# STAR Seminar

## The Commissioning of Sentinel-6 Michael Freilich, the next-generation radar altimeter

**NOAA**
**Satellite and Information Service**

5 January 2022

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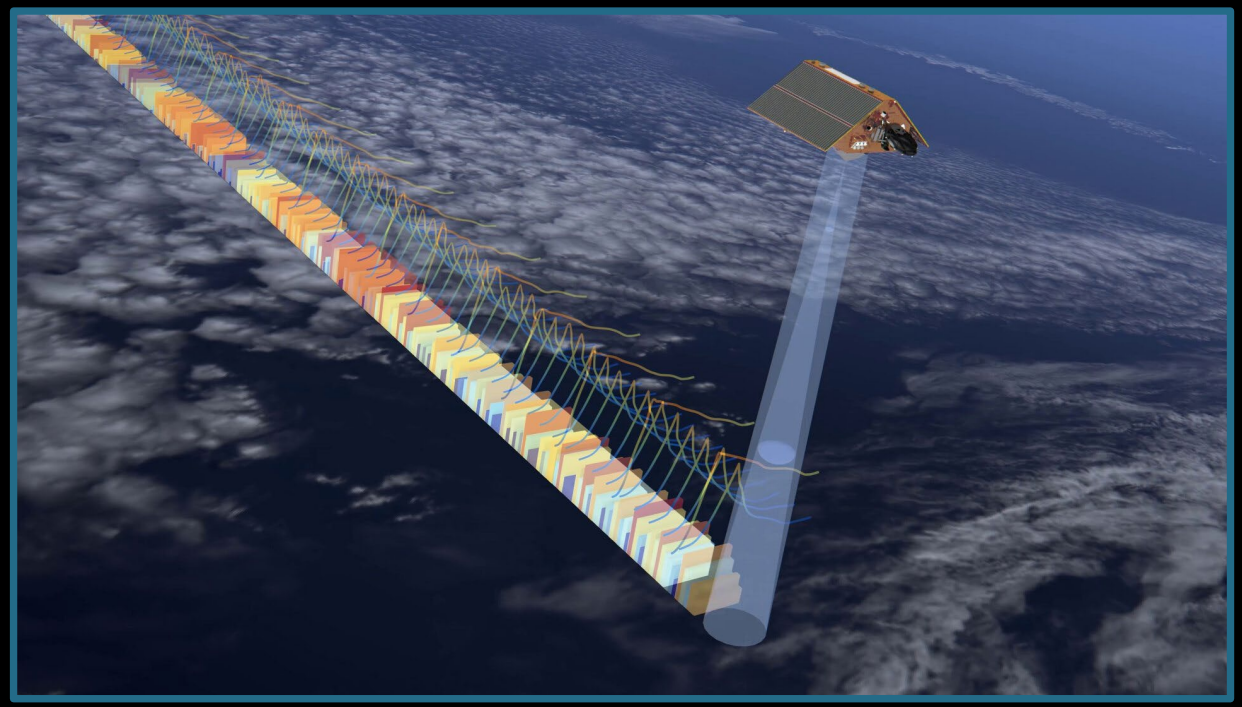
NOAA Jason Program and Project Scientist
Chief, STAR Laboratory for Satellite Altimetry

# Outline

- **Sentinel-6 mission and design**
- **Commissioning and major issues**
- **Next steps**


# Sentinel-6 Michael Freilich

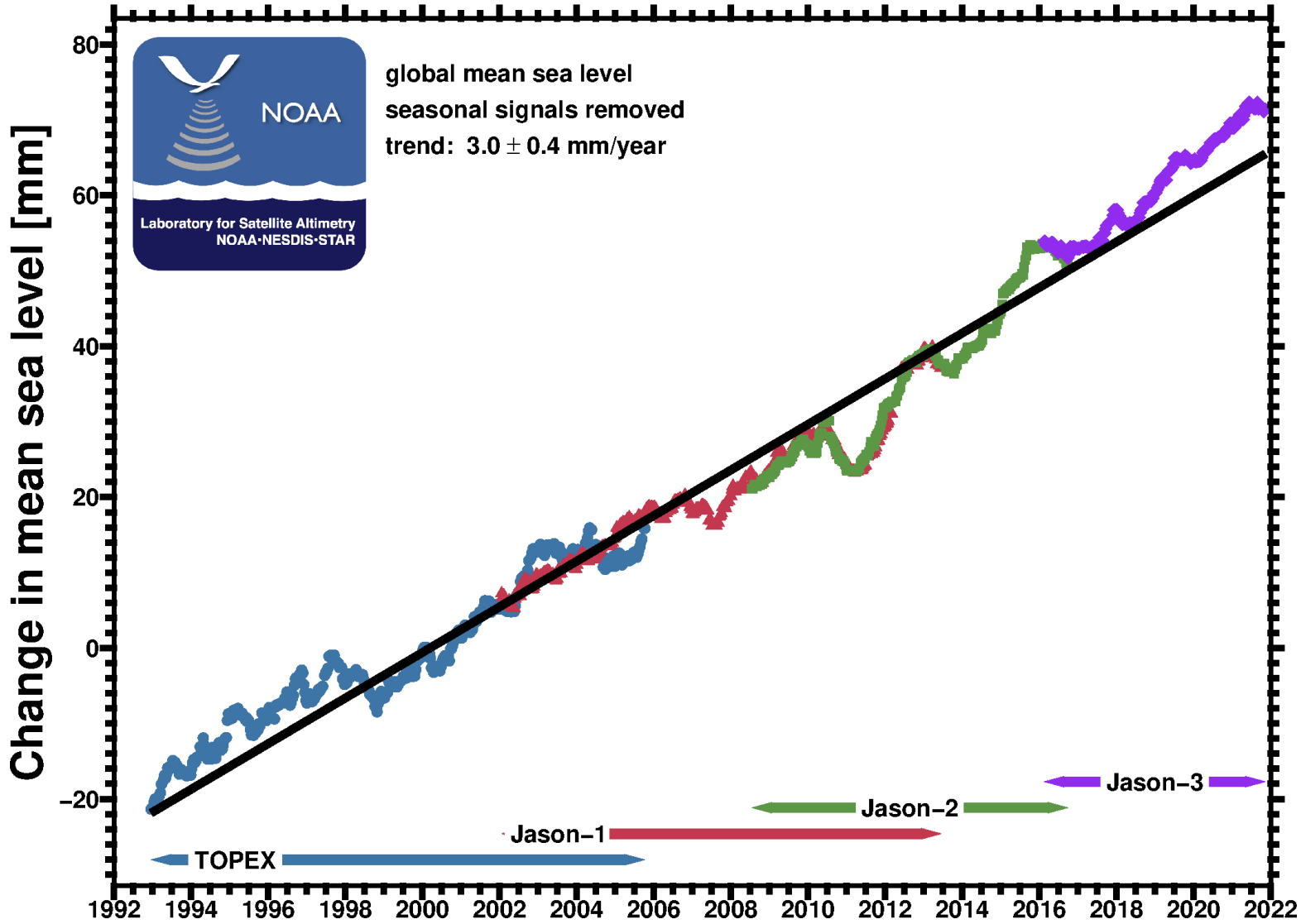
- The Sentinel-6 missions are the latest of the satellite radar altimeter “reference missions” that started with TOPEX/POSEIDON.
- These missions are an unbroken series observing sea level, waves, and marine winds.
- NOAA has been a partner starting with Jason-2.



# Global mean sea level

Continuing the altimetry series is critical to monitoring sea level change.

An acceleration in sea level rise has been identified, driven by accelerating melt of land ice and warming of the ocean.



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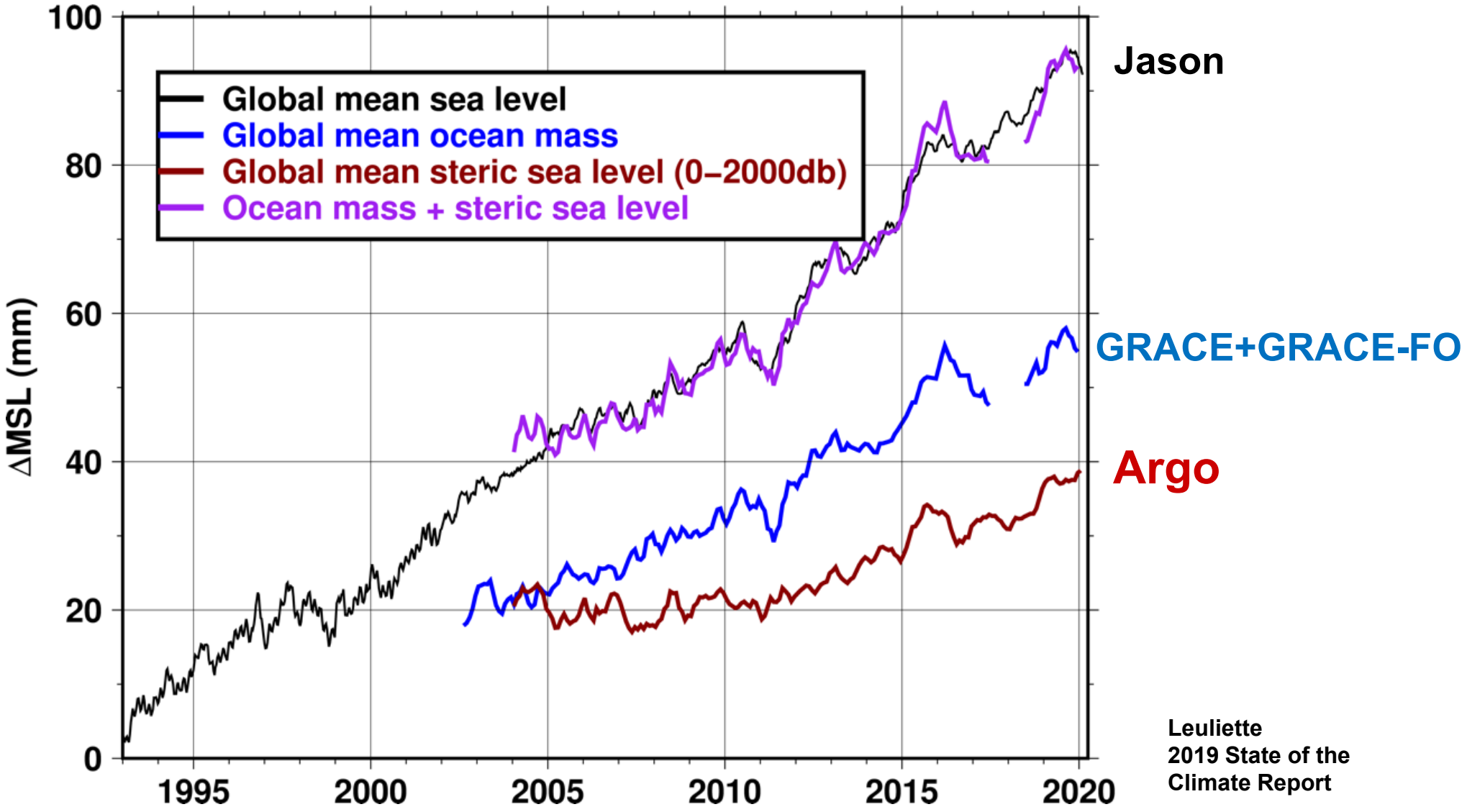



