A global perspective on observational requirements for characterizing contemporary sea level rise and predictability

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The contents of this message are mine personally and do not necessarily reflect any position of NOAA.

Global mean sea level (GMSL) requirements

- Cazenave et al. OceanObs09 Community White Paper
  - Recommended a goal of measuring sea level from altimetry with <0.3 mm/year uncertainty (~10%) in GMSL.
- The sea level community desires a global record capable of detecting an acceleration
  - e.g. Is an increase in the rate of sea level rise from one 10-year period to the next significant?

THE CHALLENGE FOR MEASURING SEA LEVEL RISE AND REGIONAL AND GLOBAL TRENDS

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ABSTRACT

This Plenary Paper on sea level is based on several Community White Papers submitted to OceanObs09. Considerable progress has been realized during the past decade in measuring sea level change globally and regionally, and in understanding the climate-related causes of observed changes. We first review current knowledge about sea level change, globally and regionally. We summarize recent results from the 2007 IPCC 4th Assessment Report (AR4), as well as post-IPCC results relevant to sea level observations, causes and projections. New challenges are identified for the coming decade in terms of observations, modelling and impact studies. From these challenges, a number of recommendations emerge, which are listed below:

a) An accurate (at the <0.3 mm/yr level uncertainty), multi-decade-long sea level record by altimeter satellites of the T/P- Jason class is essential, as is continued funding of the altimeter science team to provide leadership. To meet the goal of 0.3 mm/yr or better in sea level rate accuracy, the global geodetic infrastructure needs to be maintained on the long-term; the Terrestrial Reference Frame must be accurate and stable at the 1 mm and 0.5 mm/yr level; radiometers required for the correction of radar path delays must also be stable (or calibrated) at 0.1 mm/year. A network of tide gauges with precise positioning (GPS (Global Positioning System), or more general, GNSS (Global Navigation Satellite Systems)) should be maintained with an emphasis on long record lengths and global spatial coverage (e.g., the GLOSS (Global Sea Level Observing System) Core Network plus additional stations with especially long record lengths).

b) Continuity of GRACE-type (Gravity Recovery and Climate Experiment) space gravimetry observations is critically needed. No other data exist to measure ocean mass changes directly. To avoid an undesirable gap in data record, a GRACE Stop-Gap mission should be undertaken by space agencies to continue the geophysical time series of the current GRACE mission. Meanwhile, new concept for improving precision and resolution need to be developed.

c) Improved accuracy for the Glacial Isostatic Adjustment (GIA) forward modelling that are needed to provide corrections for GRACE, tide gauges and satellite altimetry observations over ocean, land and ice-sheets should be made available. Specifically, the GIA community should be encouraged to perform intercomparison studies of GIA modelling, similar to what has been done for coupled climate model outputs. The goal should be to produce a global, spatially varying, community wide best-estimate of GIA and its uncertainty that is appropriate for application to global sea level studies.

d) Long-term maintenance of the Argo (Array for Real-time Geostrophic Oceanography) network in its optimal configuration is imperative for measuring ocean temperature and salinity; development of a shipboard CTD (Conductivity-Temperature-Depth) measurement program for absolute calibration of other in situ hydrographic data is critical to maintain the fidelity of other networks; reanalyses of historical temperature and salinity is strongly recommended; development of new methods/systems to estimate deep changes in ocean heat content and thermal expansion is needed.

e) High priority should be given to the development of integrated, multidisciplinary studies of present-day and last century sea level changes (global and regional), accounting for the various factors (climate change, ocean/atmosphere forcing, land hydrology change—both natural and anthropogenic, solid Earth processes, etc.) that act on a large variety of spatio-temporal scales. Improvement and validation of 2-dimensional

What can altimetry, GRACE, and Argo tell us?

The sea level budget may be expressed as height changes from the main components of sea level change:

$$\Delta SSH = \Delta SH + \Delta OM$$

SSH = sea surface height, SH = steric height, *OM* = ocean mass

The Argo core array measures temperature and salinity at depths of 2000db.

$$\Delta SH = \Delta SH_{(0\text{–}2000m)} + \Delta SH_{(2000m\text{–}\infty)}$$

Using more than a decade of Jason altimetry, GRACE, and Argo observations, we can estimate a residual from observations:

$$\Delta SL_{residual} = \Delta SSH - \Delta SH_{(0\text{–}2000m)} - \Delta OM$$

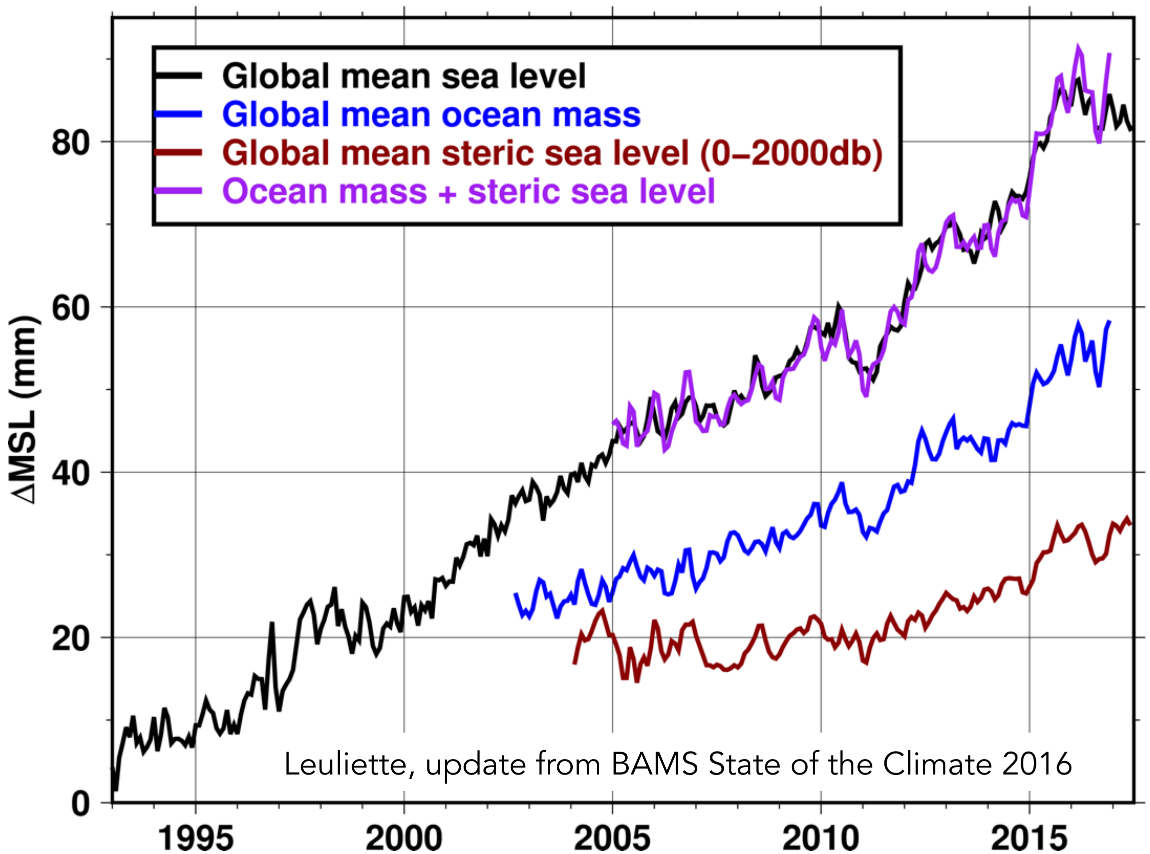
$$\Delta SL_{residual} = \Delta SH_{(2000m\text{–}\infty)} + Error$$

Sea level budget

Despite some gaps, the current observing system is able to close the global sea level budget

