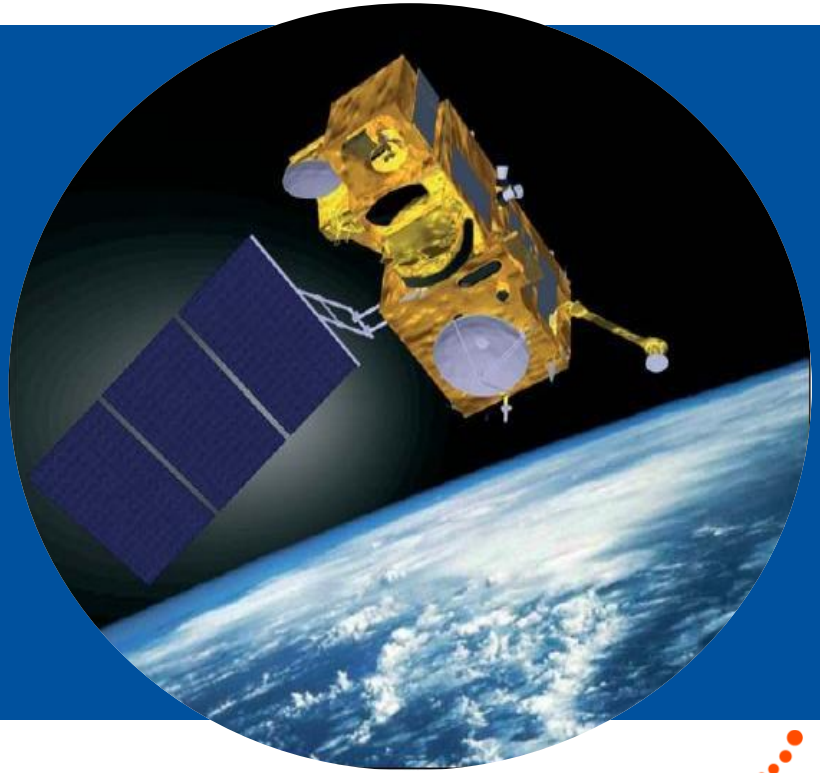
University of Stuttgart
Institute of Geodesy

Satellite altimetry



MJ Tourian

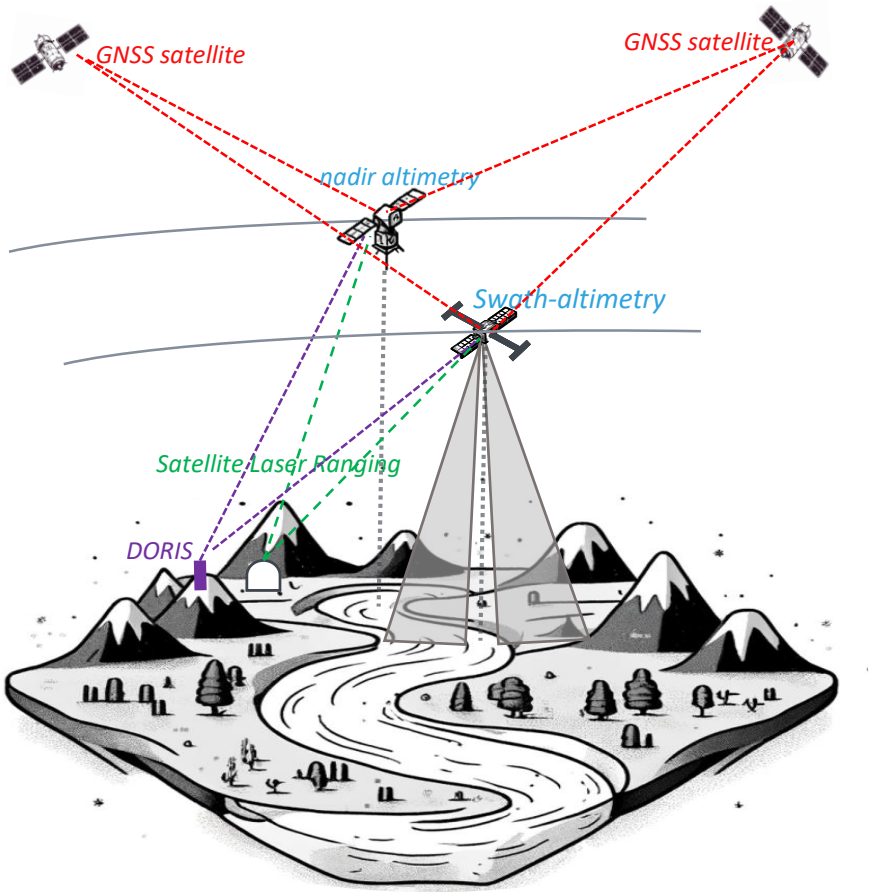
ESA Land Training Course, 2026

GIS

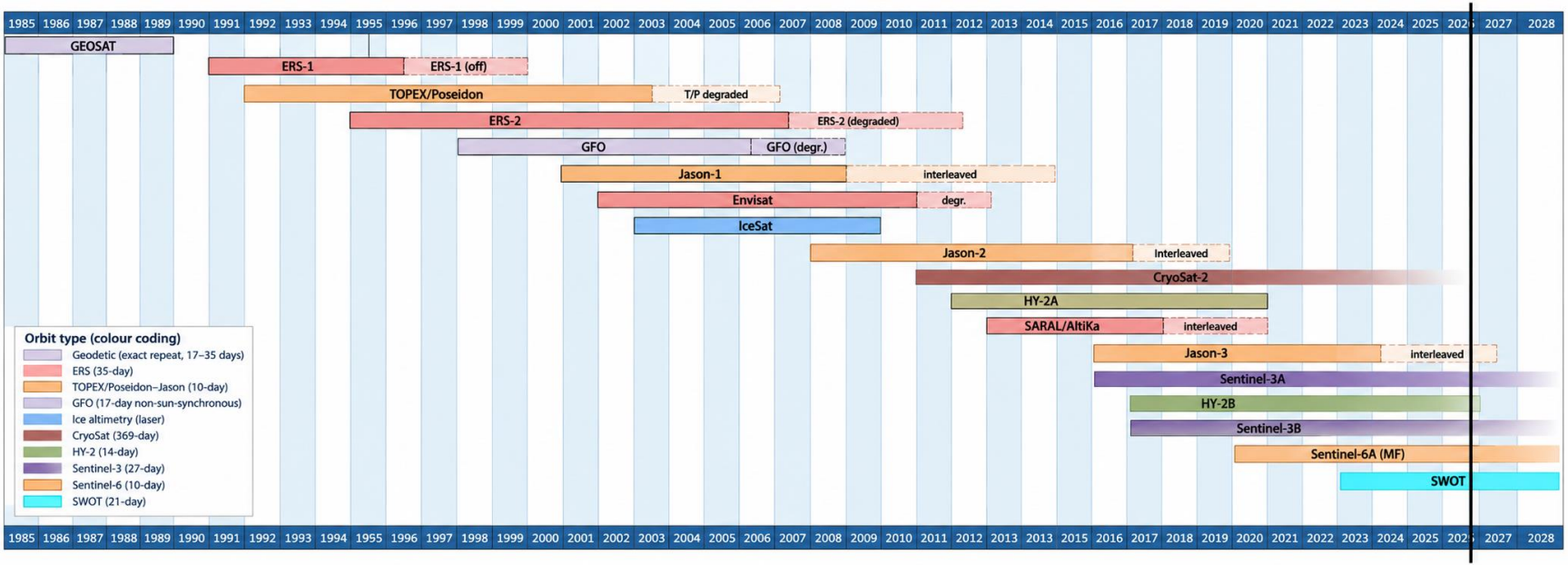


Image source: Lobsang (2016), *The Land of Snows*, "Nyenbo Yurtse Trek," accessed 6 September 2026. Nyenbo Yurtse Trek – The Land of Snows