Leuliette
2019 State of the Climate Report

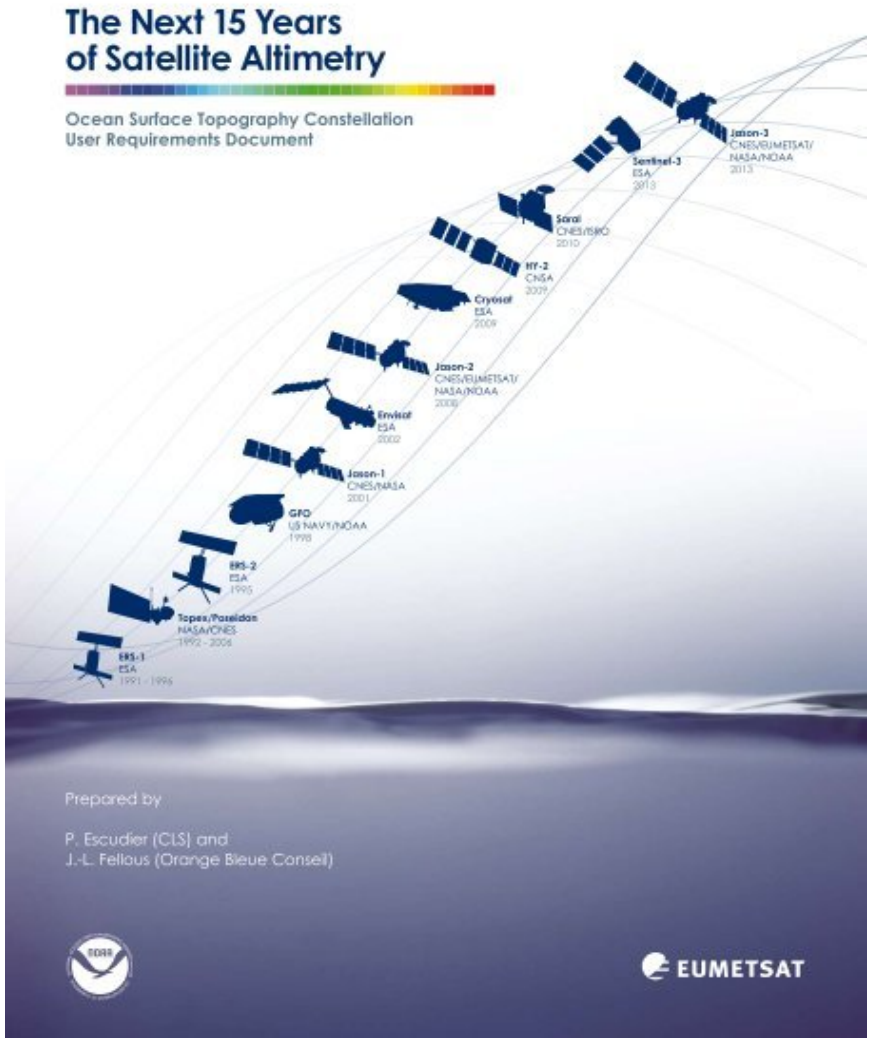
# The Road to Sentinel-6

Sentinel-6 was a response to the “Next 15 years of altimetry” Constellation User Requirement Documents adopted by CEOS Ocean Surface Topography-Virtual Constellation in 2009 to continue the reference missions.

**Reference missions** have stability requirements for regional and global sea level change monitoring ( < 1 mm/year)

All reference missions have overlapped their predecessors with tandem phases. The spacecraft have been < 1 minute apart.

Initially, ESA proposed a mission to follow Jason-2 based on SAR-Altimetry technology demonstrated with CryoSat. Jason-3 was adopted by the partners as a gap filler.



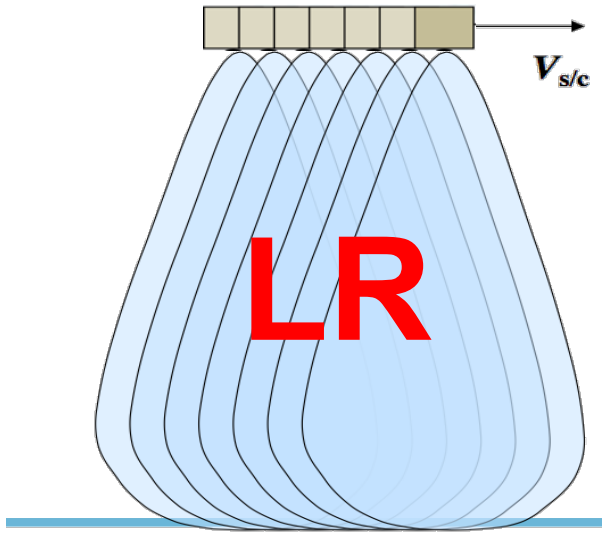
# Sentinel-6: What's in a name?



- The mission was proposed as **Jason-CS**. Originally "**CS**" reflected an ESA proposal for the Jason reference series to carry a next generation delay-Doppler, high-rate SAR altimeter demonstrated experimentally on **C**ryo**S**at-2.
- Jason-CS was backronymed to "Jason **C**ontinuity of **S**ervice" to avoid confusion
- Under Copernicus the missions were designated Sentinel-6A/B and the satellites Jason-CS
- In January 2020 the first mission was renamed **Sentinel-6 Michael Freilich**.

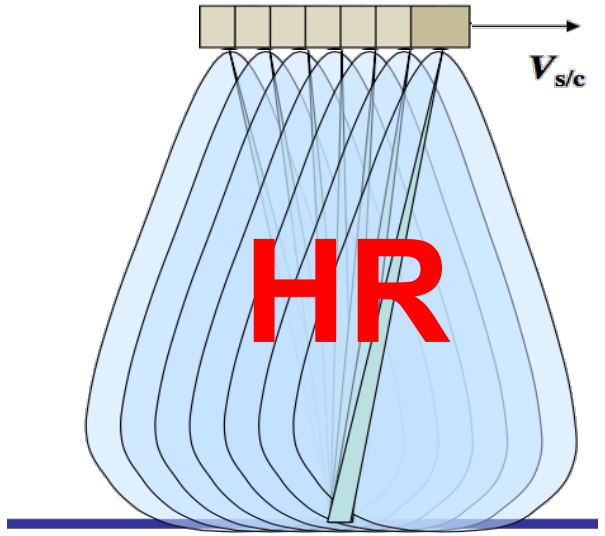
# Next-Generation Altimetry: Conventional vs Delay-Doppler/SAR

**Conventional Altimeter**
**Jason-1/2/3**




- Low Resolution Mode
- Pulse limited footprint (circular)
- Open burst operation
- PRF ~ 2 kHz

**Delay-Doppler Multilook Altimeter**
**CryoSat-2, Sentinel-3**




- Unfocused SAR processing
- Pulse limited across-track
- Closed Burst
- PRF ~ 18 KHz
- Better SNR than LR

Image K. Raney,
JHU/APL, TGARS, 1998

# Climate record need for backward compatibility

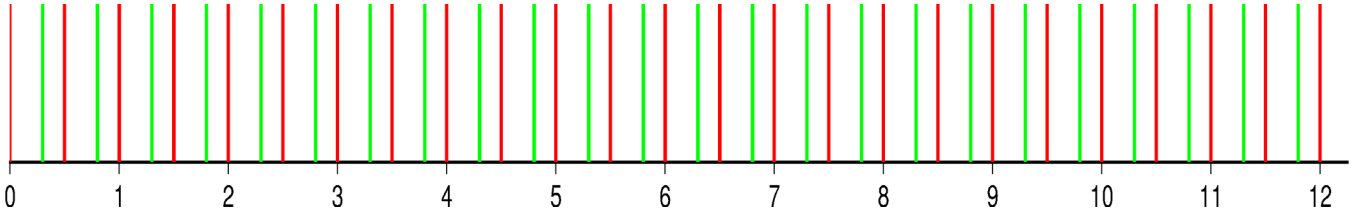
ESA initially proposed a mission with an altimeter capable of only SAR/Delay-Doppler technology (HR-only)

Walter H.F. Smith and Laury Miller of STAR pointed out that SAR/Delay-Doppler isn't backward compatible with conventional nadir altimetry

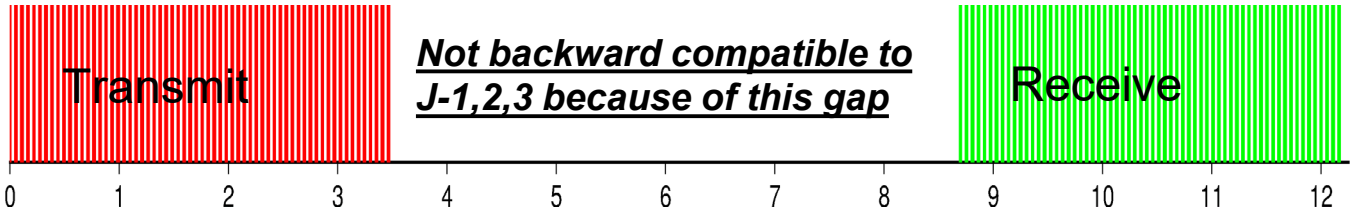
- An abrupt switch in technologies would lead to uncertainties in the sea level and wave climate records
- STAR proposed an "interleaved" mode that would alternate between High-Rate (SAR/Delay-Doppler) and Low-Rate (conventional) radar echoes
- Low-Rate is compatible with Jason-3
- High-Rate and Low-Rate differences could be studied using an interleaved mode