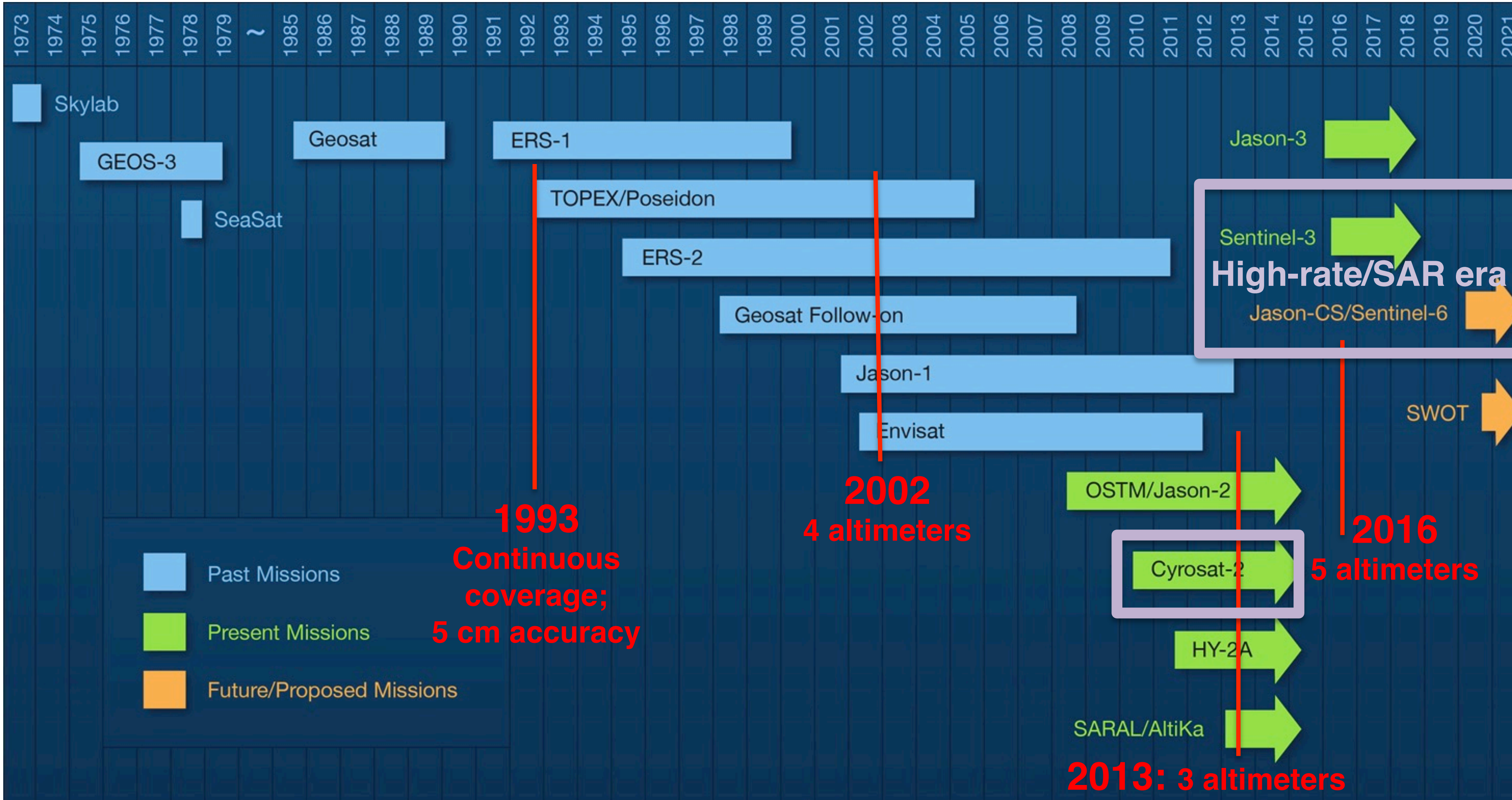
rms (>2 months) = ~ 2 mm

Drift = < 0.2 ± 0.5 mm/yr

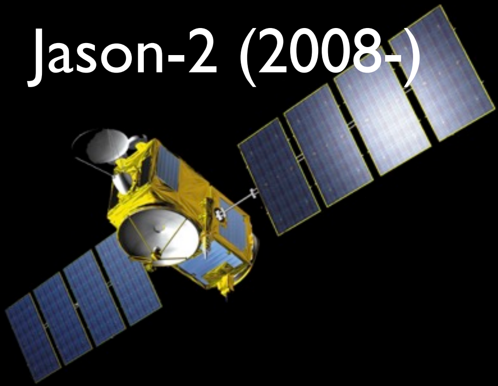


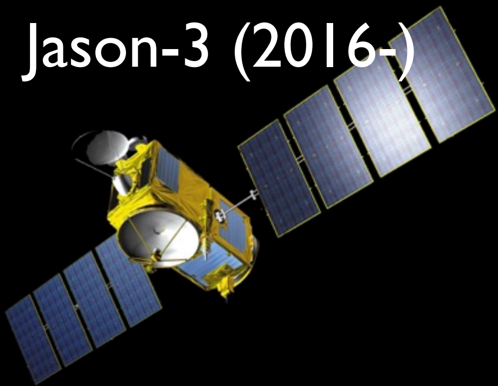
<u>Current community activity:</u> Global Sea Level Budget assessment and its link with the WCRP Grand Challenge on "Regional sea level and coastal impacts" (Cazenave)

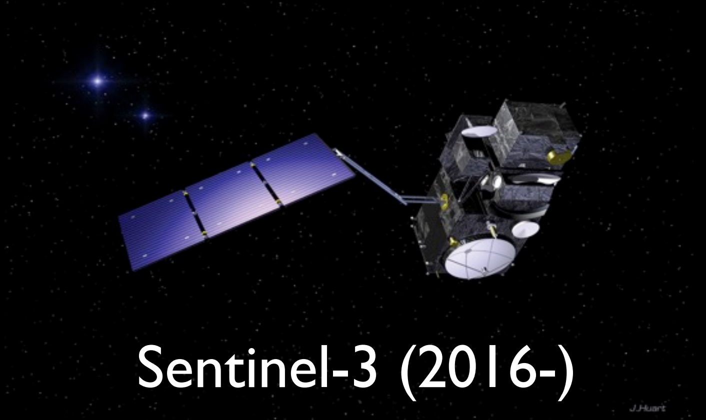
Past and present altimetry missions



Current altimeter missions





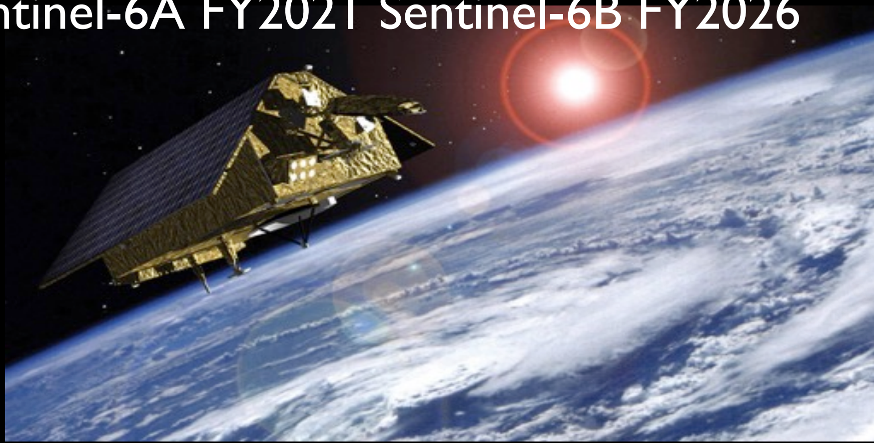


Current missions

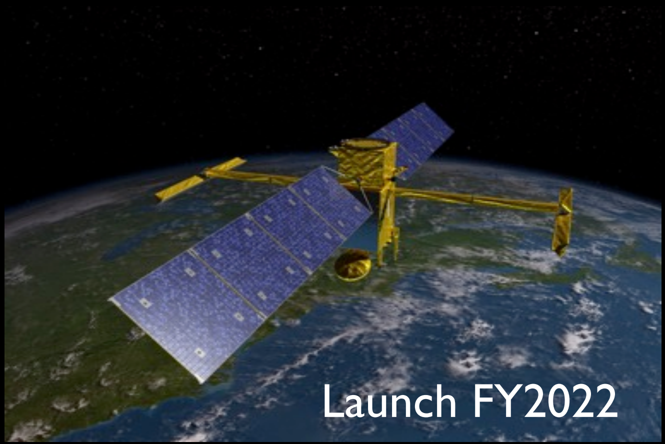
	Jason-2	CryoSat-2	AltiKa	Jason-3	Sentinel-3A/B
Launch	2008	2010	2013	2016	2016 (S3A), 2017 (S3B)
Altimeter	Poseidon-3	SIRAL-2	SARAL	Poseidon-3B	SRAL
Frequencies	Ku/C	Ku	Ka	Ku/C	Ku/C
Pulses	2kHz	2kHz/ 18kHz (SAR)	~4kHz	2kHz	18kHz (SAR)
Partners	CNES/NASA/ NOAA/ EUMETSAT	ESA	CNES/ ISRO	NOAA/ EUMETSAT CNES/NASA	ESA/ EUMETSAT
Inclination	66.1°	92.03°	98.55° Sun-sync	66.1°	98.65° Sun-sync
Repeat (days)	368; ~17 near-repeat	369	~35 (drift)	9.9	27 (~4 near repeat)