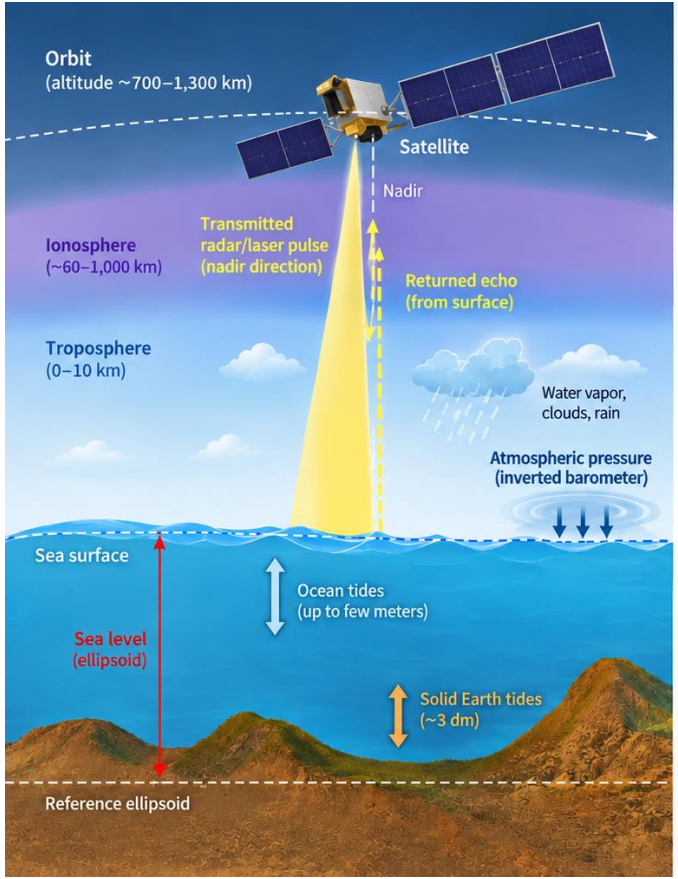
Satellite altimetry for monitoring water surfaces



Satellite altimetry



Correction and error budget, ocean surfaces



1 Orbit error (radial component) — **< 1 dm**

Uncertainty in the satellite orbit (radial direction).

2 Instrumental effects — **typically < 1 dm**

- Electronic time delay
- Clock (oscillator) drift
- Offset of antenna phase centre
- Centre of gravity (satellite attitude)
- Time tagging of observations
- Doppler shift error

3 Atmospheric refraction (signal delay)

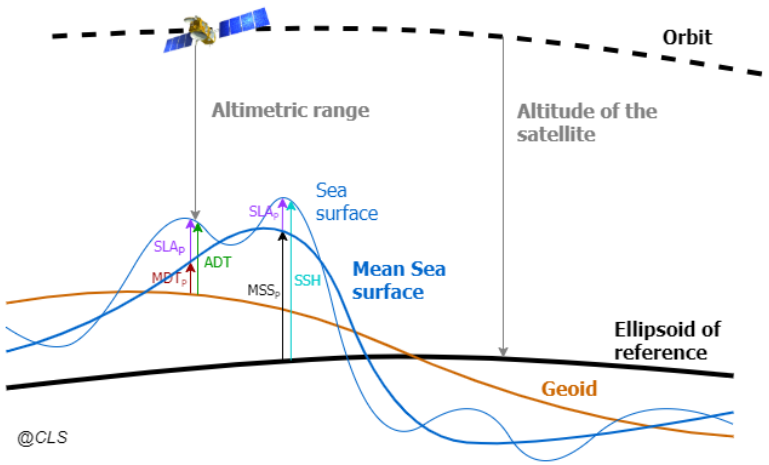
Ionosphere	~ 3–5 cm
Troposphere (dry component)	~ 2.3 m
Troposphere (wet component: water vapor, clouds, rain)	~ 3–45 cm

4 Target / geophysical effects (ocean surface)

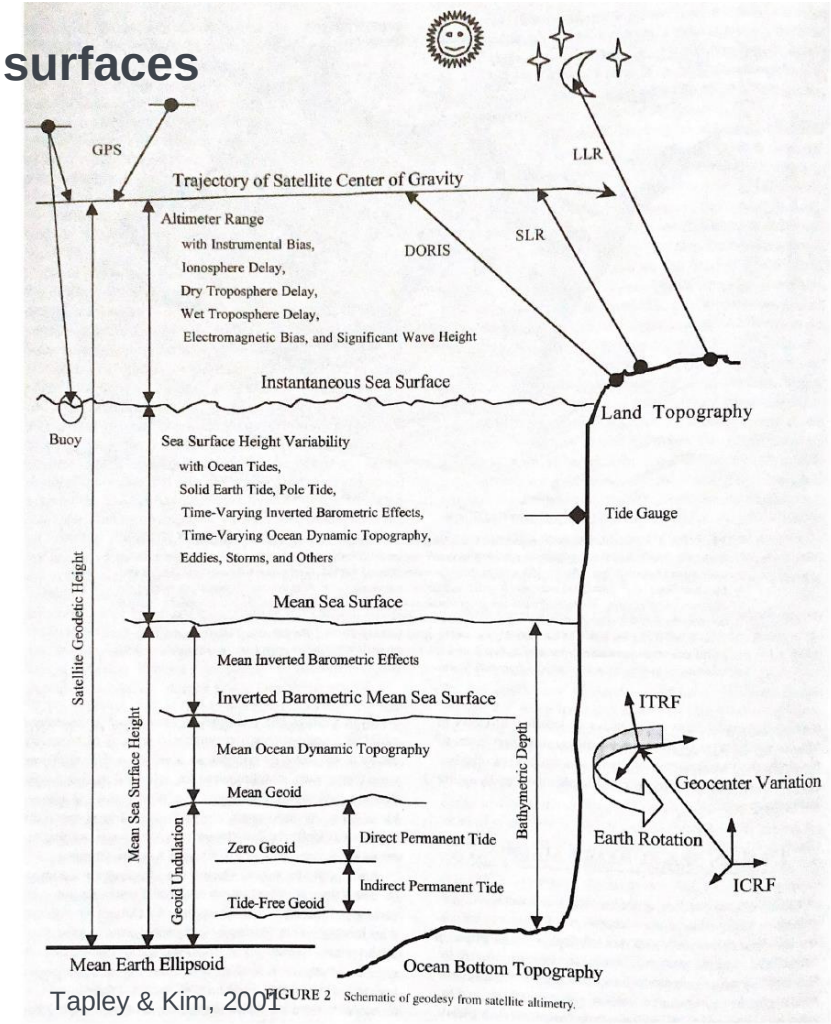
Ocean tides (astronomical)	up to few meters
Solid Earth tides	~ 3 dm
Pole tide	~ 1 cm
Ocean loading (non-tidal)	~ 10% of sea level height
Ocean electromagnetic bias (sea state, waves)	~ 5% of sea level height
Inverted barometer effect (atmospheric pressure)	up to 3 dm

➡ **Correcting for all these effects yields the sea level**
(relative to a reference ellipsoid)

