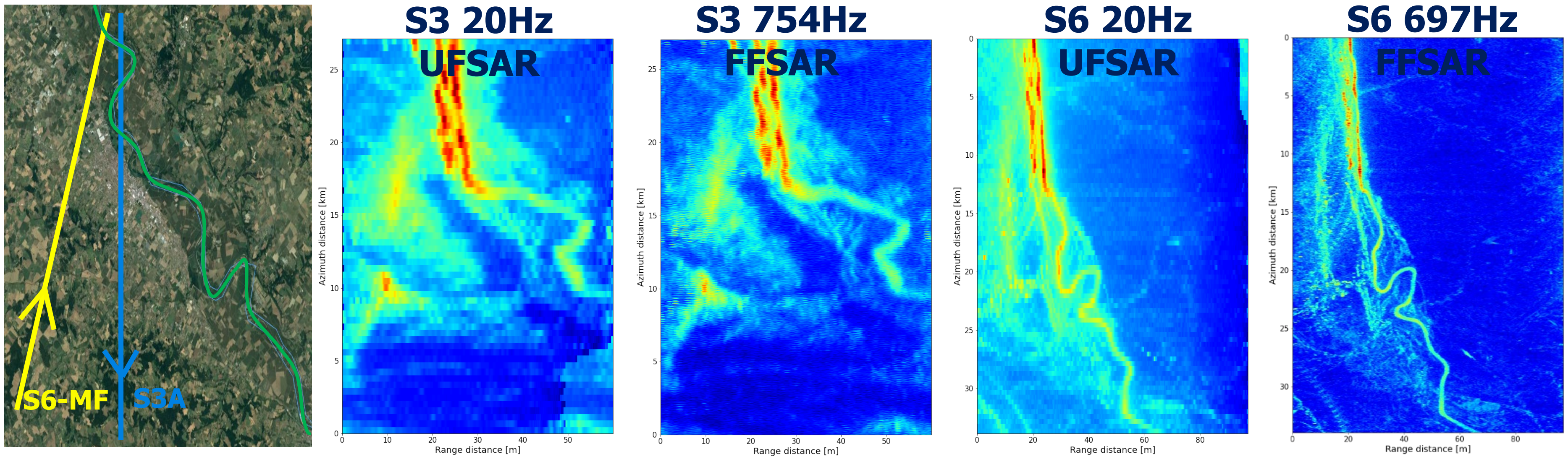


- Coherent processing on the entire scatterer illumination time (2.3 s, phase constant)

➔ Along-track resolution = 50 cm

Sentinel-6; Sentinel-3 with a few ghost detections specific processing

Benefits of FFSAR over rivers



Radargrams over Garonne river (France) at crossing point of S3A (cycle 10 pass 70) and S6-MF (cycle 68, pass 299).

- Questions? → go to Slido.com – event code: #EUMSC33

Sentinel-6 data products

Sentinel-6 at EUMETSAT user product overview

- **Level-1A**
  - Individual echoes; instrumental calibrations applied
  - From this the user can create L1B-S with software (provided by ESA); FF-SAR processing
- **Level-1B**
  - Calibrated waveforms, to be combined with Level-2 to form the equivalent of Jason's Sensor Geophysical Data Records (SGDR)
- **Level-2**
  - Equivalent to Geophysical Data Records (GDR)
  - New NetCDF format with groups
  - Provided also in **reduced format** (with 1-Hz only) and in BUFR format (in NRT)
- **Level-2P**
  - As Level-2, with computed corrected heights, only essential variables & updated corrections and models, validation flag
- **Level-3**
  - Harmonised with other missions (also distributed by Copernicus Marine Service)

Data level and cooking

	Data	Tagliatelle al ragú
Level 0	(Space agencies)	Grow your wheat, your cow, pork… tomatoes, carrots… then cook, etc.
Level 1 S3 FBR S6 waveforms	Explore new processing, new parameters, other surfaces…	Make your pasta from (bought) flour. Grow your vegetables, wash, peel and mince them.
Level 2 (aka GDRs)	Non-open ocean (non continental waters), change corrections,…	Buy meat, tomatoes, vegetables and cook the ragú; buy pasta and cook them
Level 3 (multi-satellite)	Assimilation Change corrections precise SWH	Buy ragú sauce, pasta; add a pinch of thyme, some more meat and let it cook for a (long) time.
Level 4 (grids)	Open-ocean	Buy your tagliatelle al ragú from next door Italian take-away restaurant.
Visualization tools' outputs	(png images)	Photo of the plate (artistic … or not)

Near-Real Time (NRT)	Short Time Critical (STC)	Non Time Critical (NTC)
• Mainly for **operational Met agencies** (wind and wave mainly) • Products split by **satellite dump/granules** (per ground station/10-minute chunks) • **NetCDF** and **BUFR**	• For **ocean modelling and assimilation** • Product split by pass (**pole to pole**) • **NetCDF**	• For **oceanographic and geophysical research and climate studies** • Products split by pass (**pole to pole**) • **NetCDF**
JASON-3		
• **3-hour latency** • **OGDR** • **1-Hz and 20-Hz** measurements (sea level, wind speed, wave height, etc.)	• **48-hour latency** • **IGDR** • **1-Hz and 20-Hz** measurements	• **60-day latency** • **GDR** • **1-Hz and 20-Hz** measurements • **SGDR** (including waveforms)
SENTINEL-6		