Future altimetry missions

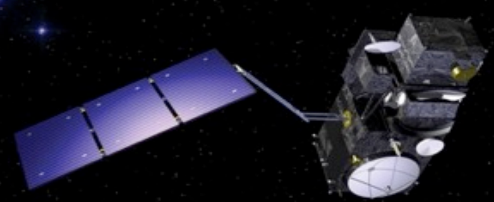
Jason-CS (NASA/NOAA/ESA/EUMETSAT/CNES)
Sentinel-6A FY2021 Sentinel-6B FY2026



SWOT (NASA/CNES)



Launch FY2022



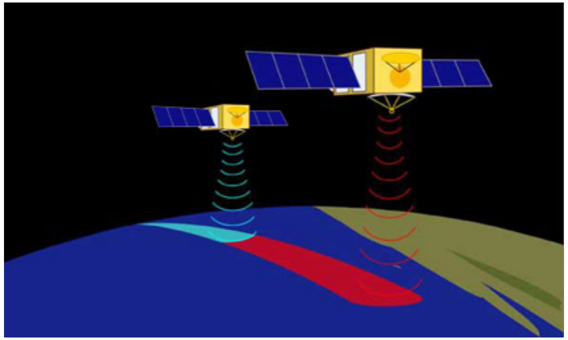
Sentinel-3B (2017-)
Sentinel-3C/D (2020s)

Cryosat FO (ESA)
(202?-)

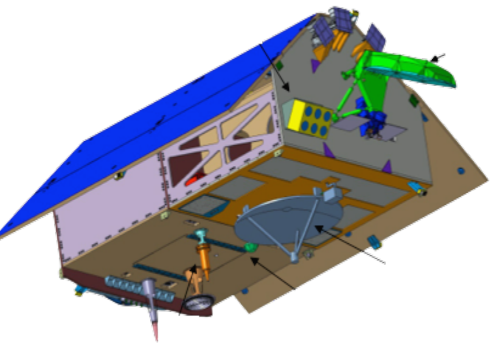
Reference series of altimeters: Jason

This series has an error budget and stability of measurements suitable for sea level change monitoring.

Uninterrupted series of missions in the same orbit. Three very successful "tandem" overlaps of 6 months with successor mission ~ 1 minute behind.



Jason-CS/Sentinel-6 2021 and 2026



SHORT DESCRIPTION

The Sentinel-6A/B mission is a U.S.-European cooperation involving NASA, the National Oceanic and Atmospheric Administration (NOAA), the European Space Agency (ESA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). It involves NASA-led U.S. participation in the development, launch, and on-orbit exploitation of two precision altimeter satellites for launch in FY 2021 and FY 2026, to measure sea-level as part of the European Copernicus system of Earth observing satellites. The 2016 President's Budget Request established a new framework in which NOAA is responsible for satellites that contribute directly to its weather and space weather missions, while NASA is responsible for other civil Earth-observing satellite missions. This resulted in the transfer of responsibility to NASA for ocean altimetry missions, including the Sentinel-6A and -6B satellites, beginning in 2016. Funds to implement the Administration proposal were appropriated by Congress in late December 2015. Accordingly, NASA inherited the Sentinel-6 acquisition strategy established prior to the transfer of responsibility from NOAA- as the previous lead agency for the U.S. - had developed in the context of the partnership with ESA and EUMETSAT. This implementation/acquisition/workshare strategy is codified in the Memorandum of Understanding (MOU) that is currently routing for approval with the partners. The acquisition scope and approach inherited by NASA entails two sets of instruments, one each for the Sentinel-6A and Sentinel-6B spacecraft, consisting of substantial rebuilds of the Advanced Microwave Radiometer – Climate Quality (AMR-C) from the OSTM/Jason-2, Jason-3, and the Surface Water and Ocean Topography (SWOT) missions; substantial rebuilds of the Global Navigation Satellite System for Radio Occultation (GNSS-RO) receiver from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)-2 mission with minor software updates, a 1553 interface, and radio occultation antennas adapted from the COSMIC-1 mission; and build-to-print copies of the Laser Retroreflector Array (LRA) from Jason-3. The NASA workshare/approach also includes provision of two intermediate class launch vehicles and services for the Sentinel-6A and Sentinel-6B spacecraft that will be competitively procured through standard NASA Launch Services Program (LSP) processes. JPL-FFRDC is the Implementing Center given its role on Sentinel-6 supporting NOAA on a reimbursable basis prior to the transfer of the project to NASA, and its expertise, involvement, and previous accomplishments for all previous NASA altimeter missions. Sentinel 6A is targeted for launch in FY 2021 and Sentinel 6B is targeted for launch in FY 2026.

HIGHLIGHTS OF KEY ACHIEVEMENTS PLANNED FOR FY 2017 – FY 2020

- Complete Key Decision Point C and establish Agency Baseline Commitment in FY 2017.

PARTNER OVERVIEW

- **NASA Center(s):** JPL-FFRDC
- **Federal Agencies:** NOAA
- **International:** European Space Agency (ESA), European Organisation for the Exploitation of Meteorological Satellites

Altimetry requirements: Jason reference series

The 10 February 2017 revision of the Sentinel-6 End-User Requirements Document (EURD) changed the global and regional sea level performance from requirements to goals.

- <1 mm/year for GMSL
- <5 mm/year along-track (new to Jason-CS)

[EURD] R-U-00540 T, A, R

Jason-CS shall monitor the stability of the global mean sea level measurements with a drift less than 1 mm/year (standard error).

Note: As a goal, Jason-CS will attempt to measure global mean sea level (as derived from ALT-NTC Level 2 products) with a drift error as defined in [GTA] of less than 1 mm/year.

Note: Global mean sea level measurements are those obtained by averaging the 1-Hz sea level measurements over any repeat cycle. As such this requirement constrains the relative standard error of those numbers to approximately 6 mm.

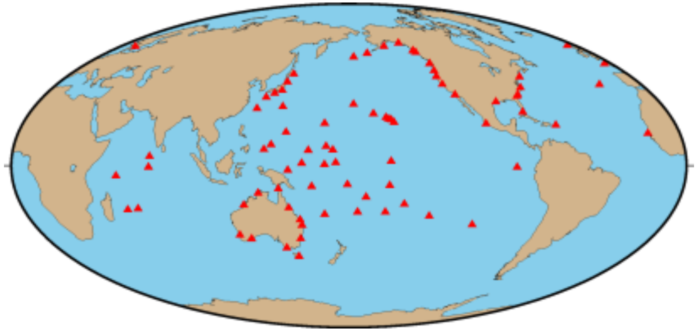
[EURD] R-U-00550 T, A, R

Jason-CS shall measure regionally averaged sea level (as derived from ALT-NTC Level 2 products) with a drift error as defined in [GTA] of less than 5 mm/year.

Note: With "regionally averaged sea level" we mean: the average of all sea level measurements within one repeat cycle within an ocean area of approximately 40000 km^2.

Note: Assuming that we are able to correct for all recognized significant systematic effects and given that for NTC products, the combined standard uncertainty (precision) of the 1-Hz sea surface height measurements will be less than 3.2 cm during the whole operational period, we have an implicit local/regional drift requirement of about 3.5 cm in 7 years.

<u>Jason-3 Requirement:</u> SYS-R-965: Accuracy of globally averaged sea level relative to levels established during the cal/val phase will be verified by comparison with no less than 50 tide gauges that provide the widest possible geographic coverage.