Correction and error budget, ocean surfaces



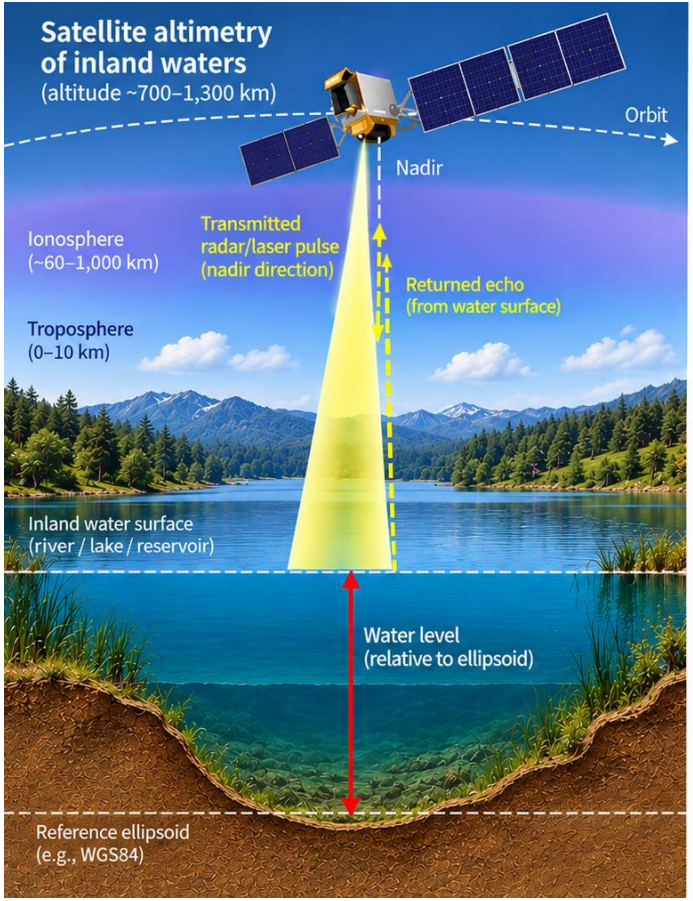
SSH: Sea Surface Height
SLAp: Sea Level Anomaly compared to the mean situation over the period P
MSSp: Mean Sea Surface representative of the period P
ADT: Absolute Dynamic Topography
MDTp: Mean Dynamic Topography representative of the period P



Tapley & Kim, 2001

FIGURE 2 Schematic of geodesy from satellite altimetry.

Correction and error budget, inland water surfaces



		Typical magnitude
1	**Orbit error (radial component)** • Uncertainty in the satellite orbit (radial direction)	**< 1 dm**
2	**Instrumental effects** • Electronic time delay • Clock (oscillator) drift • Offset of antenna phase centre • Centre of gravity (satellite attitude) • Time tagging of observations • Doppler shift error	**< 1 dm**
3	**Atmospheric refraction (signal delay)**	
	• Ionosphere	~ 3–5 cm
	• Troposphere (dry component)	~ 2.3 m
	• Troposphere (wet component: water vapor, clouds, rain)	~ 3–45 cm
4	**Geophysical effects (inland waters)**	
	• Solid Earth tides	~ 3 dm
	• Pole tide	~ 0.1–1 cm
	• Loading effects (atmospheric, hydrological)	~ 1–5 cm

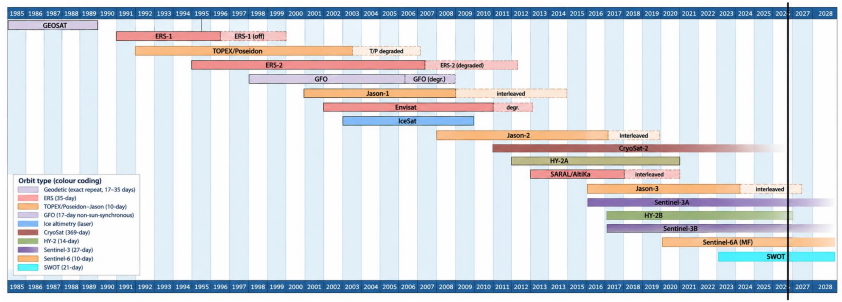
After correcting for these effects, we obtain the inland water level
(relative to a reference ellipsoid, e.g., WGS84)