# POSEIDON4 adopted interleaved mode

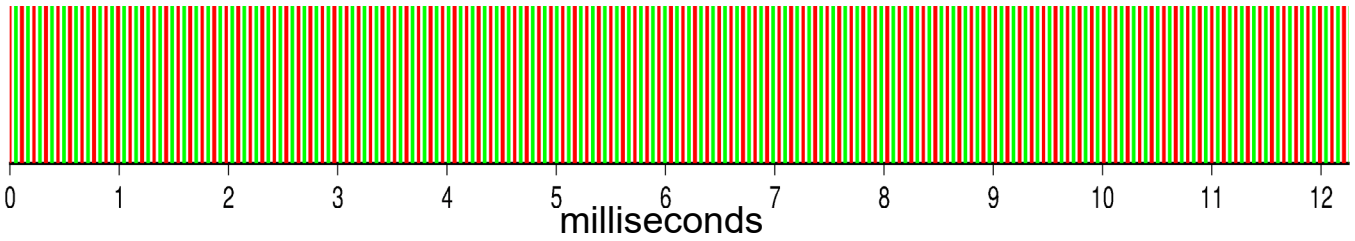
Jason-1,2,3 – Continuous Sampling but Low Resolution (no SAR)




Sentinel-3 SAR– enables High Resolution but samples only about 25% of the available time




Sentinel-6 multiple-look Interleaved – Continuous High Resolution allows 100% SAR and 100% backward compatibility to Jason-3



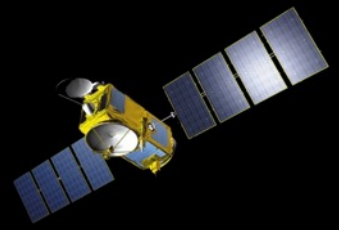

Walter Smith, STAR/LSA

# Sentinel-6 Heritage

TOPEX/Poseidon
1992-2006

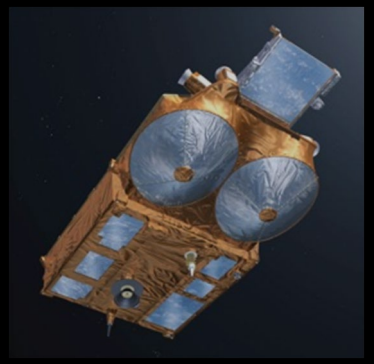
Jason-1
2001-2013

Jason-2
2008-2019



Jason-3
2016-

Conventional pulse-limited, low-rate reference missions



CryoSat-2
2010-

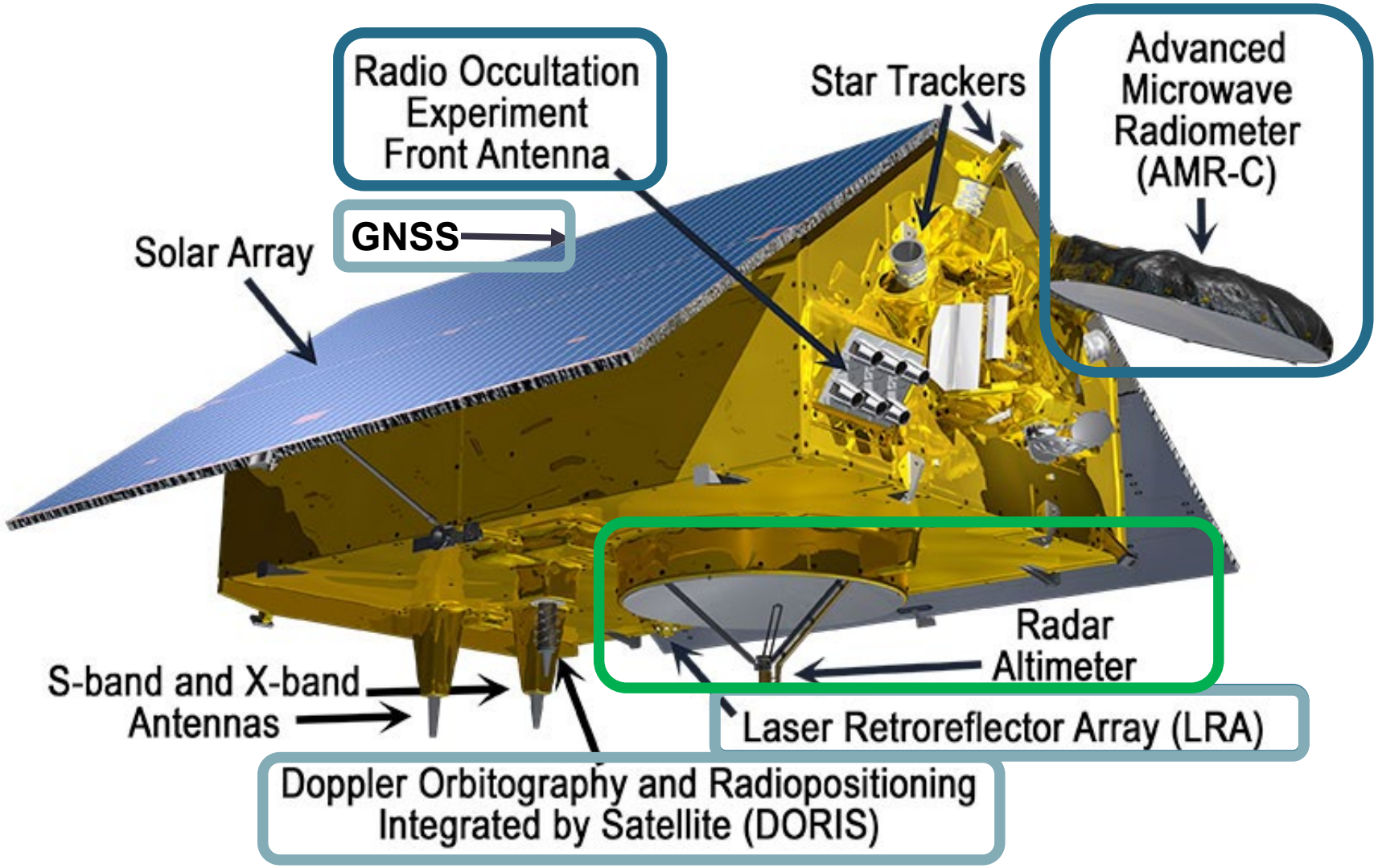
Sentinel-3A,-3B
2016-

Delay-Doppler/SAR, multilook, high-rate

Sentinel-6 MF
2020-

Delay-Doppler
Reference missions

# Sentinel-6 instruments



# Sentinel-6 MOU responsibilities

## NOAA responsibilities

- Provide US TT&C and mission data acquisition services (Fairbanks) (OPSO, SEWG)
- Provide dissemination of ocean topography NRT Products to operational users with in the U.S. in coordination with EUMETSAT (OSPO, STAR assistance)
- Support in collaboration with NASA, the U.S. component of the Ocean Surface Topography Science Team (OSTST) research announcement and process (STAR)

## Joint responsibilities

- Establish and control system performance budgets, mission Cal/Val, and data product validation, including intercalibration with Jason-3 (STAR, MPWG)
- Organize and support the Mission Advisory Group (MAG) and Validation Team (S6VT) and interface with the OSTST (STAR)

Jason-3 responsibilities included NRT L2 product generation and archiving

# Commissioning

## Programmatic

- Mission Performance Working Group
- Sentinel-6 Validation Team
- Timeline and mission phases

## Results and issues

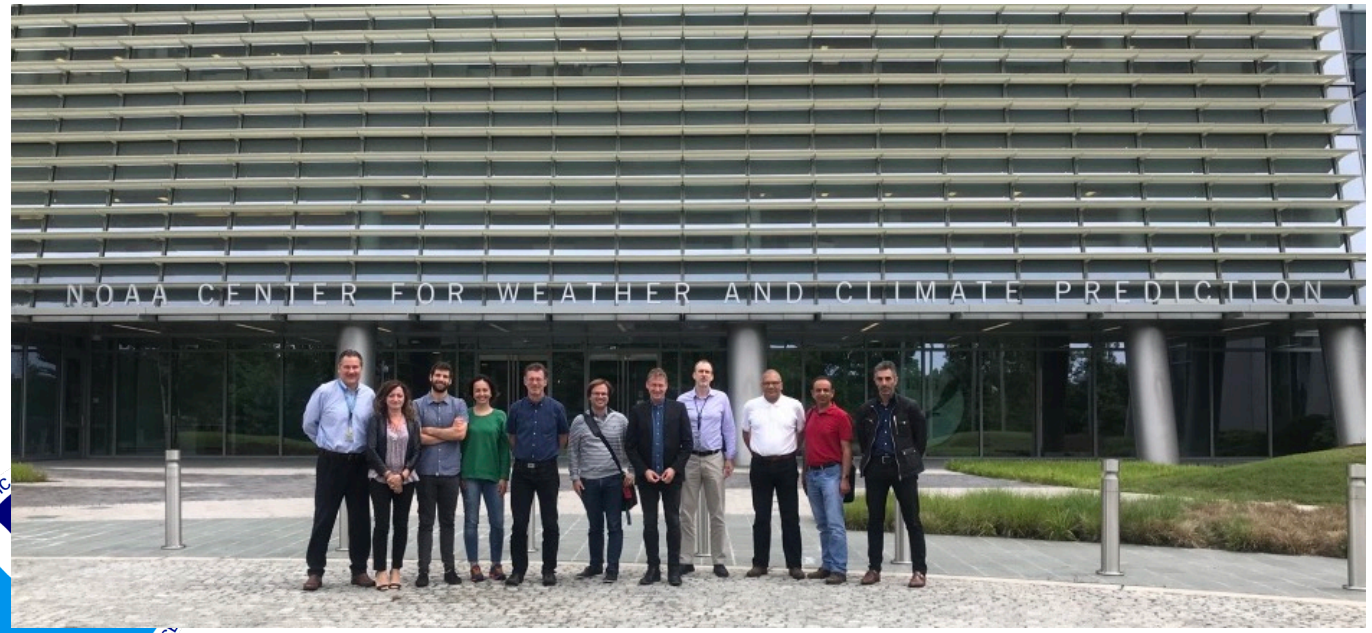
- Low-Rate and High-Rate performance
- Power degradation issue and switch to redundant altimeter
- STAR contributions
  - Transponder results
  - Vertical wave motion to wave heights

# Sentinel-6 Commissioning:
# Mission Performance Working Group (MPWG)

Defined in the 5-partner MOU and ToR

NOAA membership

- Eric Leuliette, Jason Project Scientist
- Alejandro Egido, Jason Measurement System Engineer
- Walter H. F. Smith (informal)