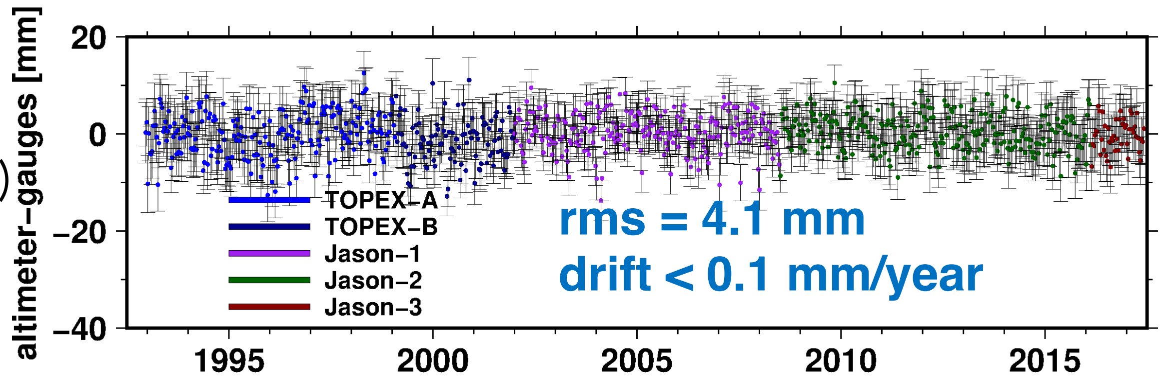
Tide gauge (TG) comparisons

Comparing the 25-year TOPEX/Jason series with the global tide gauge network shows an insignificant drift (–0.02 mm/year) [Beckley, Ray, Hancock, Mitchum 2017 in review].

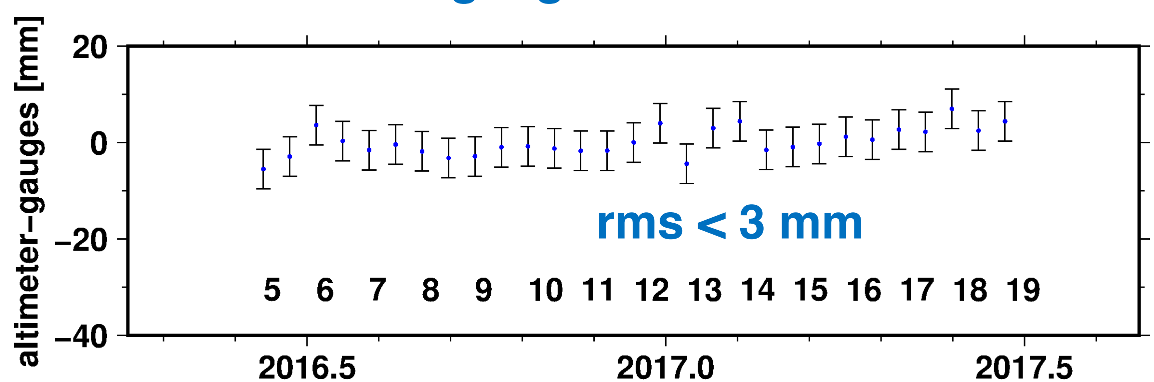
The residuals imply that the tide gauge network is capable of determining drifts to 0.7 to 0.9 mm/year (standard error).

However, Sentinel-3A – TG residuals suggest that high-rate altimetry is significantly less noisy. Jason-CS – TG drifts may be bound by < 0.5 mm/year.