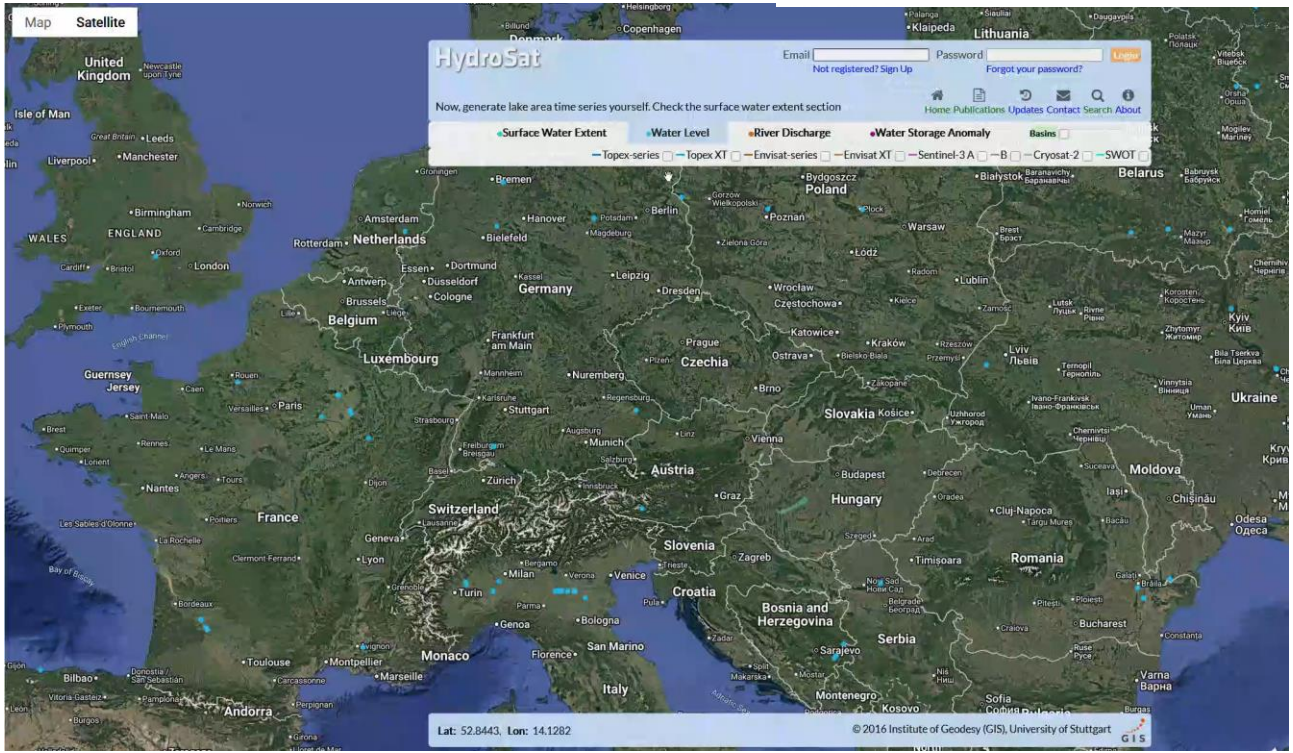
Nadir altimetry

Altimetry missions from 1985

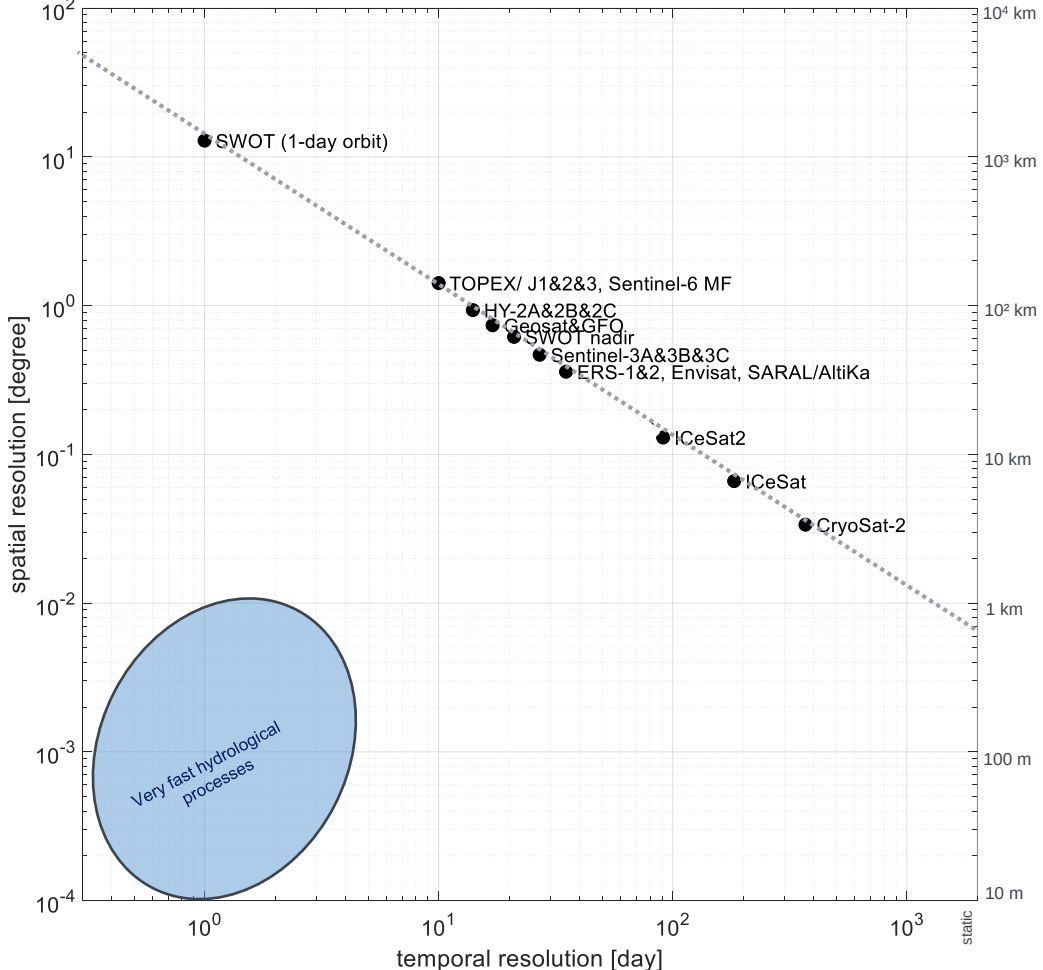
Mission	Operated by	Lifetime / data period	Height [km]	Incl. [°]	Rev. / repeat [days]	Altimeter / mode	OLTC	Frequency
Geosat	US Navy / NOAA	03.1985–09.1989	785	108.0	244 / 17	LRM	—	Ku: 13.5 GHz
ERS-1	ESA	07.1991–03.1996	785	98.5	501 / 35[1]	LRM	—	Ku: 13.8 GHz
TOPEX/Poseidon	CNES / NASA	09.1992–01.2006	1,336	66.0	127 / 10	LRM	—	Ku/C: 13.6 / 5.3 GHz
ERS-2	ESA	04.1995–09.2011	785	98.5	501 / 35	LRM	—	Ku: 13.8 GHz
GFO	US Navy / NOAA	02.1998–11.2008	~800	108.0	244 / 17	LRM	—	Ku: 13.5 GHz
Jason-1	CNES / NASA	12.2001–06.2013	1,336	66.0	127 / 10	LRM	—	Ku/C: 13.6 / 5.3 GHz
Envisat	ESA	03.2002–04.2012	~800	98.5	501 / 35	LRM	—	Ku/S: 13.575 / 3.2 GHz
ICESat	NASA	2003–2009	~600	94.0	2,723 / 183[2]	**Laser**	n/a	1064 / 532 nm
Jason-2 / OSTM	CNES / NASA / NOAA / EUMETSAT	06.2008–10.2019	1,336	66.0	127 / 10	LRM	✓[3]	Ku/C: 13.575 / 5.3 GHz
CryoSat-2	ESA	04.2010–present	~719	92.0	5,344 / 369	**LRM / SAR / SARIn**	—[4]	Ku: 13.575 GHz
HY-2A	CNSA / NSOAS	08.2011–2020	~971	99.3	193 / 14	LRM	—	Ku/C: 13.58 / 5.25 GHz
SARAL/AltiKa	ISRO / CNES	02.2013–present[5]	~800	98.55	501 / 35[5]	LRM	✓[3]	Ka: 35.75 GHz
Jason-3	CNES / NASA / NOAA / EUMETSAT	01.2016–present	1,336	66.0	127 / 10	LRM	✓	Ku/C: 13.575 / 5.3 GHz
Sentinel-3A	ESA / EUMETSAT	02.2016–present	~815	98.65	385 / 27	**SAR**	✓	Ku/C: 13.575 / 5.41 GHz
Sentinel-3B	ESA / EUMETSAT	04.2018–present	~815	98.65	385 / 27	**SAR**	✓	Ku/C: 13.575 / 5.41 GHz
ICESat-2	NASA	10.2018–present	~496	92.0	1,387 / 91	**Photon-counting laser**	n/a	532 nm
HY-2B	CNSA / NSOAS	10.2018–present	~971	99.3	193 / 14	LRM	—	Ku/C: 13.58 / 5.25 GHz
Sentinel-6 Michael Freilich	EUMETSAT / ESA / NASA / NOAA / CNES	11.2020–present	1,336	66.0	127 / 10	**SAR (HR) + LRM**	✓	Ku/C: 13.575 / 5.41 GHz
SWOT	NASA / CNES / CSA / UKSA	12.2022–present[6]	~891	77.6	292 / 21	KaRIn + **LRM nadir**	✓[7]	Ka: 35.75 GHz; Ku/C nadir: 13.575 / 5.3 GHz
Sentinel-6B	EUMETSAT / ESA / NASA / NOAA / CNES	11.2025–present	1,336	66.0	127 / 10	**SAR (HR) + LRM**	✓	Ku/C: 13.575 / 5.41 GHz