## Responsibilities

- System Requirements Document
- End Users Requirements Document
- Mission Performance Budget (MPB)
- Product Specifications Document (PSD)
- Cal/Val Concept (CVC)
- Cal/Val Implementation Plan (CVIP)

# Sentinel-6 Commissioning: Sentinel-6 Validation Team (s6vt.org)

The partners (NOAA, NASA, ESA, EUMETSAT, and CNES) created a validation team of independent investigators

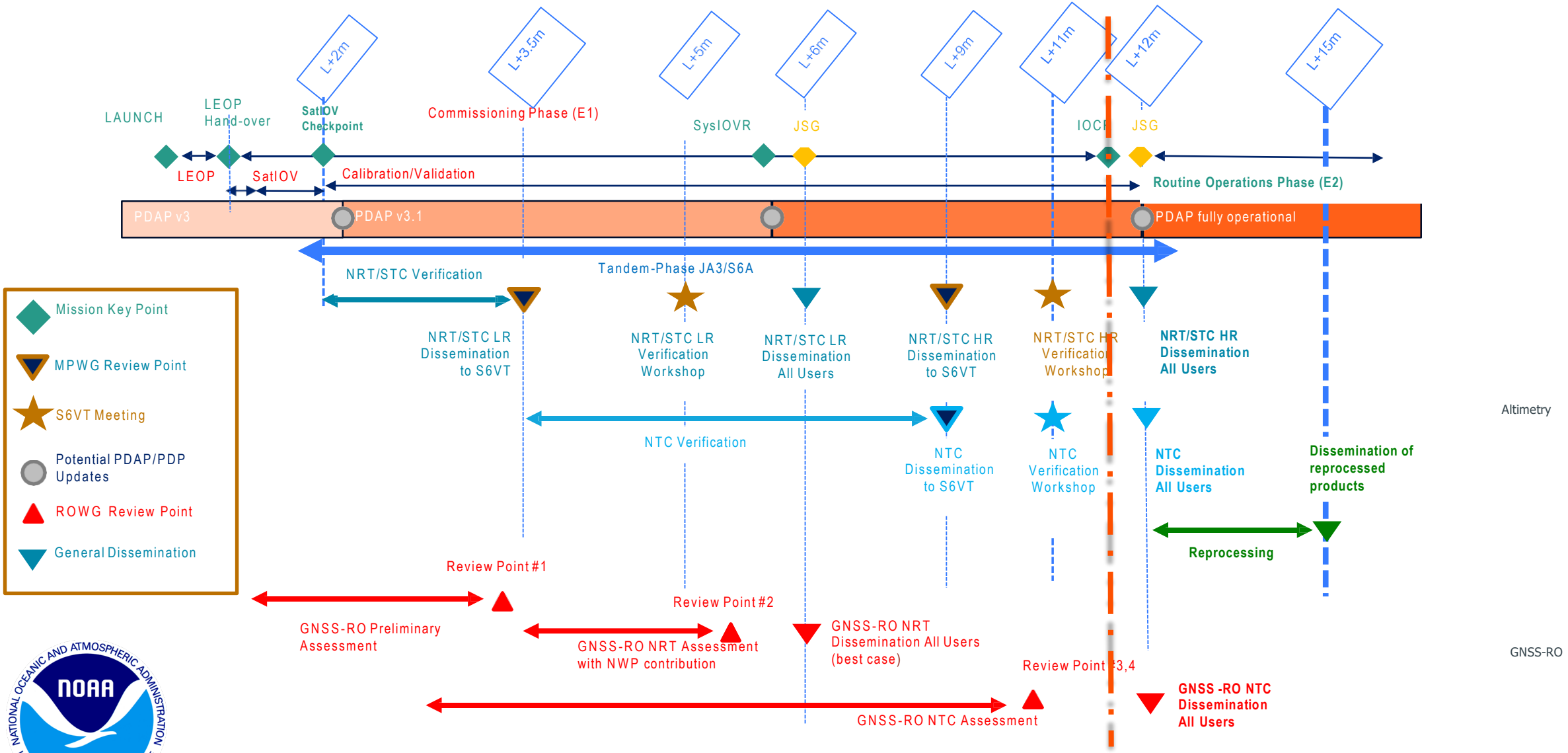
- The Team had early access to data products for evaluation
- NOAA and NASA appointed funded members of the Ocean Surface Topography Science Team

Two workshops were held during commissioning

- May 2021: evaluate Low-Rate NRT and Slow-Time Critical products
- October 2021: evaluate High-Rate and Non-time Critical (climate) products



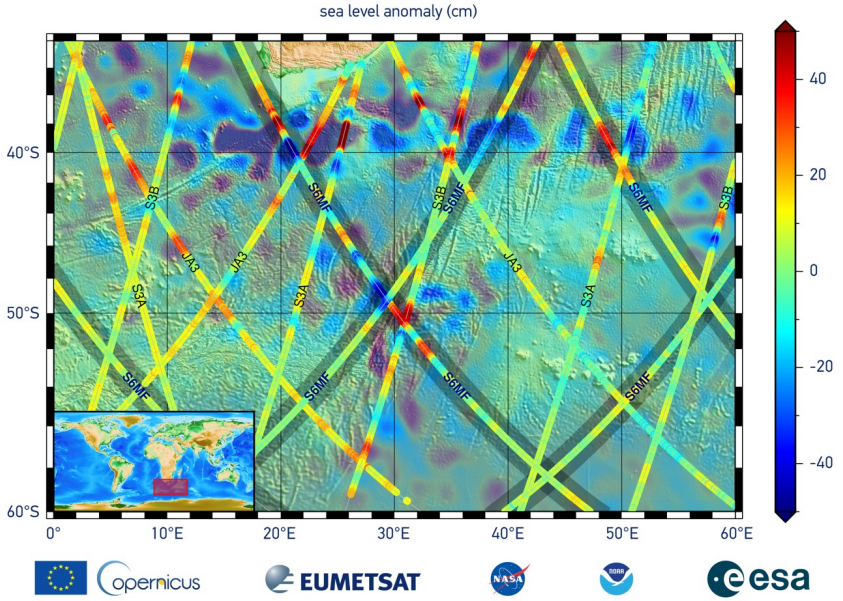
# The 12-month commissioning was more complex than Jason-1/2/3 because both LR and HR products needed to be evaluated at 3 latencies (3 hours; 36 hours; 30 days).



Launch on a SpaceX Falcon 9 rocket from Space Launch Complex 4E at Vandenberg Air Force Base in California on Saturday, 21 November 2020 at 12:17 p.m. ET

The Falcon 9 was acquired by NASA as part of the US contribution. The launch had remained on schedule more than 3 years. First mission in the TOPEX/Jason series to be on orbit during the design life of its predecessor.

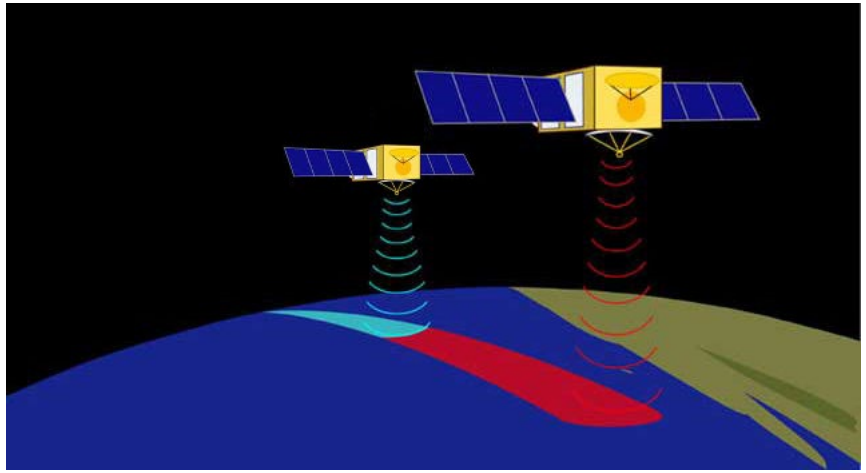
A first image using preliminary data (using initial calibrations) was released 10 December 2020.

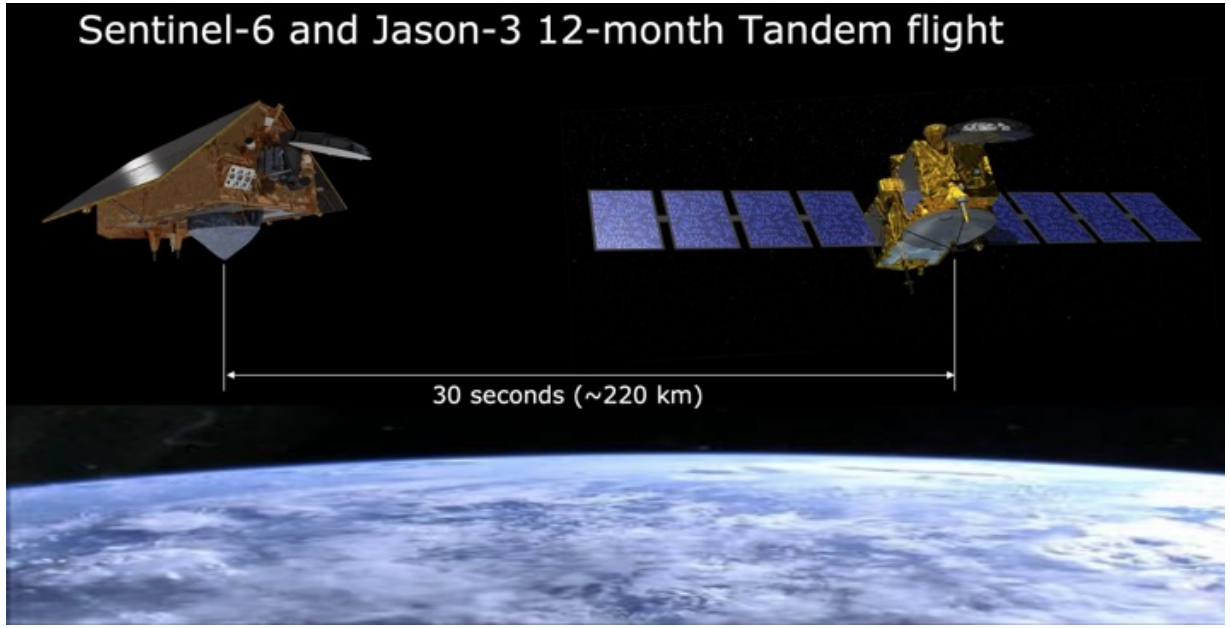


# Sentinel-6 commissioning with Jason-3

The original plan was for Sentinel-6/MF to fly in tandem formation with Jason-3 during a 12 month commissioning

- 18 December 2020 to ~~November 2021~~ March 2022 (because of power decay issue)
- Jason-3 and Sentinel-6/MF fly 220 km (~30 seconds) apart, providing redundant data
- Jason tandem commissioning phases were < 7 months. The Sentinel-6 phase is longer because of the major changes in technology.