Reference series vs tide gauges



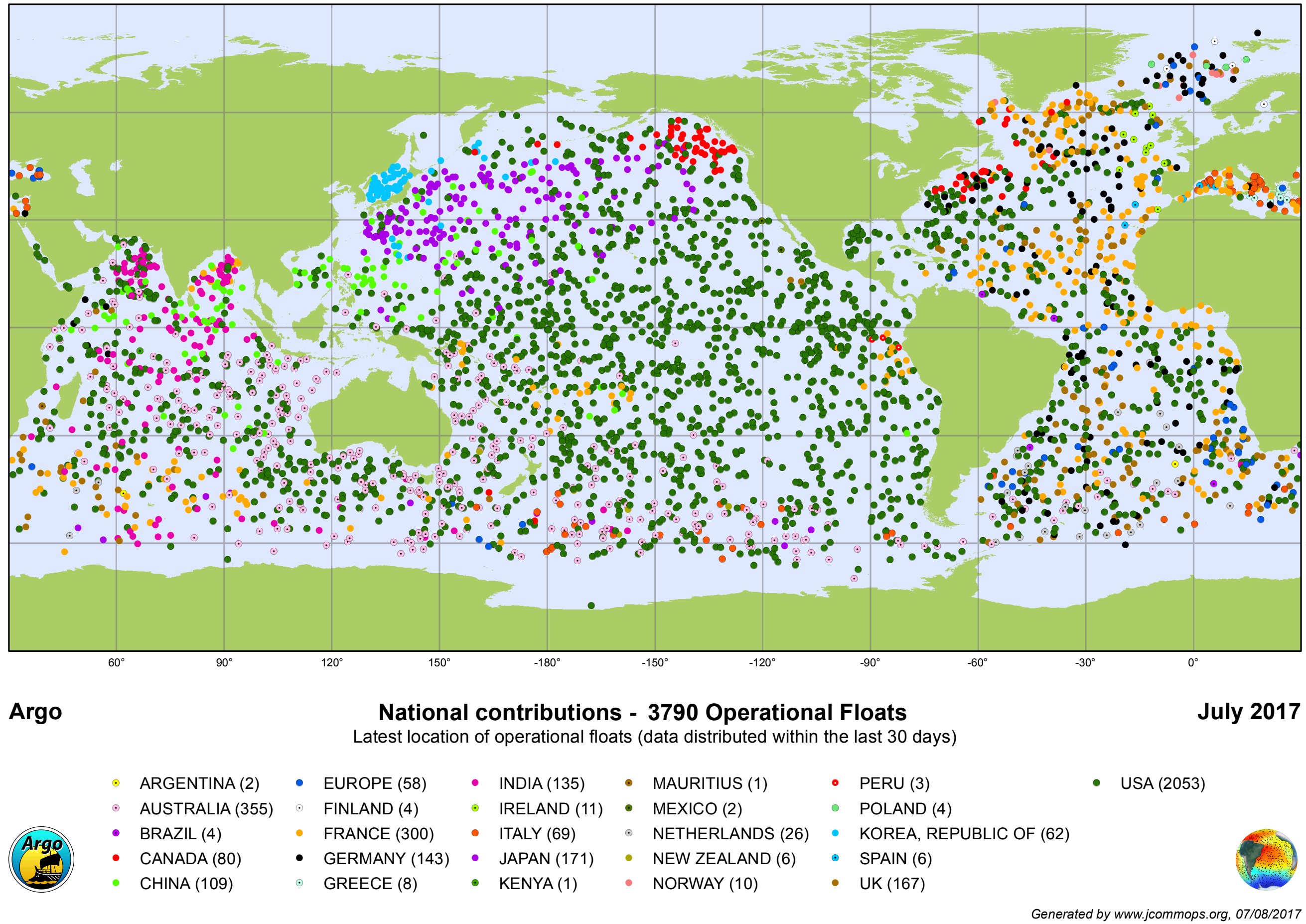
Sentinel-3A vs tide gauges



The Argo core array

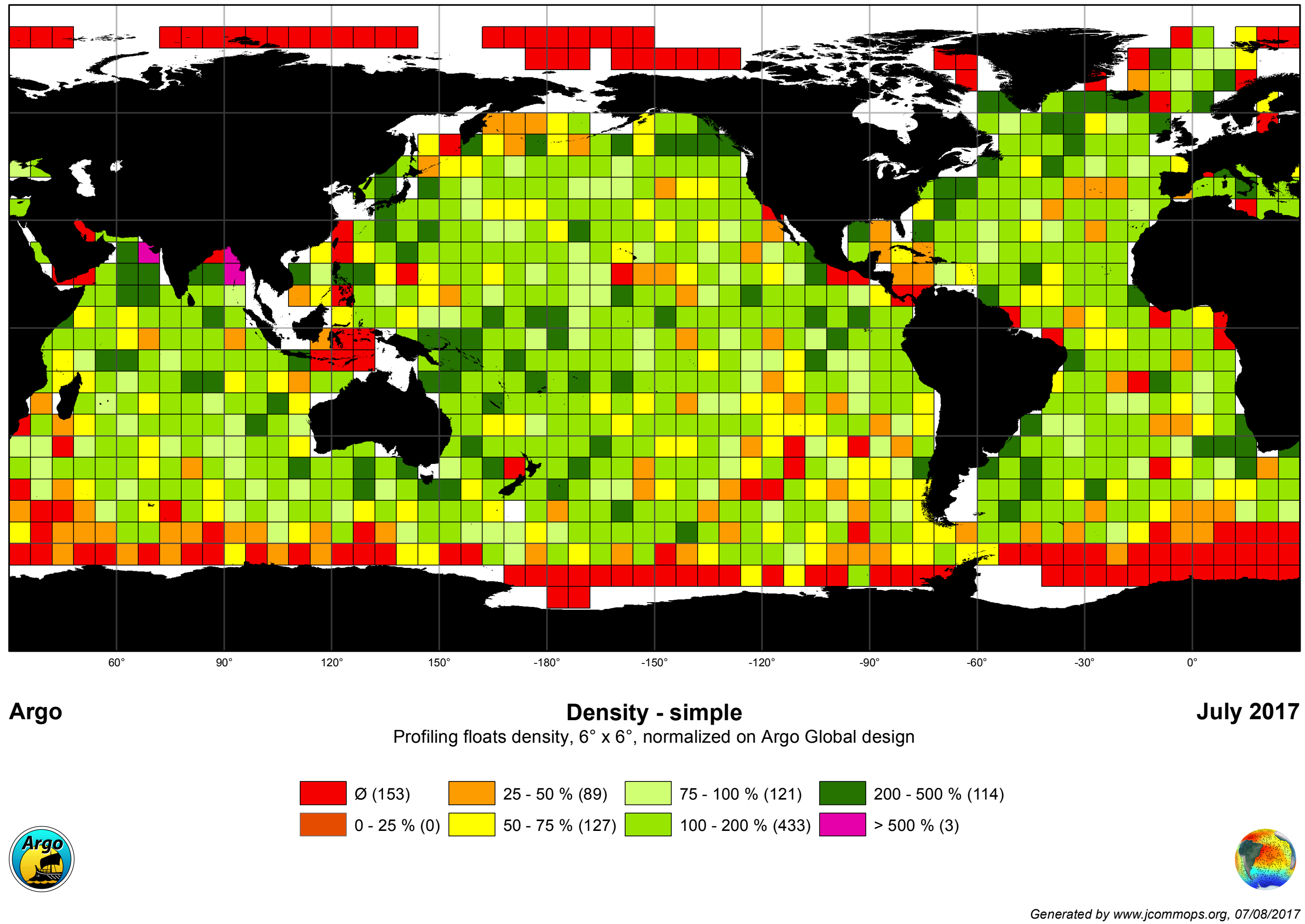
Thanks to improved float lifetimes, the Argo core array has achieved coverage of T,S to 2000db greater than 3°x3°.

The US contribution to the current array is over 50%.



The Argo core array: gaps

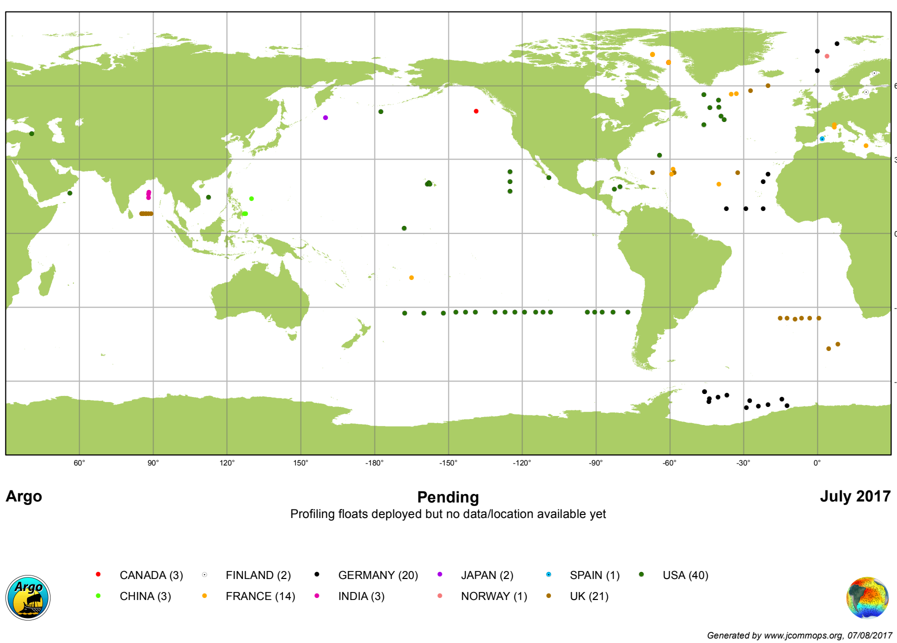
Current gaps in the coverage of the Argo core array are primarily in the Arctic and the South Atlantic.

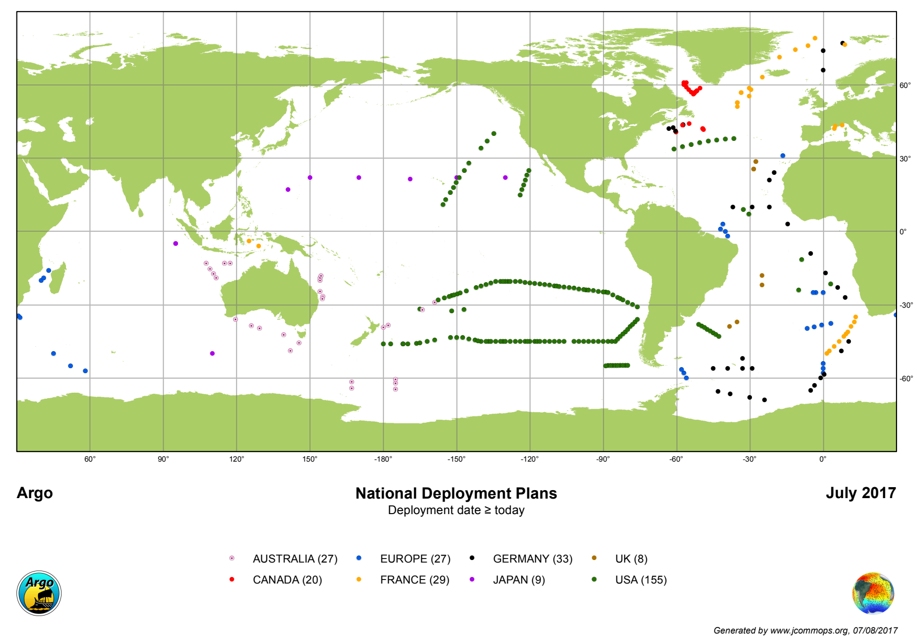


Argo core array gaps: deployments

Pending and planned deployments will address the south Atlantic gaps.

Southern Ocean Carbon and Climate Observations and Modeling Project (SOCCOM) floats will also close the coverage gap.



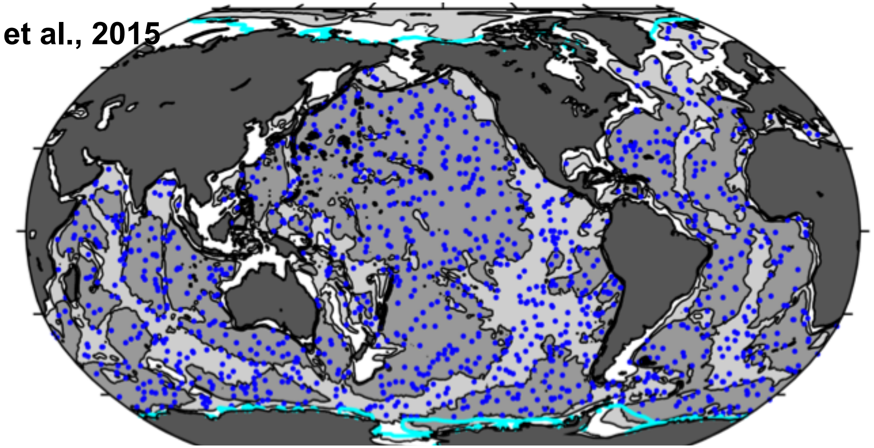


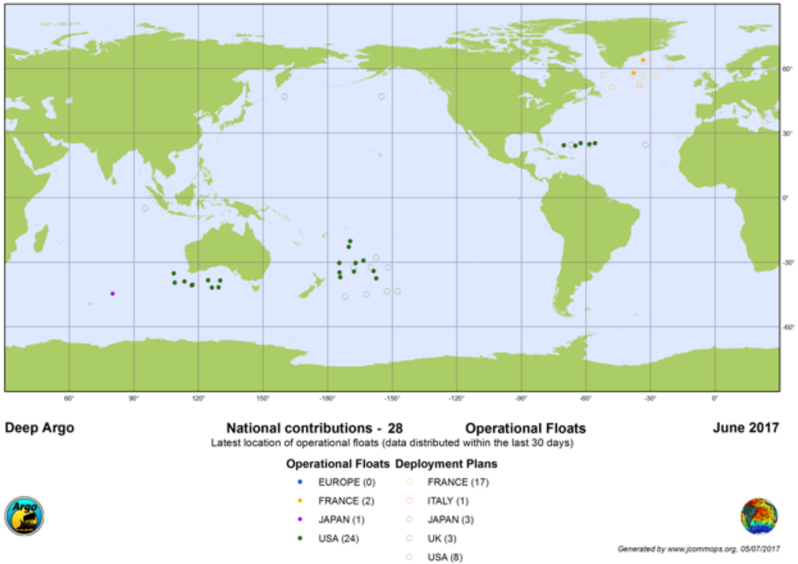
Deep Argo straw plan and current deployments