Nadir altimetry

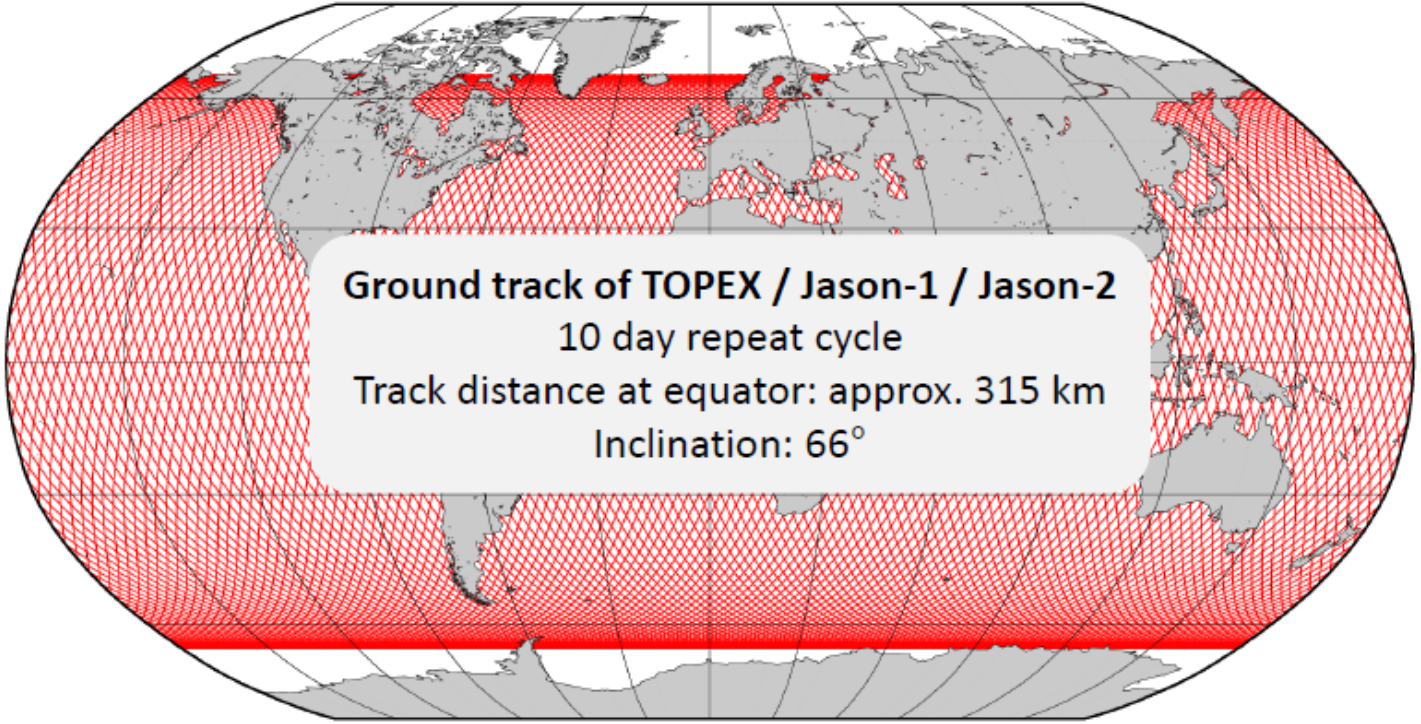




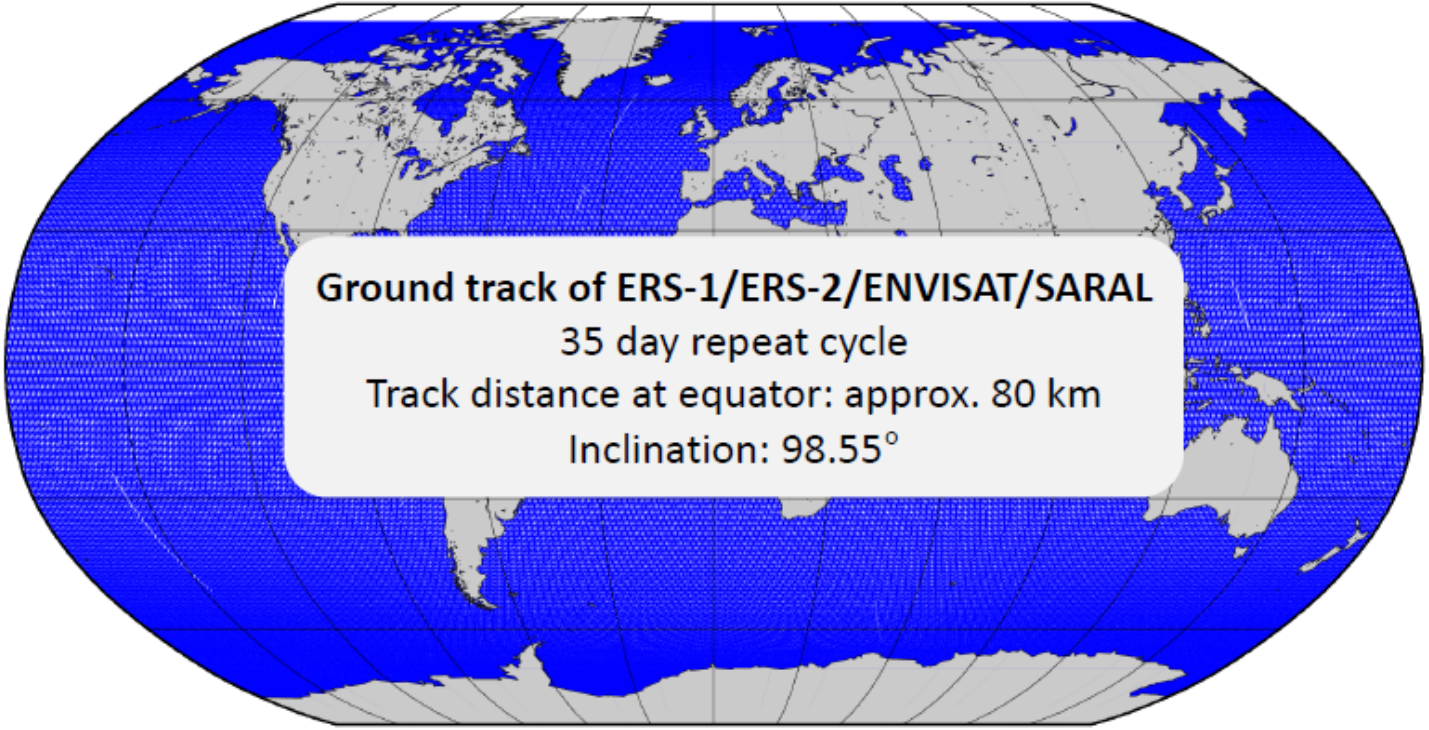
Spatio-temporal resolution/coverage: A challenge