# L2 LR Product Performances: Released May 2021 after SysIOVR

| | NRT 3 hours | STC 36 hours | NTC 60 days | Observed |
|---|---|---|---|---|
| **Altimeter noise (Ku)** | [1.2, 1.5, 2.4, 3.2] cm at [1, 2, 5, 8] m SWH | | | [1.25, 1.44, 1.93, 2.41] cm |
| **Altimeter noise (C)** | [4.5, 5.7, 9.1, 12.0] cm at [1, 2, 5, 8] m SWH | | | [4.5, 5.2, 7.9, 10.1] cm |
| **Ionosphere** | 0.5 cm | | | 0.1 cm |
| **Sea State Bias** | 2.0 cm | | | 0.6 cm (compared to JA3) |
| **Dry troposphere** | 0.8 cm | 0.7 cm | 0.7 cm | Based on historical analysis |
| **Wet troposphere** | 1.2 cm | 1.2 cm | 1.0 cm | 0.2 cm (compared to JA3)<br>0.8 cm (compared to ECMWF) |
| **Altimeter range RSS** | 2.93 cm | 2.90 cm | 2.83 cm | < 2.5 cm with bias < 1 cm |
| **RMS Radial Orbit** | 5 cm | 2 cm | 1.5 cm | NRT/STC/NTC: < 2 cm / ~1 cm / ~0.8 cm |
| **Total RSS sea surface height** | 5.79 cm | 3.53 cm | 3.20 cm | NRT/STC/NTC: 3.3 cm / 2.8 cm / 2.5 cm |
| **Significant wave height** | 15 cm + 5% | | | Far below 15 cm + 5% |
| **Wind speed** | 1.5 m/s | | | 0.5 m/s |
| **Sigma naught** | 0.3 dB | | | 0.18 dB |

# Processor updates and Products releases after SysIOVR (June 2021)

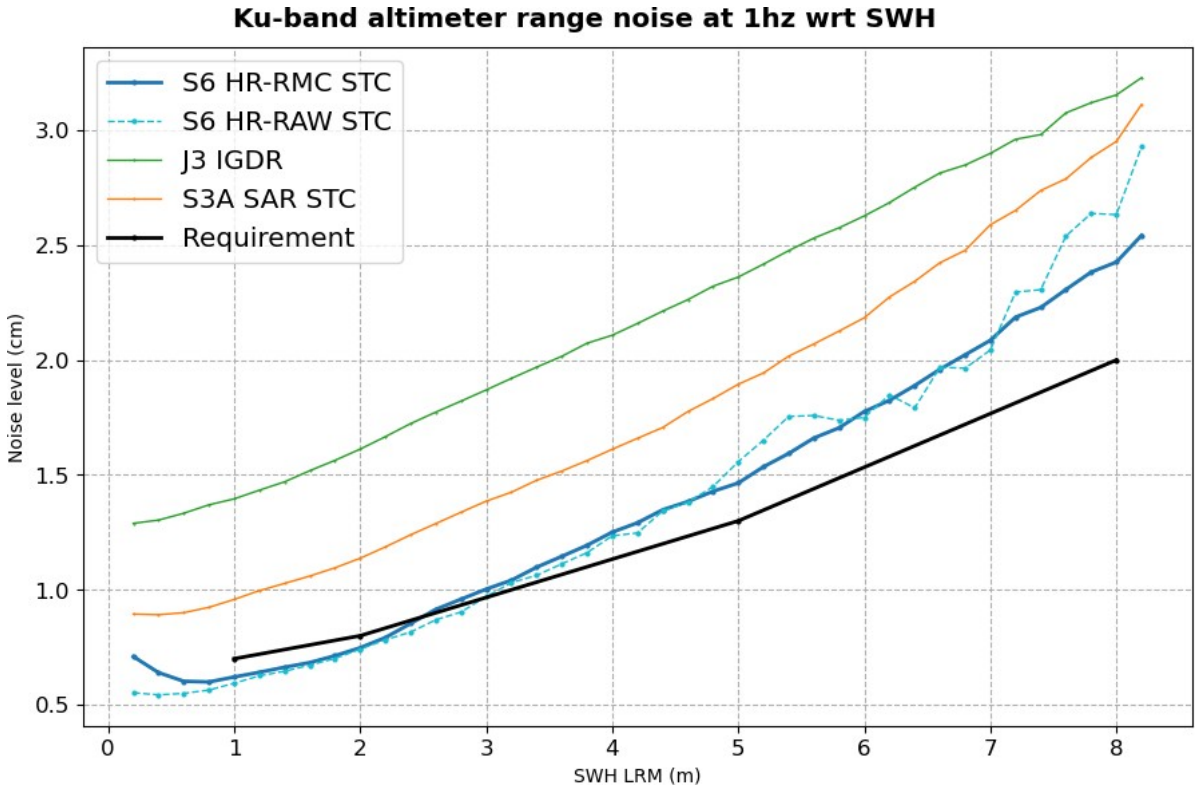
| Date | Item | Comments |
|---|---|---|
| 14 June 21 | RO-NTC v3.4 | Updates on the L1A/L1B processors, updates on POD, addressing anomalies |
| 22 June 21 | **Product Release** | Start of dissemination of ALT LR L1B (STC) and LR L2 (NRT/STC) products.<br>Start of dissemination of AMR L2 Products (NRT/STC). |
| 3 Aug 21 | PDP 3.3.2 | AR fixes for ALT HR and BUFR product header (baseline collection F03). |
| 24 Aug 21 | **Product Release** | Start of dissemination of RO NRT L1B and L2 BUFR Products by JPL. |
| 8 Sept 21 | PDP 3.3.3 | Fix for BUFR messages AR. |
| 9 Sept 21 | **Product Release** | Start of dissemination of ALT L2 LR (NRT) BUFR products on GTS. |
| 19 Oct 21 | ADFs 1.23 | Update of L2 CONF and CHDR following swap P4 to side-B. |
| 25 Oct 21 | RO-NTC v3.5 | Updates on L1A/L1B processor, updates on POD, addressing anomalies (yaw flip). |
| 8 Nov 21 | PDP 3.4.2 | AR fixes. (baseline collection F04). |
| 29 Nov 21 | **Product Release** | Start of dissemination of ALT HR (NRT/STC/NTC) and LR (NTC) products,<br>Start of dissemination of RO L1B NTC products. |
| 29 Nov 21 | **Product Release** | Start of dissemination of RO L2 |

# L2 HR Product Performances: Products released November 2021

| | NRT 3 hours | STC 36 hours | NTC 60 days | Observed |
|---|---|---|---|---|
| **Altimeter noise (Ku)** | [0.7, 0.8, 1.3, 2.0] cm at [1, 2, 5, 8] m SWH | | | [0.62, 0.75, 1.46, 2.42] cm<br>Sensitivity to swell at higher SWH |
| **Sea State Bias** | 2.0 cm | | | < 0.5 cm |
| **Altimeter range RSS** | 2.64 cm | 2.61 cm | 2.53 cm | Fulfilled in STC and NTC (NRT to be assessed) |
| **Total RSS sea surface height** | 5.65 cm | 3.29 cm | 2.94 cm | NRT/STC/NTC: 3.84 cm / 2.18 cm / 2.15 cm |
| **Significant wave height** | 15 cm + 5% | | | NOK but way forward identified<br>(correction for vertical waves velocity to be implemented) |
| **Wind speed** | 1.5 m/s | | | 0.5 m/s |
| **Sigma naught** | 0.3 dB | | | < 0.15 dB |

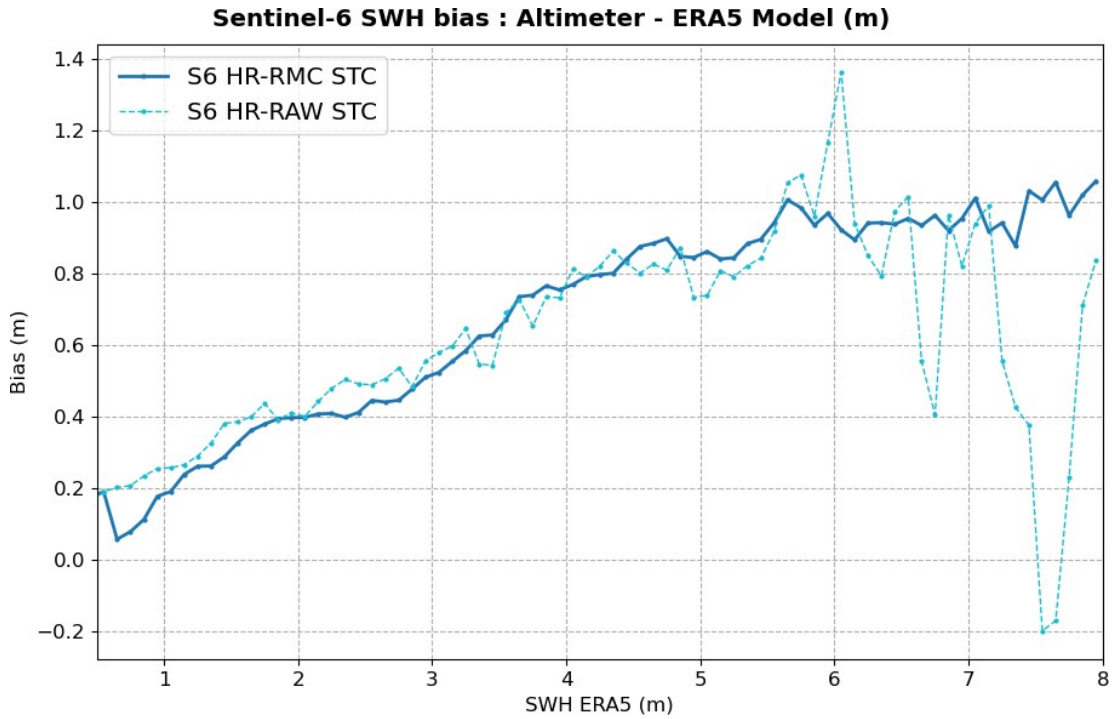
# Requirement on HR altimeter noise

- Overrun of requirement at higher wave heights
- Due to larger sensitivity of HR altimetry to swell than considered when writing the requirement
- Noise level much lower than Jason-3 and Sentinel-3