Deep Argo straw plan

- Sample to the ocean bottom (6000 m)
- 5° x 5° spacing: ~1200 floats
- Resolve abyssal decadal signals locally (not just globally)
- Increase the accuracy of global heat budget and sea level budget
- Measure circulation changes in the deep-ocean
- Start at high latitudes (deep-ocean warming signal) -> equator -> global

Johnson et al., 2015

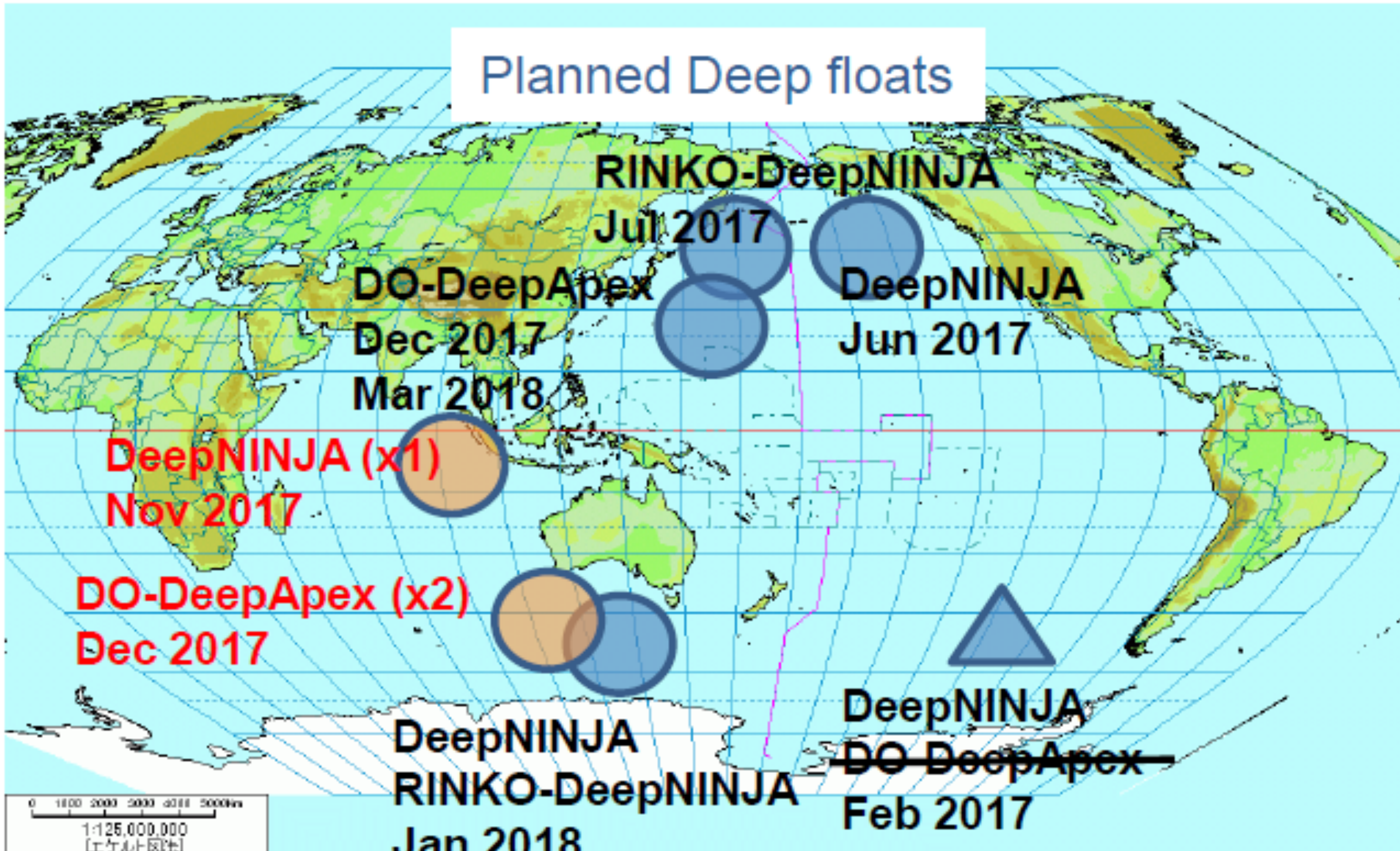




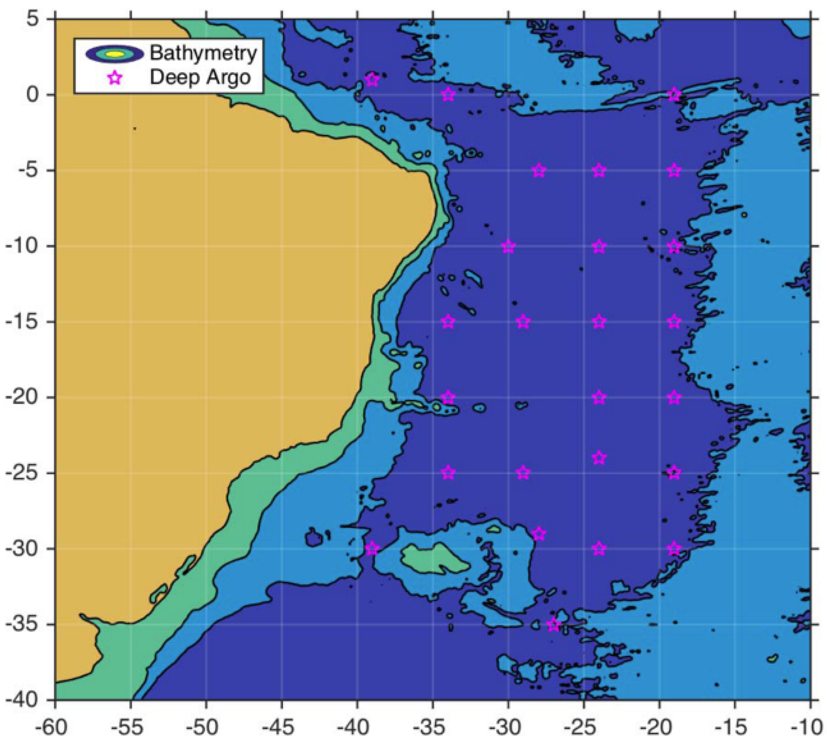
Planned Deep Argo floats

Several near-term pilot deployments and ramp ups. (Talk by Johnson tomorrow)

The US government contribution to Deep Argo will deploy 10-12 floats/year.