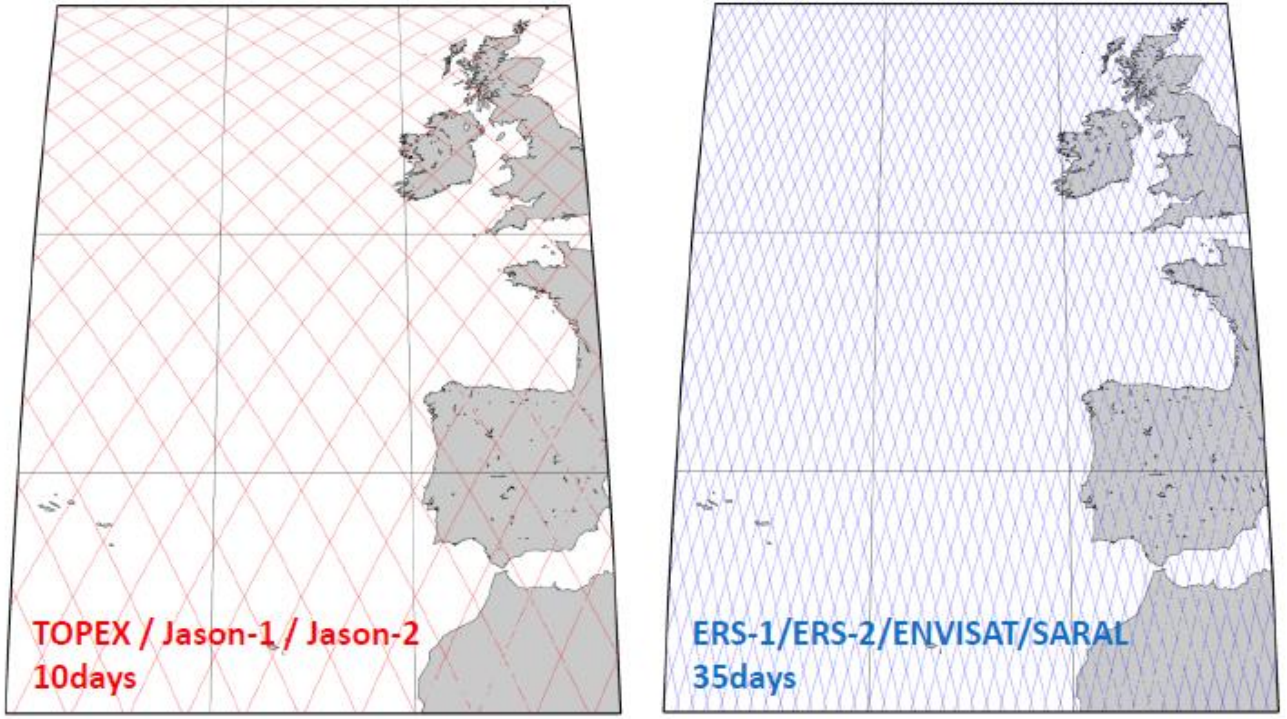
Satellite altimetry orbits



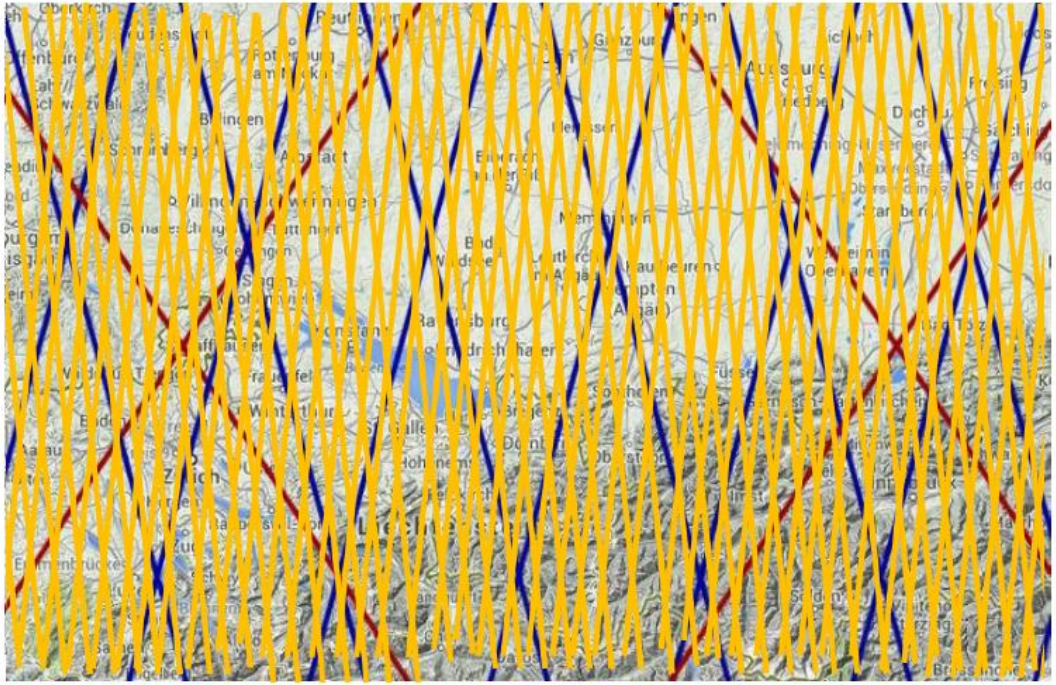
Satellite altimetry orbits



Orbits, Ground tracks



Orbits, Ground tracks



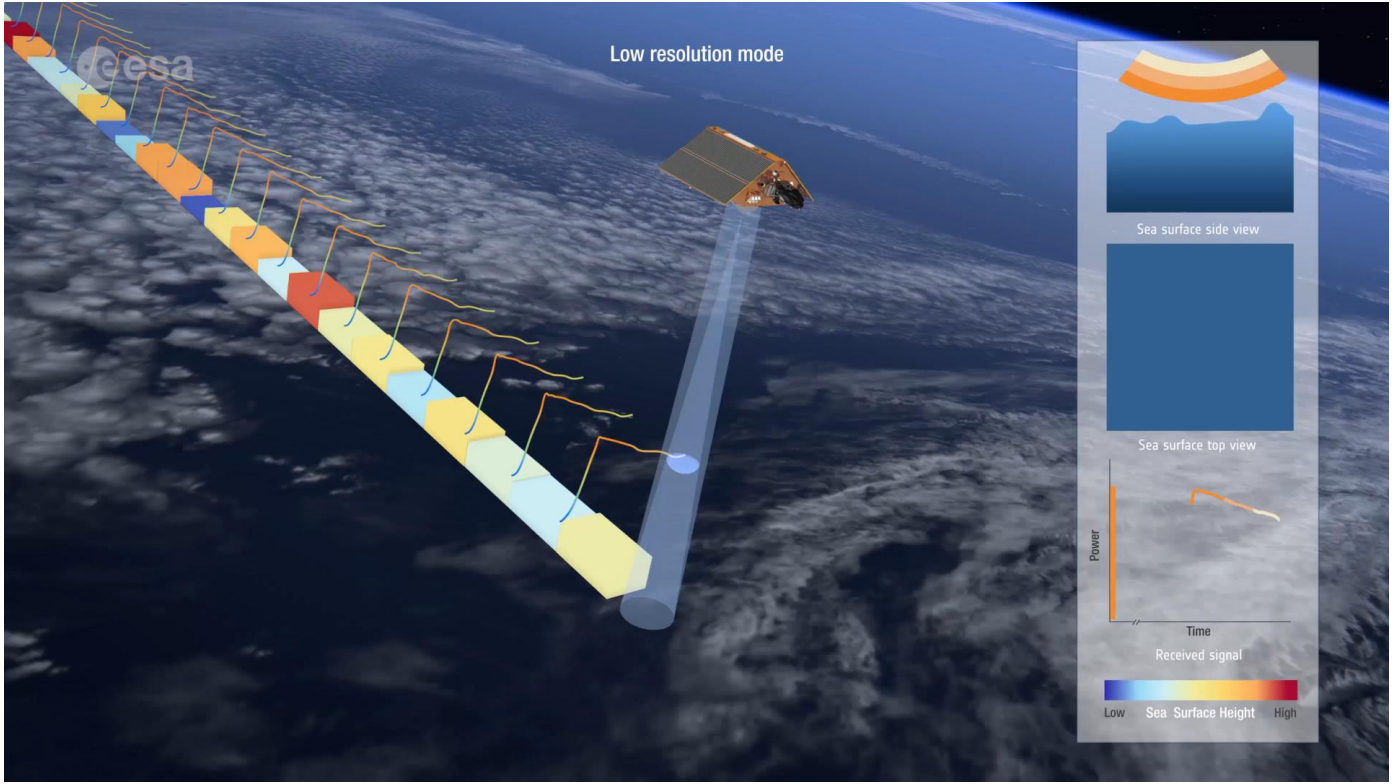
TOPEX / Jason-1 / Jason-2: 10 day repeat (315 km)

ERS-1 / ERS-2 / Envisat / SARAL: 35 day repeat (80 km)

Cryosat-2: 369 day repeat (8 km)