# Requirement on Significant Wave Height

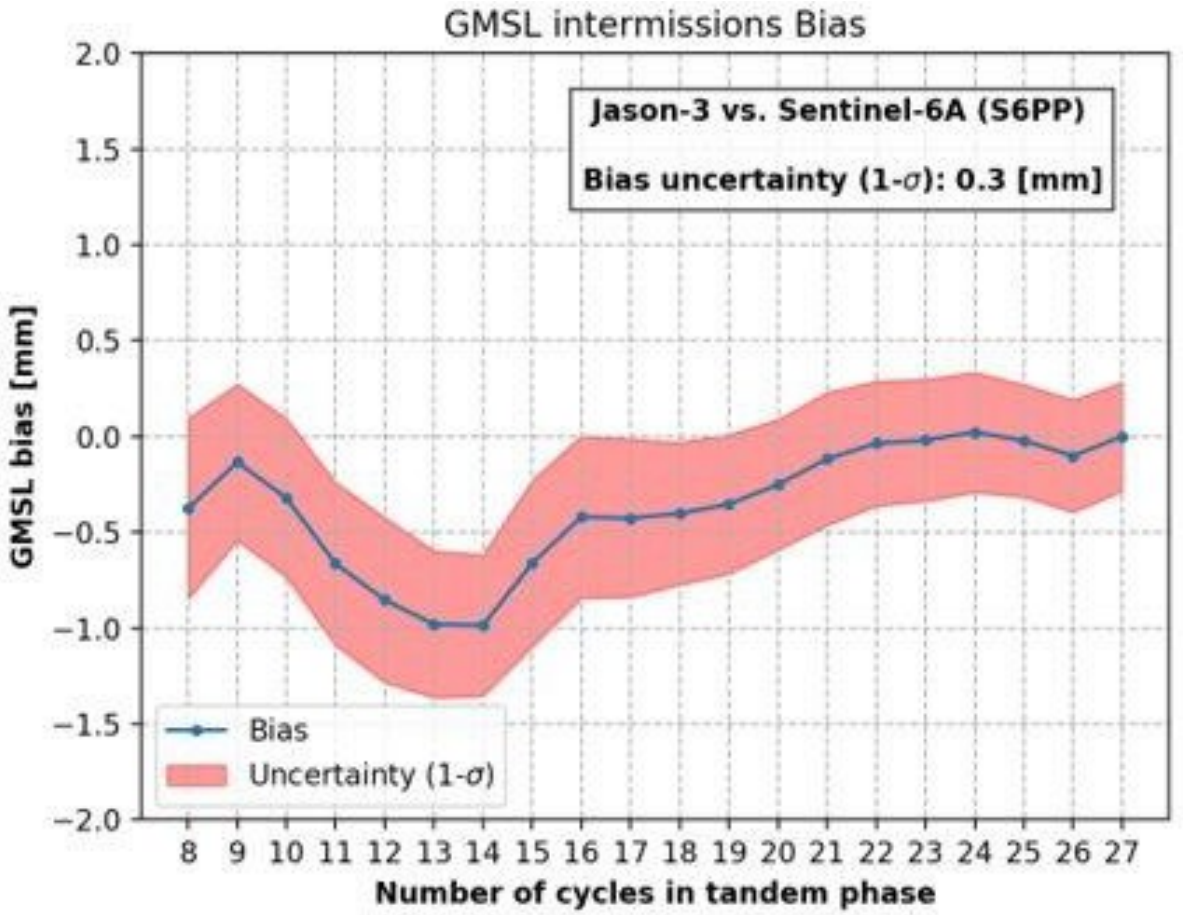
- Overrun of requirement over entire range
- Presently understood: general issue with HR altimetry, an impact of  vertical wave velocity, more prominent in S6A than lower flying S3
- To be fully corrected by an evolution in the processor look-up table driven by wave height and modelled mean wave period provided by STAR



# Altimetry Product Performance: Climate

## Long-term stability: Drift

- **The intermission bias with Jason-3 can be determined to 0.3 mm!**
- The requirement to have a drift in global mean sea level of less than 1 mm/yr can inherently only be verified after 2 years,
- Changes in the Point Target Response on Side A led to a drift of 0.8 mm/yr in global mean sea level; likely less on Side B
- Any currently observed drift will be mitigated by implementing a number of "Day-2" evolutions in the processors, to be implemented by 2022 Q4, prioritizing updates to LR processing



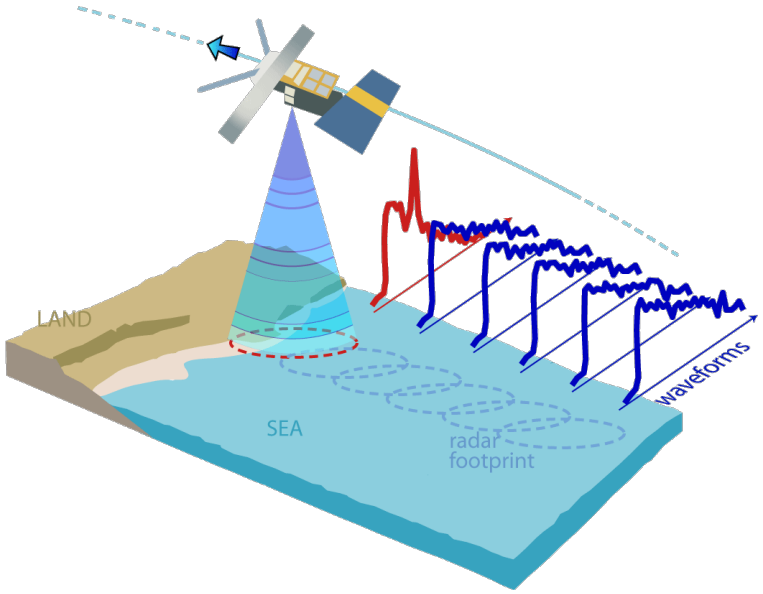
# Power degradation issue

All altimeters carry high-power amplifiers (HPAs) for the transmitted radar echoes

- Because HPA performance decays (loss of gain) over time, the design needs sufficient margin to guarantee the Signal-to-Noise ratio needed to meet mission requirements.
  - RID submitted as part of Satellite Design Review in 2012-2013

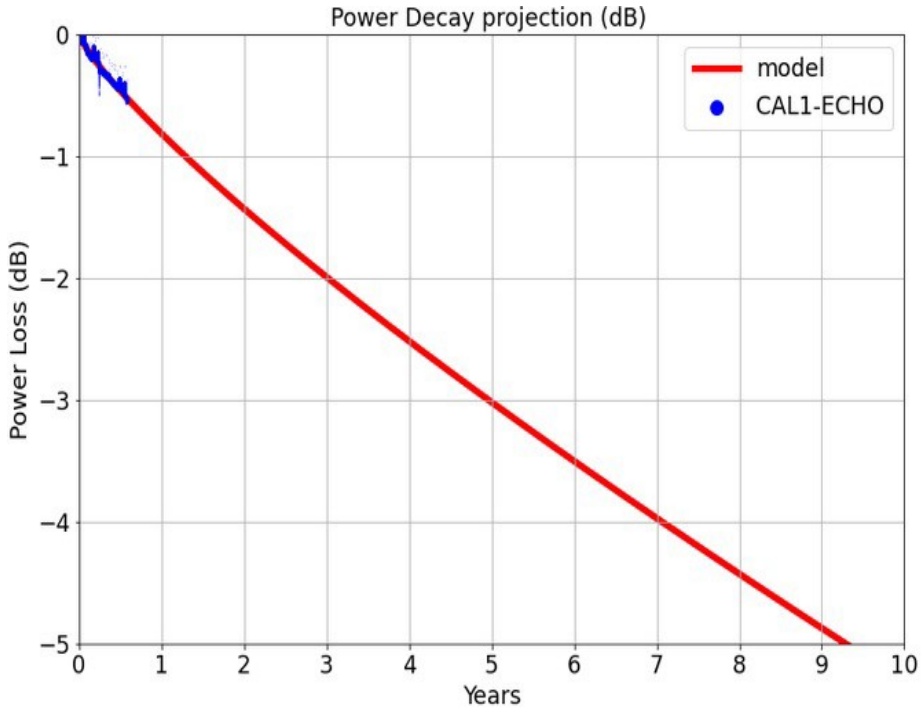
The HPAs originally designed for S6 had performance issues in 2018

- To keep the launch on schedule before the end of Jason-3's prime mission (5-years, January 2021) the partners approved a plan to replace the HPAs designed for Sentinel-6A with a different HPA for Sentinel-3D.
  - Sentinel-6 has a >50% higher altitude and the interleaved mode is a more demanding duty cycle, reducing the margin



# High Power degradation on primary altimeter

- Monitoring of HPA power is based on an internal calibration
- Exponential fit, proven very effective in the long term, based on Sentinel-3A/B experience