• **3-hour latency**
• **Level 2:** Low- and high-resolution products
    • **Standard** (1-Hz and 20-Hz)
    • **Reduced** (1-Hz)
    • **BUFR** (1-Hz and 20-Hz)
• **Level 2P:** Harmonised L2 (1-Hz)
	• **36-hour latency**
	• **Level 1A:** Individual echoes (High-Resolution (HR) only)
	• **Level 1B:** Low-Resolution (LR) and High-Resolution (HR)
	• **Level 2:** Low-Resolution (LR) and High-Resolution (HR)
	    • **Standard** (1-Hz and 20-Hz)
	    • **Reduced** (1-Hz only)
	• **Level 2P:** Harmonised L2 (1-Hz)
	• **Level 3:** With orbit error correction, error information (1-Hz)
		• **60-day latency**
		• **Level 1A:** Individual echoes (High-Resolution (HR) only)
		• **Level 1B:** Low-Resolution (LR) and High-Resolution (HR)
		• **Level 2:** Low-Resolution (LR) and High-Resolution (HR)
		    • **Standard** (1-Hz and 20-Hz)
		    • **Reduced** (1-Hz only)
		• **Level 2P:** Harmonised L2 (1-Hz)
		• **Level 3:** With orbit error correction, error information (1-Hz)

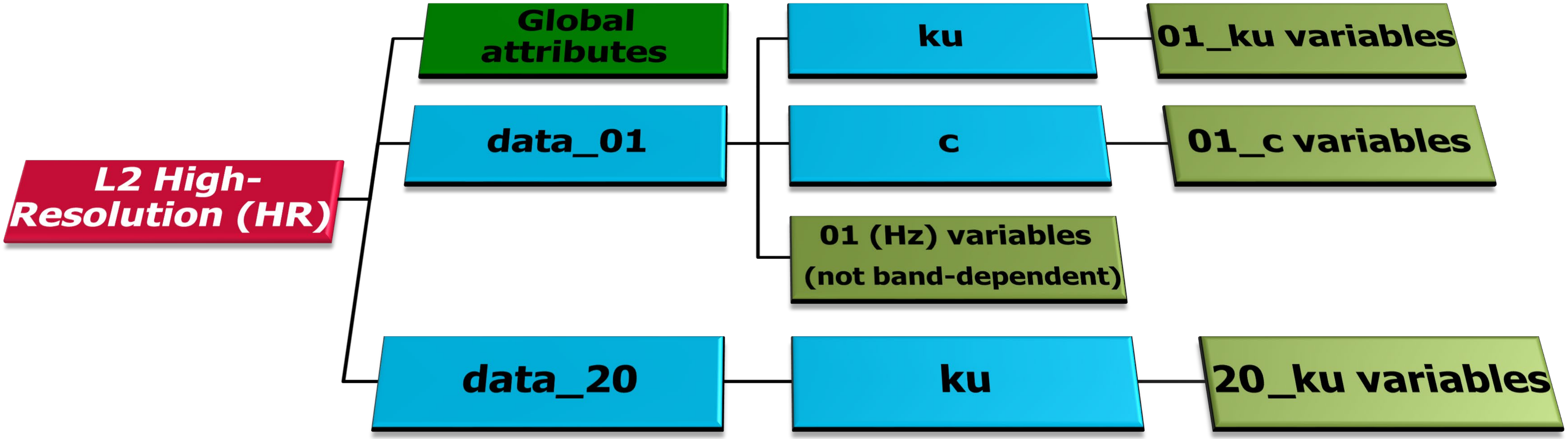
"Annual" reprocessing of NTC products

- With any major product evolution
- To ensure consistency of data standard throughout the mission
- This is the new **"climate product"**

Product novelties in Sentinel-6

- NetCDF data grouping
  - more convenient variable naming
  - Compartmentalise data (avoid a long list of fields only alphabetically-sorted)
- Separate High-Resolution (HR) and Low-Resolution (LR) products
- Waveforms in L1B product (link to L2 to have some corrections)
- “unique” internal filename, *à la Jason* (“SAFE” packaging)
- Separate Level 2 radiometer product (MWR)

Example: NetCDF groups in Level 2 High-Resolution (HR) product



Conclusions

- Sentinel-6 introduces High-Resolution (HR) on the reference altimeter missions
  - “Interleaved mode” (radar emission/reception pattern) will allow Low-Resolution (LR)/High-Resolution (HR) simultaneously, thus ensuring continuity and opening the door to a lot more R&D
  - New type of data products
  - 1-Hz range noise below 1 cm at low SWH (0.62cm)!
- Sentinel-6 will produce Short-Time Critical data faster than previous Jason missions
  - Assimilation into ocean forecasting models
- All Sentinel-6 data produced by EUMETSAT
  - Availability through EUMETCast and EUMETSAT Data Archive
  - BUFR provided in NRT (through GTS, mainly for Met Offices)

Take-home message

Sentinel-6 Michael Freilich:

- Changes AND continuity
  - Benefitting from unremitting work on accuracy for the past 30 years
  - Enabling a seamless transition
  - Also improvements on data accuracy, capabilities
  - New possibilities to be explored…
  - Format close to the last Jason-3 format, reprocessing ongoing for older missions
- The story continues! (Sentinel-6B to be launched Nov. 2025)

- Questions? → go to Slido.com – event code: #EUMSC33