Atlantic Deep pilot array



North-Atlantic Deep pilot array (52)

Program	Funding	Scientific project	Float type and numbers	Deployment	Region
Argo-France	NAOS V. Thierry	OVIDE, RREX, OSNAP	16 Deep-Arvor	2017 and 2018	Subpolar gyre (Maybe 3 in Southern Ocean)
Euro-Argo	AtlantOS	OVIDE, RREX, OSNAP, others	7 Deep-Arvor	2017 and 2018	North-Atlantic
Argo-France	CPER Euro-Argo (Brittany)	OVIDE, RREX, OSNAP	15 Deep-Arvor/year (5 years)	2018-2022	North-Atlantic
Argo-UK		OSNAP, RAPID, ?	8 Deep-APEX O2	2017	?
Argo-US	Deep-Argo SIO		6 Deep-SOLOS	2017	Rapid Line at 26° N

Gravity Recovery and Climate Experiment

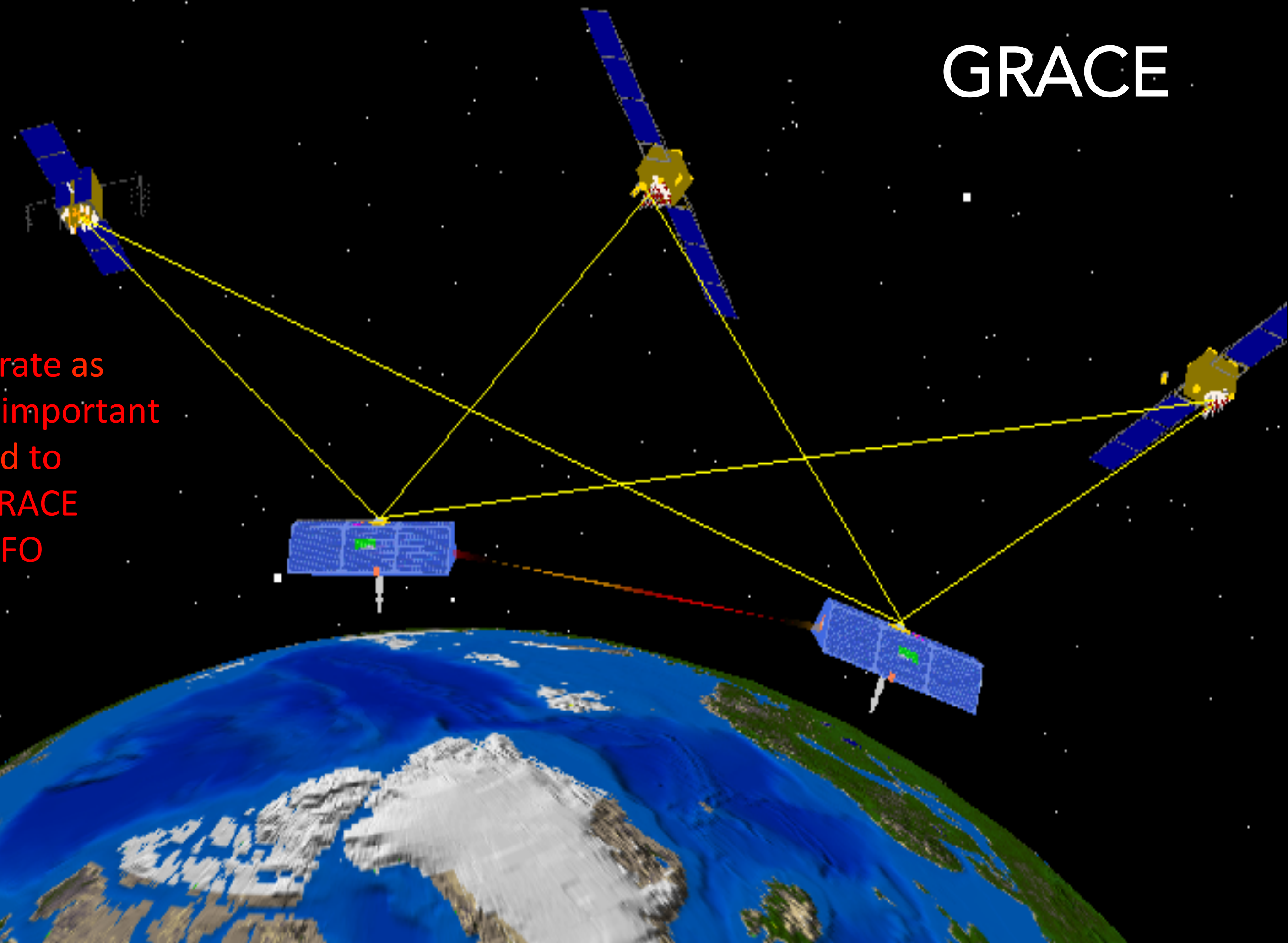
Launched: March 17, 2002

On-orbit life is 15.3 years)

Initial altitude: 485 km

Current altitude: ~ 325.4 km (-69 m/d)

Operations Challenge: Operate as long as possible to support important on-going data utilization and to ensure connection of the GRACE science record with GRACE FO

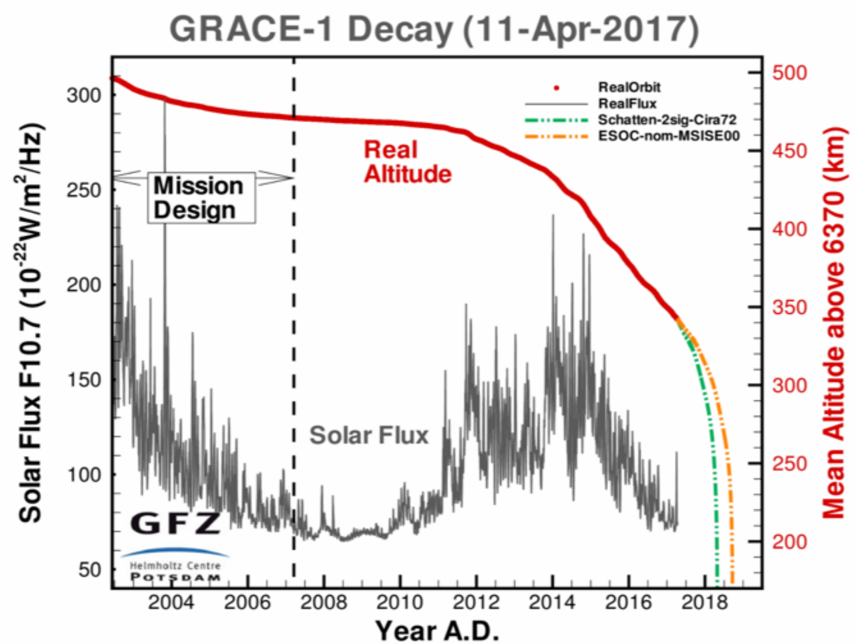


Current GRACE Mission Status

Mission Status:

Starting in November 2016 one GRACE satellite lost onboard accelerometers and gravity solutions are being made using the accelerometers on only one of the spacecraft.

This has increased the error on global ocean mass estimates by an unknown amount.



Mission Lifetime Issues:

Altitude Decay: Drag estimates predict lifetime until May 2018

Battery Capacity: Uncertain, but current strategy projects possible peration through 2017.

Propellant for Attitude Control: Projections estimate operations until June 2018

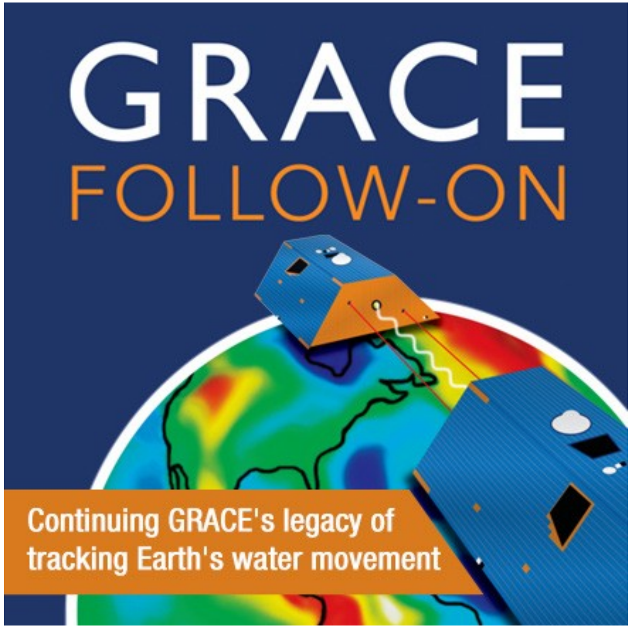
Single String Instrument Failures: Could end the nominal mission at any point

Status of GRACE Follow-on

To continue measuring time-variable gravity, a GRACE Follow-on mission is scheduled for launch in early 2018, again with a nominal 5-year lifetime.

It is primarily a duplicate of GRACE, with evolved versions of the GRACE K/Ka-band microwave interferometer, GPS, and accelerometers.

A secondary objective is to demonstrate the effectiveness of a laser ranging interferometer (LRI) in improving measurement performance.