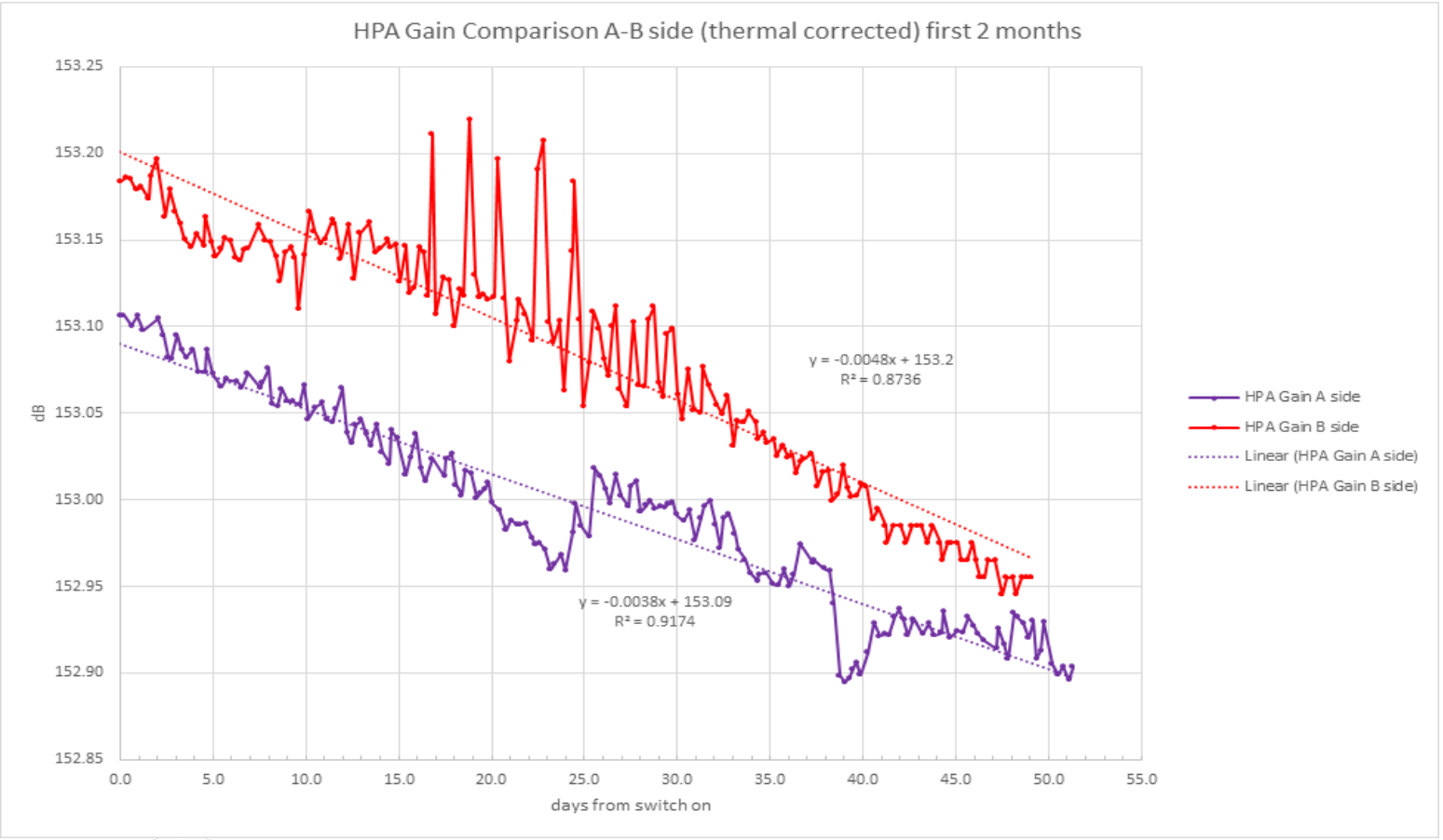

Given the SNR of 14 dB reported on the primary Side A, requirements would be violated after a power drop of ~3 dB (as soon as 5 years)

- However, there is some additional margin because the Side A-reported SNR is recognized by the Mission Performance Working Group (MPWG) to be under-estimated

The Project endorsed recommendations to switch to the redundant Side B altimeter on 15 September

- Pre-launch, Side B had 0.5 dB more margin
- Reduces risk of introducing uncertainty in the sea level record if a switch became necessary later
- Error in mean sea level would take ~8 years to reduce

# High-power amplifier degradation: side-B




- POS-4 was switched to side-B following the recommendation from the steering committee to cross calibrate side-B with Jason-3.
- Side-B is 1°C colder than Side-A because of the different location of the POS-4 units on the satellite.
- The rate of degradation of the HPA gain on side-B is similar to side-A, although further time is required to fully characterise this.

- **It should be possible to avoid switching back to Side A before the launch of Sentinel-6B**

# STAR's contributions to commissioning

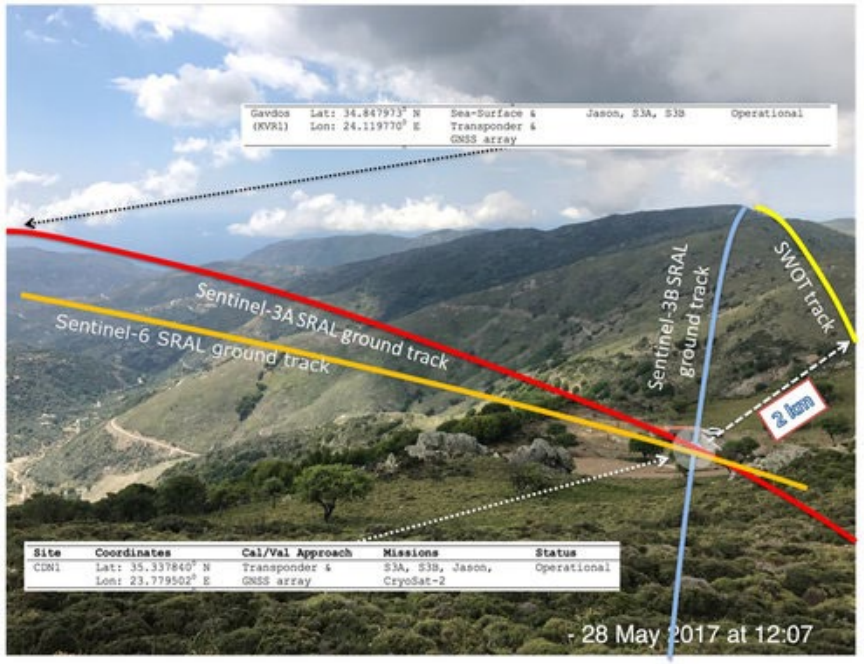
## Product evaluation

- Comparison with tide gauges
- Wind and wave comparisons with NOAA buoys
- Intermission crossover differences with Sentinel-3A/B, Jason-3

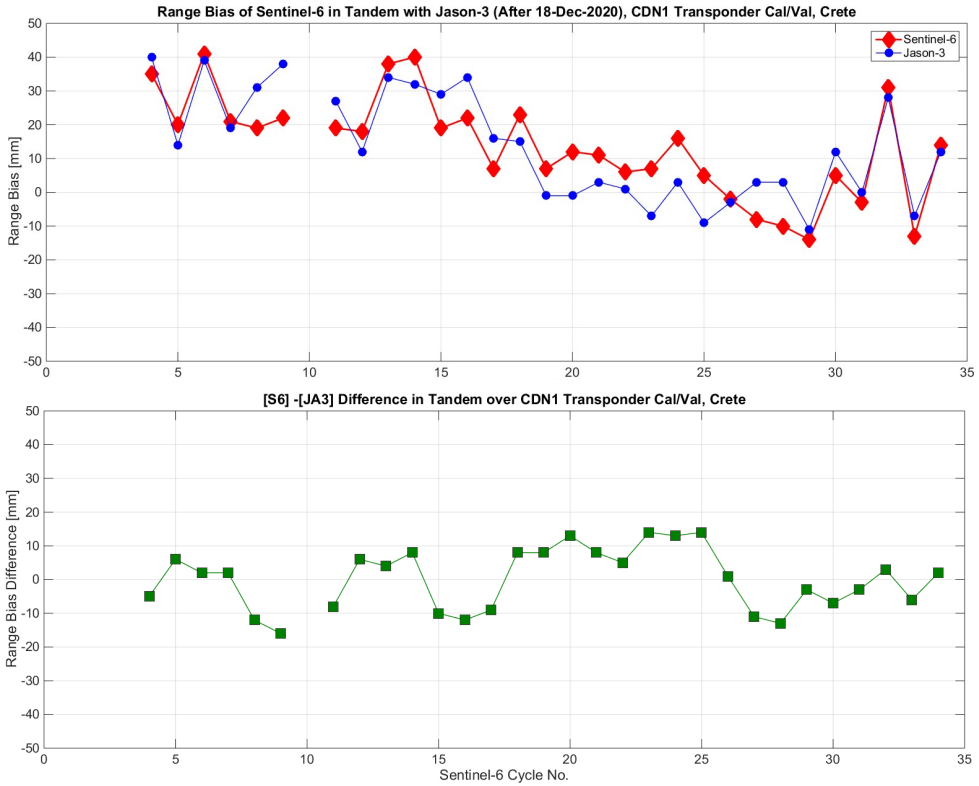
## Algorithm development

- Fully-focused SAR (FF-SAR)
  - FF-SAR Processor developed by Egido and Smith greatly improved transponder measurements (Crete) of absolute range
- Vertical wave motion correction
  - Identified issue that HR observations depend on vertical wave motion
  - Developed a look-up table correction
  - Worked with CNES on testing the correction
  - Delivered to EUMETSAT

# STAR's contributions to commissioning: transponder


The transponder Working Group adopted a coherent SAR processing method developed at STAR (Fully-focused SAR) by Egido and Smith.




FF-SAR improves SNR by up to 100x

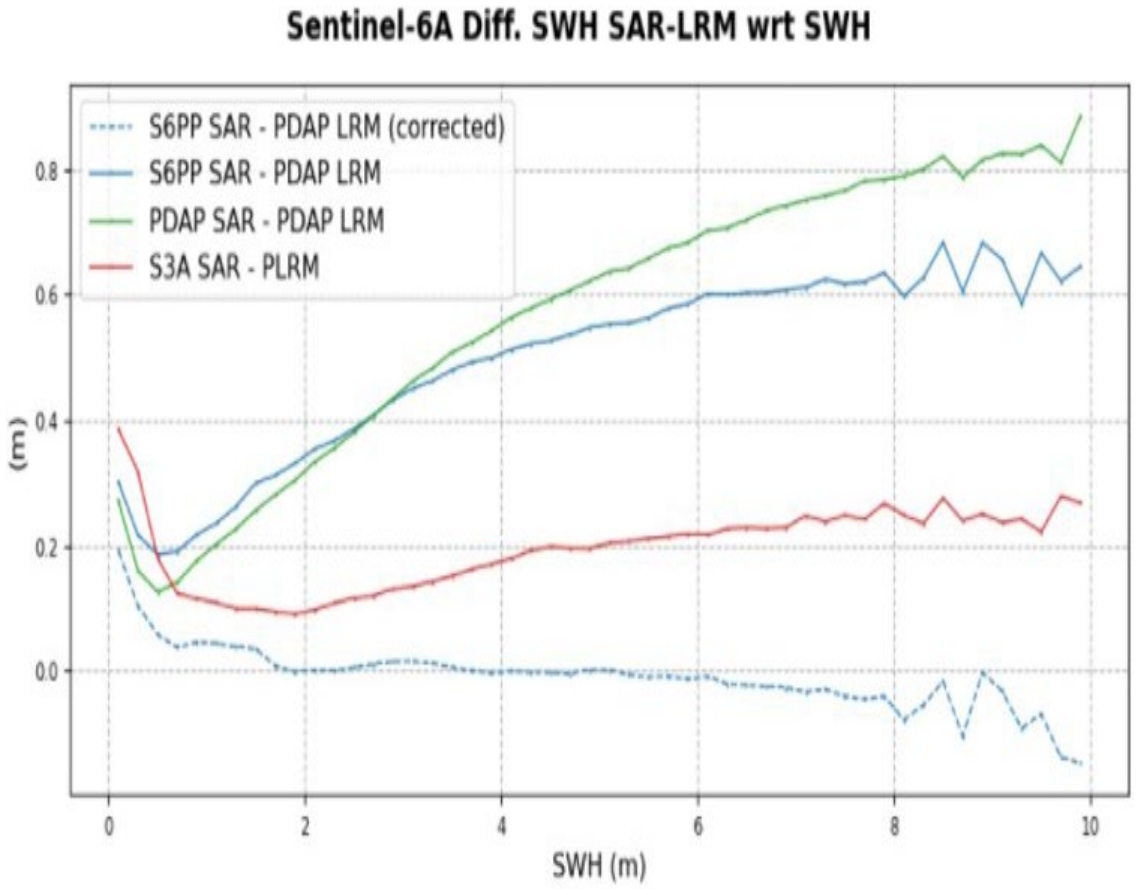
**Range bias (N=30) :**

- **Sentinel-6 = +14 mm ± 15 mm**
- **Jason-3 = +14 mm ± 16 mm**
- **Difference = + 0.0 mm ± 9 mm**

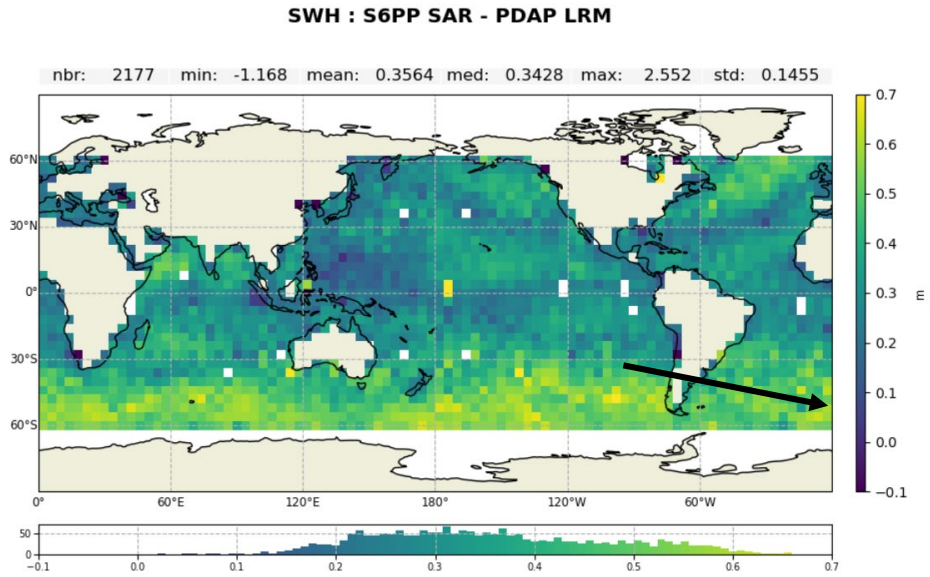
# Correcting for the Discrepancies in the HR Wave Height measurements

Alejandro Egido (1,2), Christopher Buchhaupt (1,3), François Boy (4), Claire Maraldi (4) and CLS Team
1) NOAA-LSA, 2) GST Inc., 3) UMD, 4) CNES

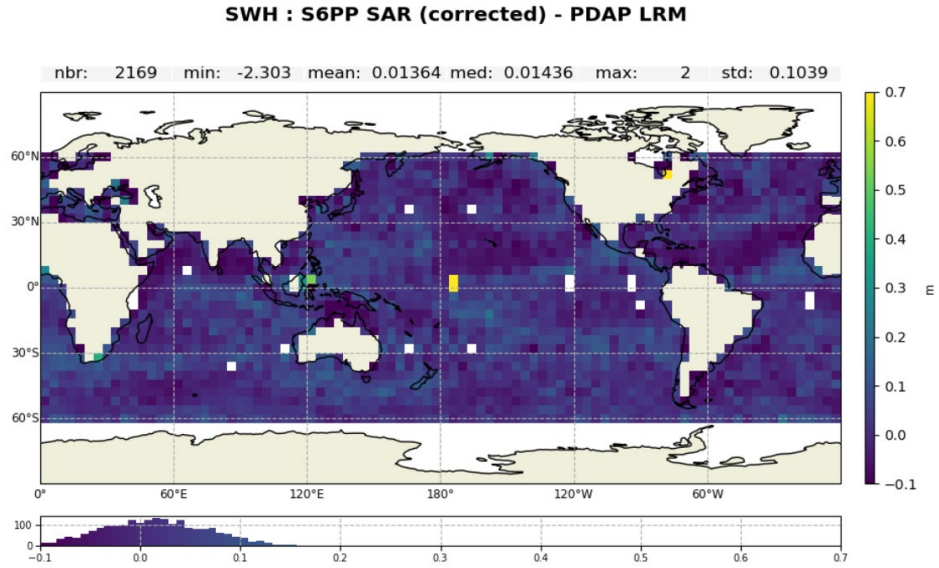
- We have been able to demonstrate that the discrepancies between the Sentinel-6/MF LR and HR SWH measurements can be attributed to the ocean waves' vertical motion.
- We have generated a look up table correction for the HR SWH measurements that depends on the LR SWH and mean wave period (from wave model).
- The application of this correction highly reduces the biases between the HR and LR SWH measurements and cleans up the SWH spectrum.
- Applying this correction is essential for the consistency of the HR and LR datasets.



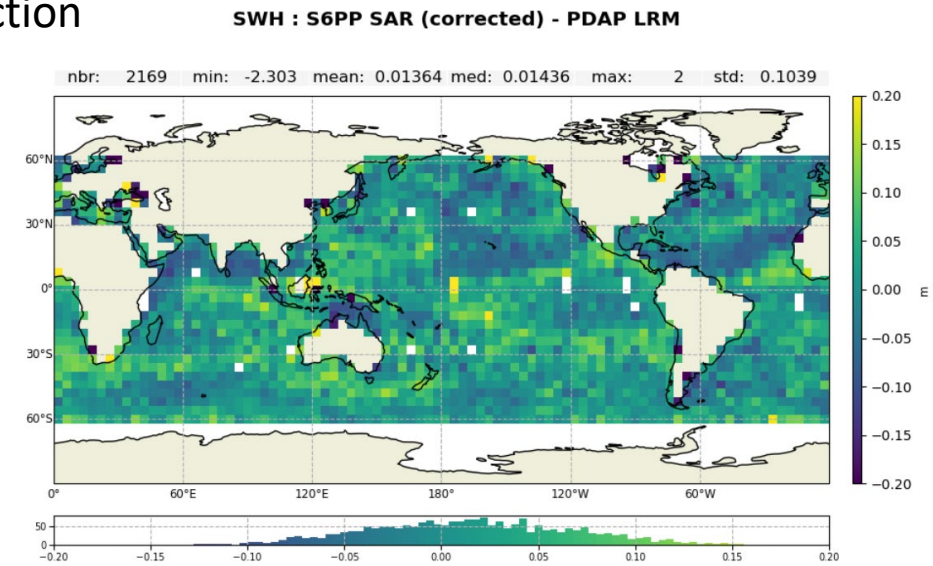
# SWH LUT Correction Assessment (CNES/CLS)




With NOAA Correction (same scale)




With NOAA Correction (scale change)



# Summary

- Despite pandemic, ground system, and amplifier issues, commissioning ended on a schedule established 4+ years ago
- Initial products mostly meet short-term requirements
  - STAR is advising end users to use Low-Rate products until HR issues resolved
- Major remaining issues have identified mitigations

# Next steps

- Tandem with Jason-3 has been extended to 31 to continue cal/val of the side-B altimeter
- Jason-3 will be move to an interleaved orbit starting mid-April; operations begin 1 May
- STAR working with OPC, NHC, NCEP, and Navy on inclusion of Sentinel-6 in operational products
- Full-mission reprocessing planned 2022 Q1
- Day-2 evolutions including NOAA's wave height correction planned to be effective 2022 Q4
- Sentinel-6B launch in 2025 with robust High-Power Amplifiers
  - NASA will select launch services soon

# Backup slides

# Instrument changes from Jason-3

**Poseidon 4** is an all digital radar altimeter that can operate in both High Rate (delay-Doppler) and Low Rate modes simultaneously (interleaved).

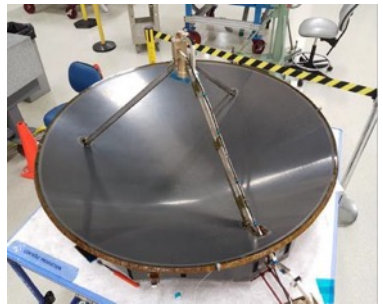
- Mostly backward compatible with Jason-3's pulse-limited low-rate mode on Poseidon 3B

The **Advanced Microwave Radiometer-C** (Climate) includes an external calibrator, a hot reference source.

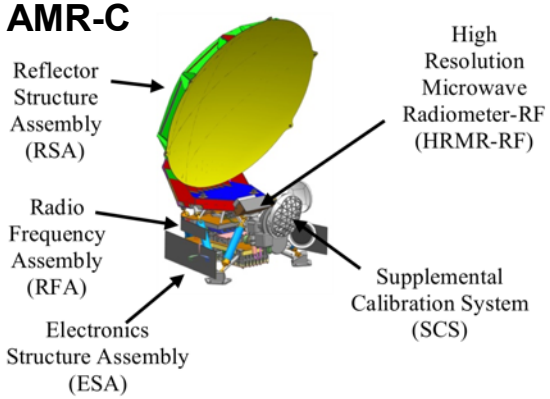
- New requirements on drift (0.7 mm/yr) are addressed in the design using a dedicated calibration pulse.
- AMR-C carries a 4th channel for coastal observations

**GNSS-RO** is a secondary mission to provide radio occultation observation services to meteorological users. The Sentinel-6 instrument is essentially the same as COSMIC-2, but will cover higher latitudes.

**Poseidon-4 Antenna FM1**



**AMR-C**




**GNSS-RO Antenna**