- Laser-ranging could improve the accuracy of mass measurements
- Increased spatial resolution for future gravity missions remains a challenge
- To prevent gap with GRACE-FO, GRACE-II planning will need to begin soon

Key points: current status

- The current and planned observing system appears to be capable of continuing to monitor and characterize sea level rise.
  - The altimetry constellation has redundancy
  - Under the FY18 budget US Argo can maintain an array of 1,500 Argo core floats through 2021, possibly into 2022 if lifetimes continue to improve.
  - Deep Argo is progressing, addressing the largest gap in heat content monitoring
  - GRACE-FO is on schedule to minimize a gap with GRACE
- Closure of the sea level budget and the tide gauge network are the best sources of verification of the observing system.
  - Very few US gauges need GNSS receivers to monitor vertical land motion

Key points: Gaps

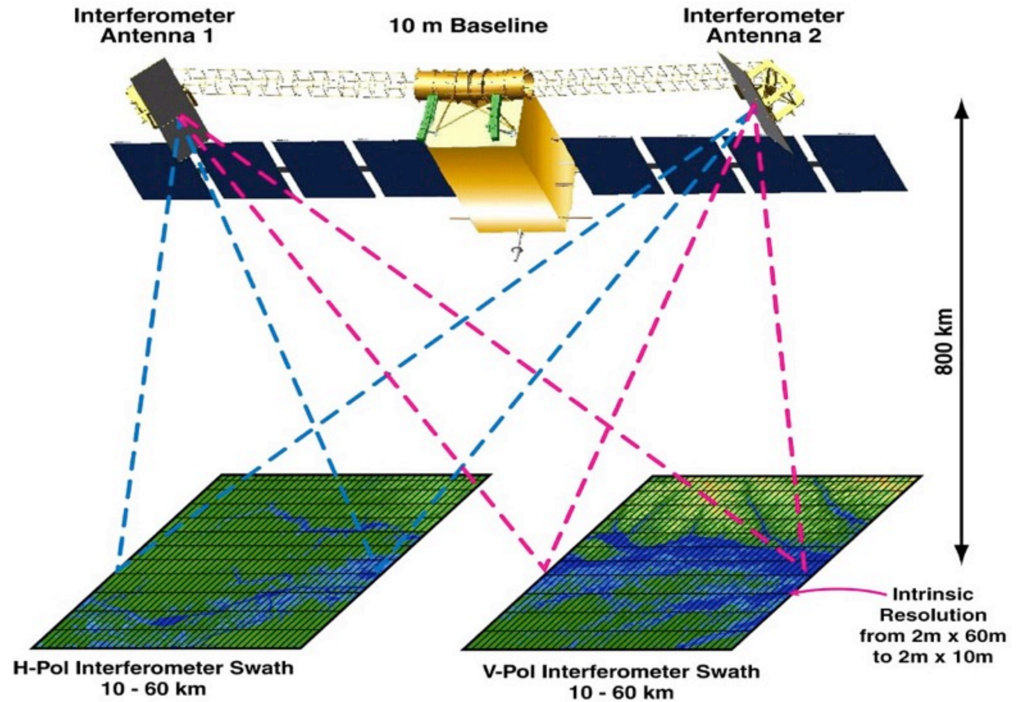
- Some gaps remain unaddressed
  - Monitoring the Arctic Ocean with Argo and altimetry is inadequate to complete global coverage of sea level rise
  - The pace of US Deep Argo deployments may have to be increased to achieve 5x5 coverage
  - GRACE-FO represents a potential single-point failure for mass monitoring; GRACE-II planning needs to begin soon
  - GLOSS network needs to be maintained
  - Long-term support of the reference frame, particularly for satellite laser ranging, is needed

Additional slides

SWOT (FY2022)

SWOT is the Surface Water and Ocean Topography mission, employing KaRIN, a Ka-band [SAR] Radar Interferometer. The mission costs are shared by NASA and CNES. It aims for a FY2022 launch.

It will also carry a conventional Ku nadir altimeter.

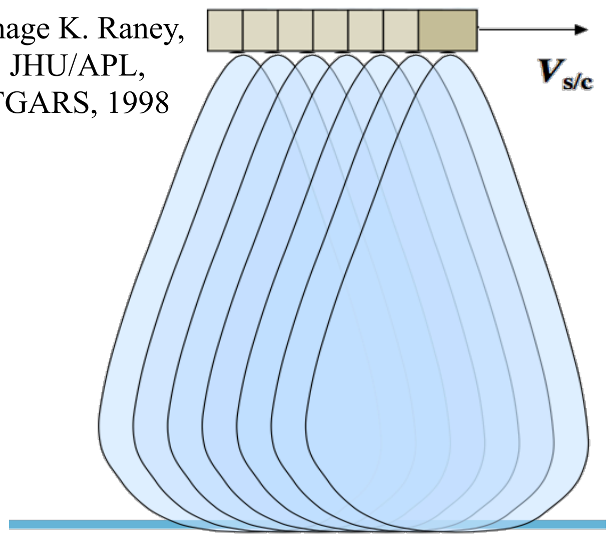


The main technological challenge is the interferometer antenna system, which must be collapsed during launch, then deployed on orbit, after which it must remain sufficiently rigid, and its position sufficiently well-known, to support cross-track phase interferometry and along-track focused Doppler beam sharpening. NOAA/STAR work with fully-focused altimetry has demonstrated that 20 dB SNR (operational altimetry standard) requires knowledge of pulse-to-pulse antenna motion to better than 0.1 mm, and this is at Ku band. At Ka-band the requirement is 3x more stringent, so SWOT's antenna motion must be known to 30 microns!

From Conventional to Focused SAR Altimetry

Conventional Altimeter

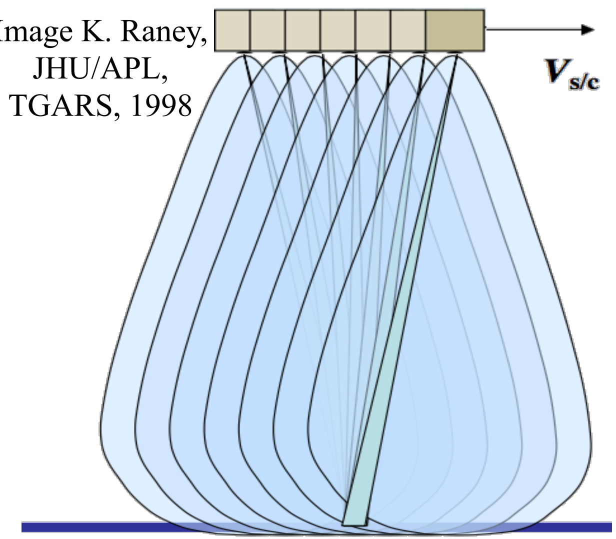
Image K. Raney, JHU/APL, TGARS, 1998



- Low Resolution Mode
- Pulse limited footprint (circular)
- 1.5 / 5 km resolution depending on SWH
- Open burst operation
- PRF ~ 2 kHz

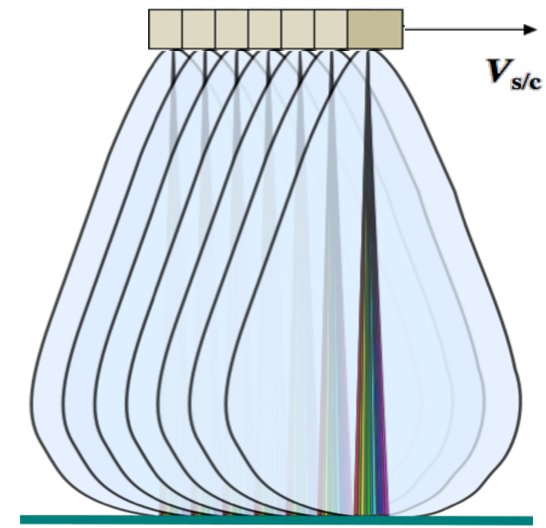
Delay-Doppler Altimeter

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



- Unfocused SAR processing
- ~300 m resolution Along-Track
- Pulse limited across-track
- Closed Burst
- PRF ~ 18 KHz

Focused SAR Altimeter



- Fully Focused SAR processing
  Coherent processing for ~2 seconds
- Resolution Along-Track ~0.5m
- Pulse limited across-track
- Closed Burst
- PRF ~ 18 KHz

Walter Smith and Alejandro Egido