http://hydrosat.gis.uni-stuttgart.de

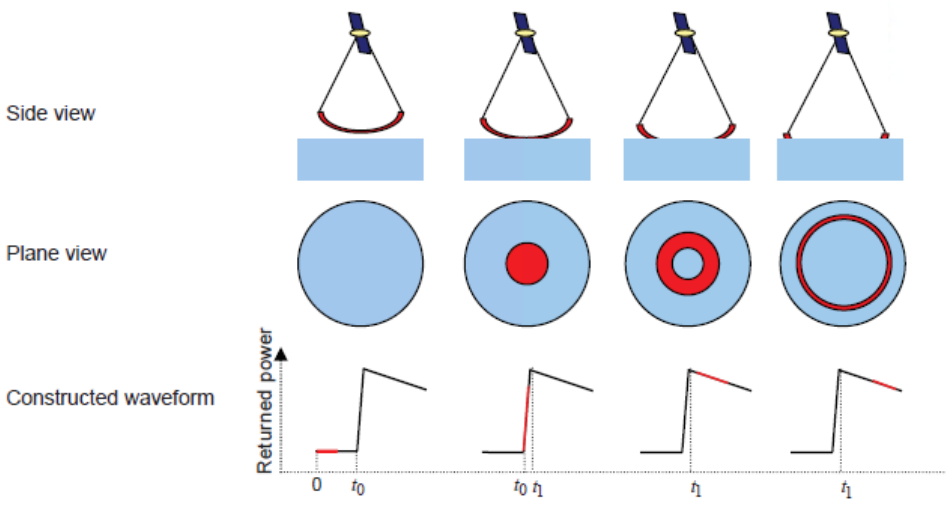
Principle of measurement



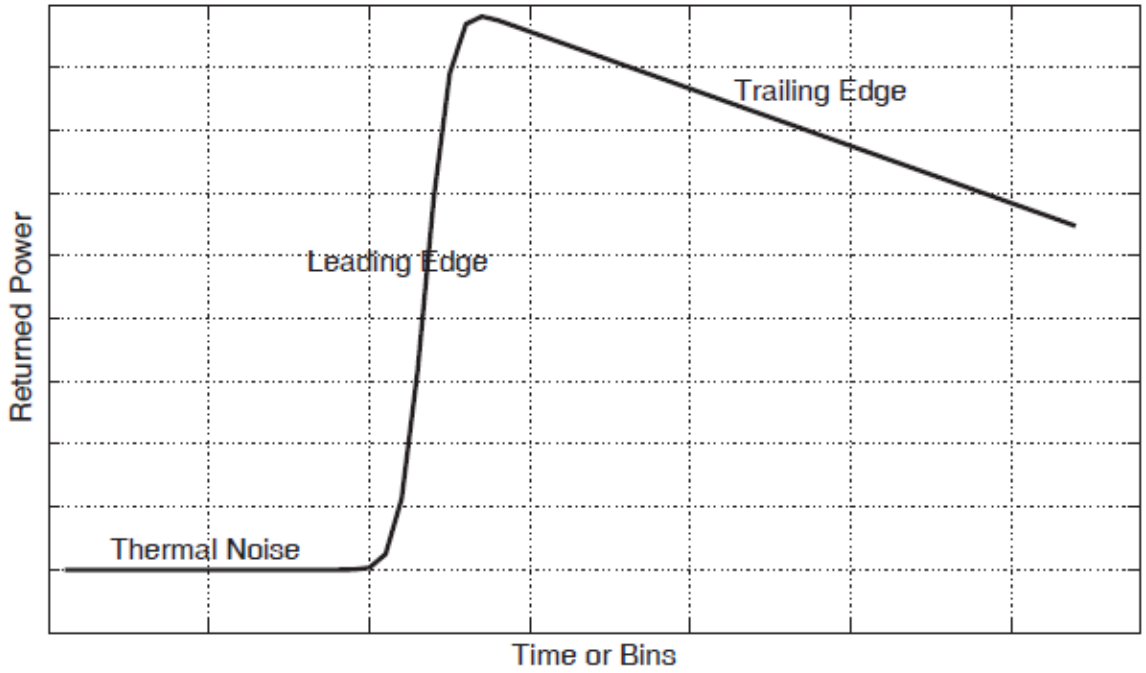
Principle of measurement

- distance of satellite to footprint on the sea surface:

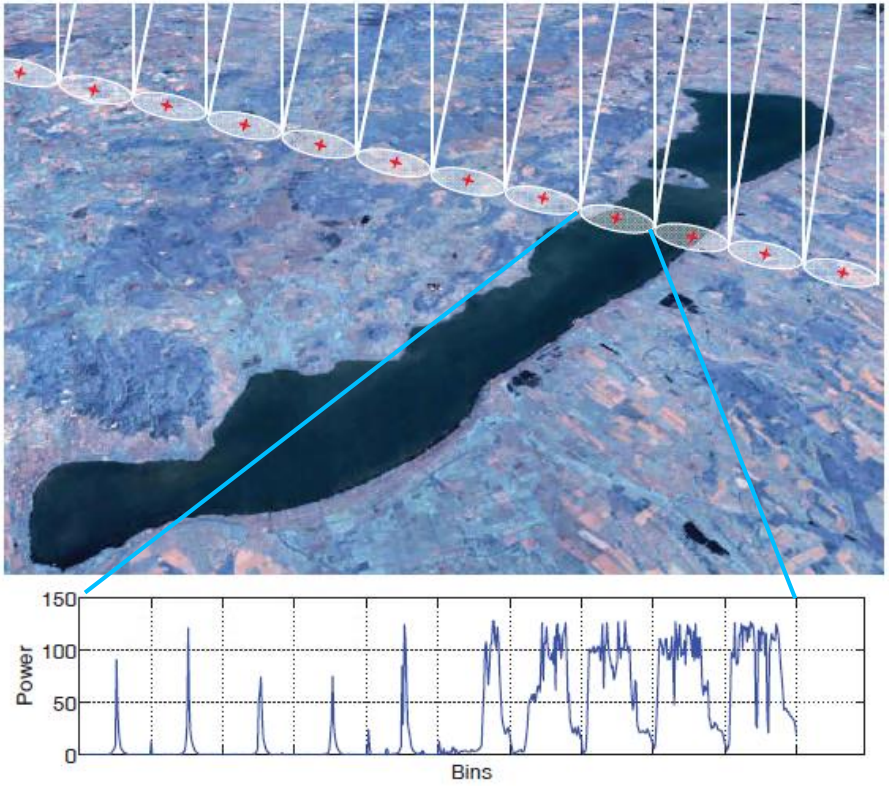
$$\rho = c \cdot \frac{\Delta t}{2}$$



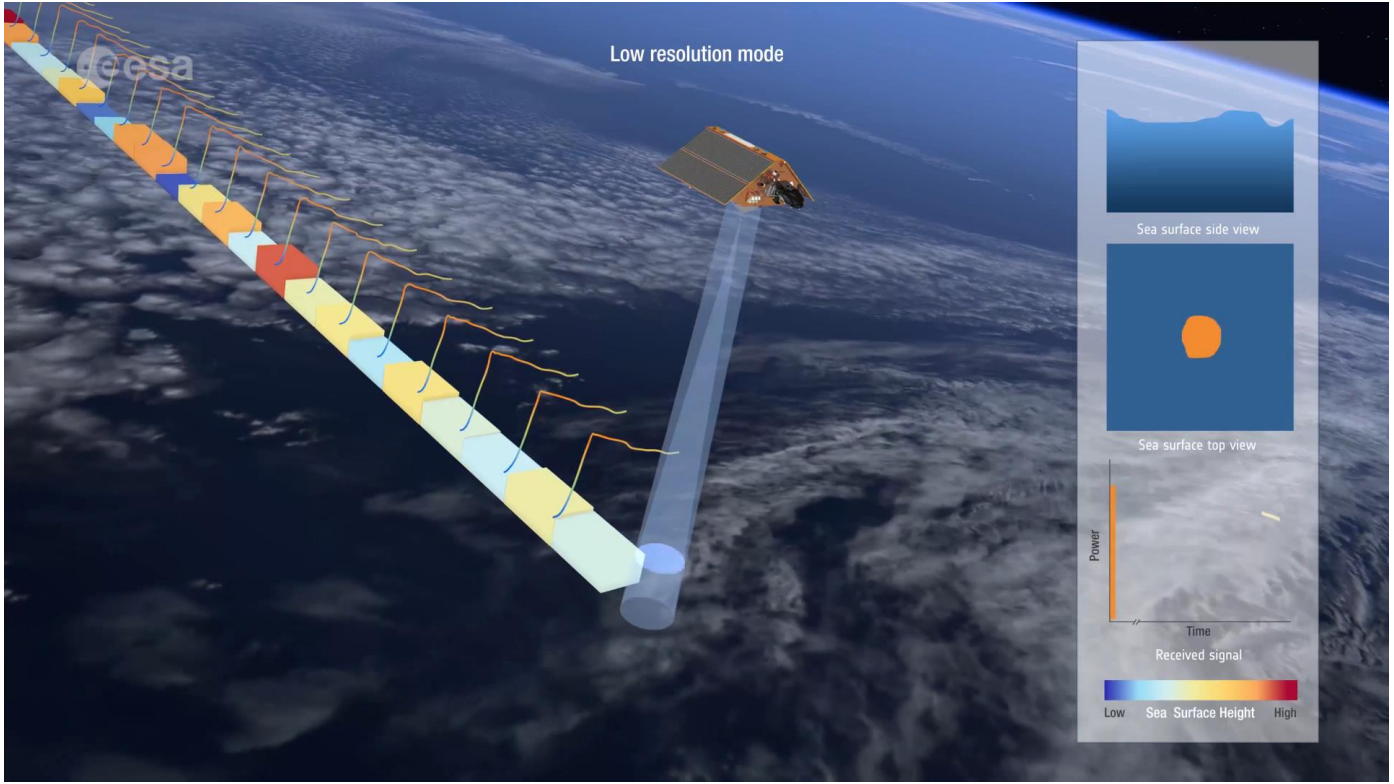
Ideal waveform



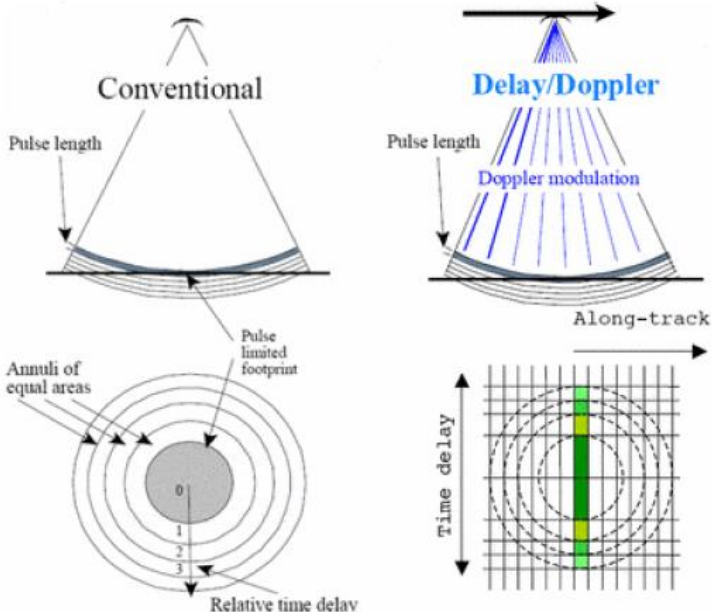
…but

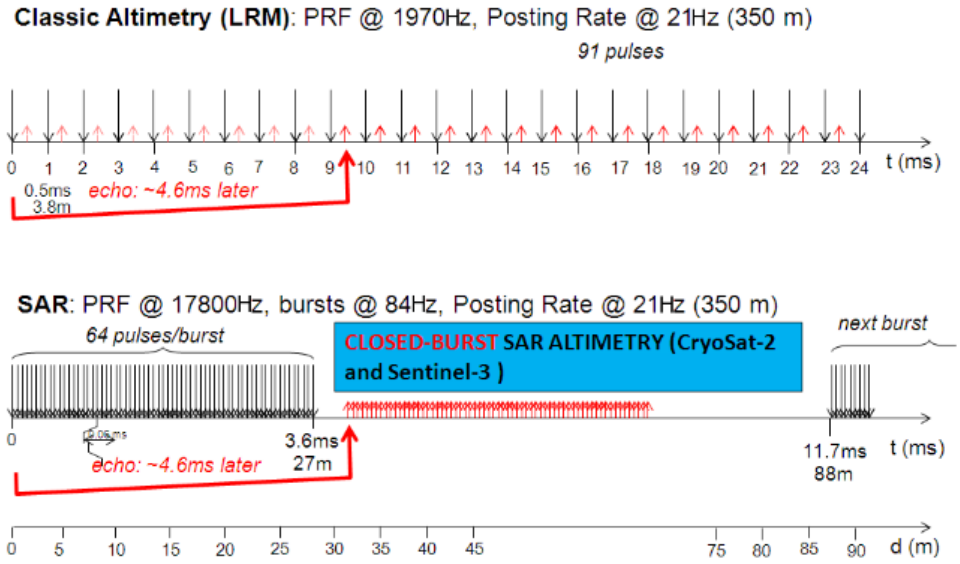


SAR altimetry



Conventional vs. delay-Doppler (or SAR) nadir altimetry



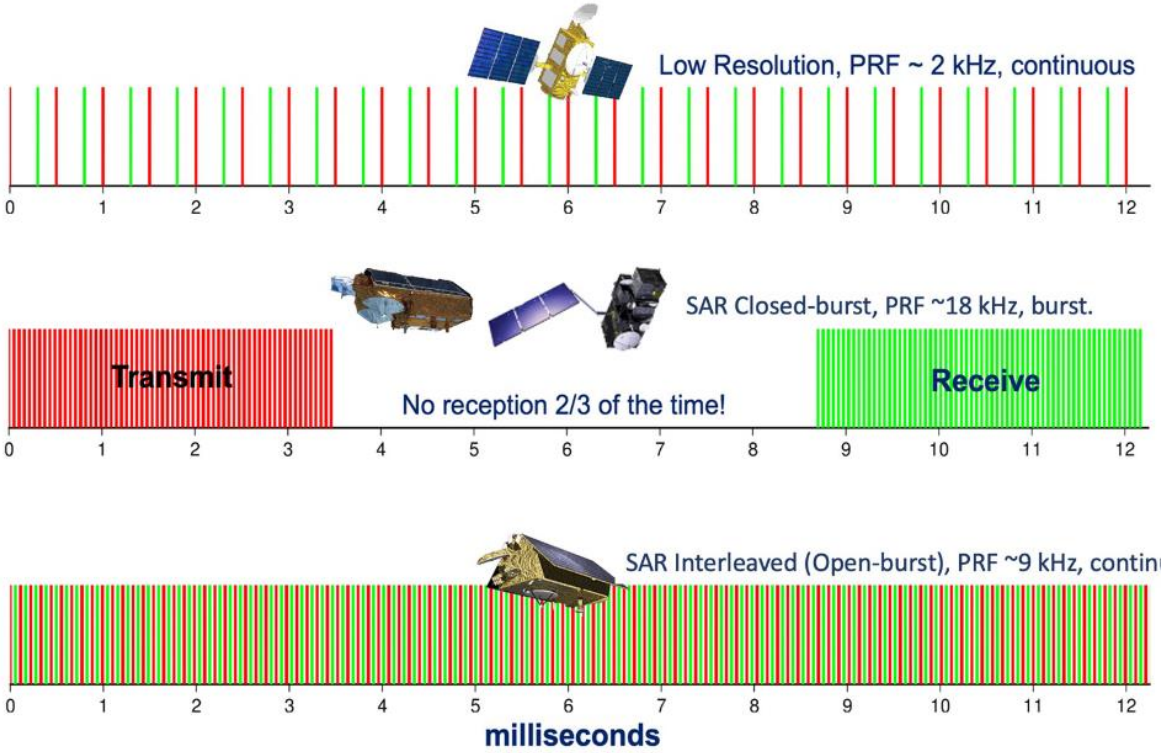


Comparison between conventional radar altimeter (left) and Delay Doppler/SAR (right) altimety (Credits R.K. Raney, Johns Hopkins University Applied Physics Laboratory)

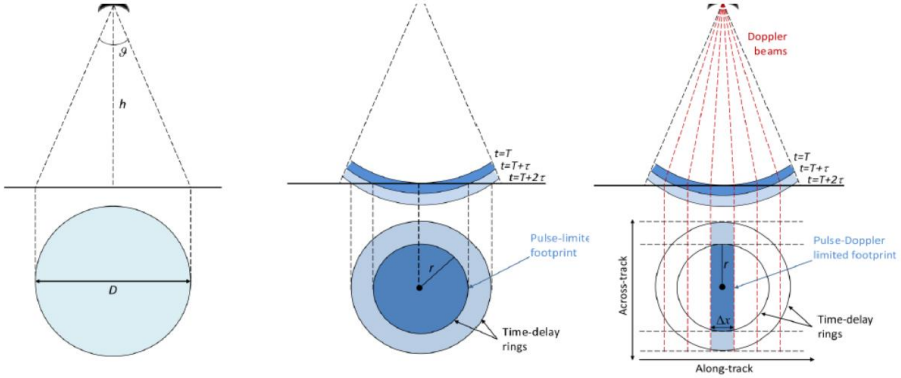
Credit S. Dinardo

Conventional vs. delay-Doppler (or SAR) Altimetry

- Low Resolution
- SAR altimetry, closed burst
- SAR altimetry, open burst



Radar footprint



$$D = 2h \tan\frac{\theta}{2} \qquad r = \sqrt{h\,c\tau} = \sqrt{h\,\frac{c}{B}} \qquad \Delta x = h\,\frac{\lambda}{2N_s}\mathrm{PRF}$$

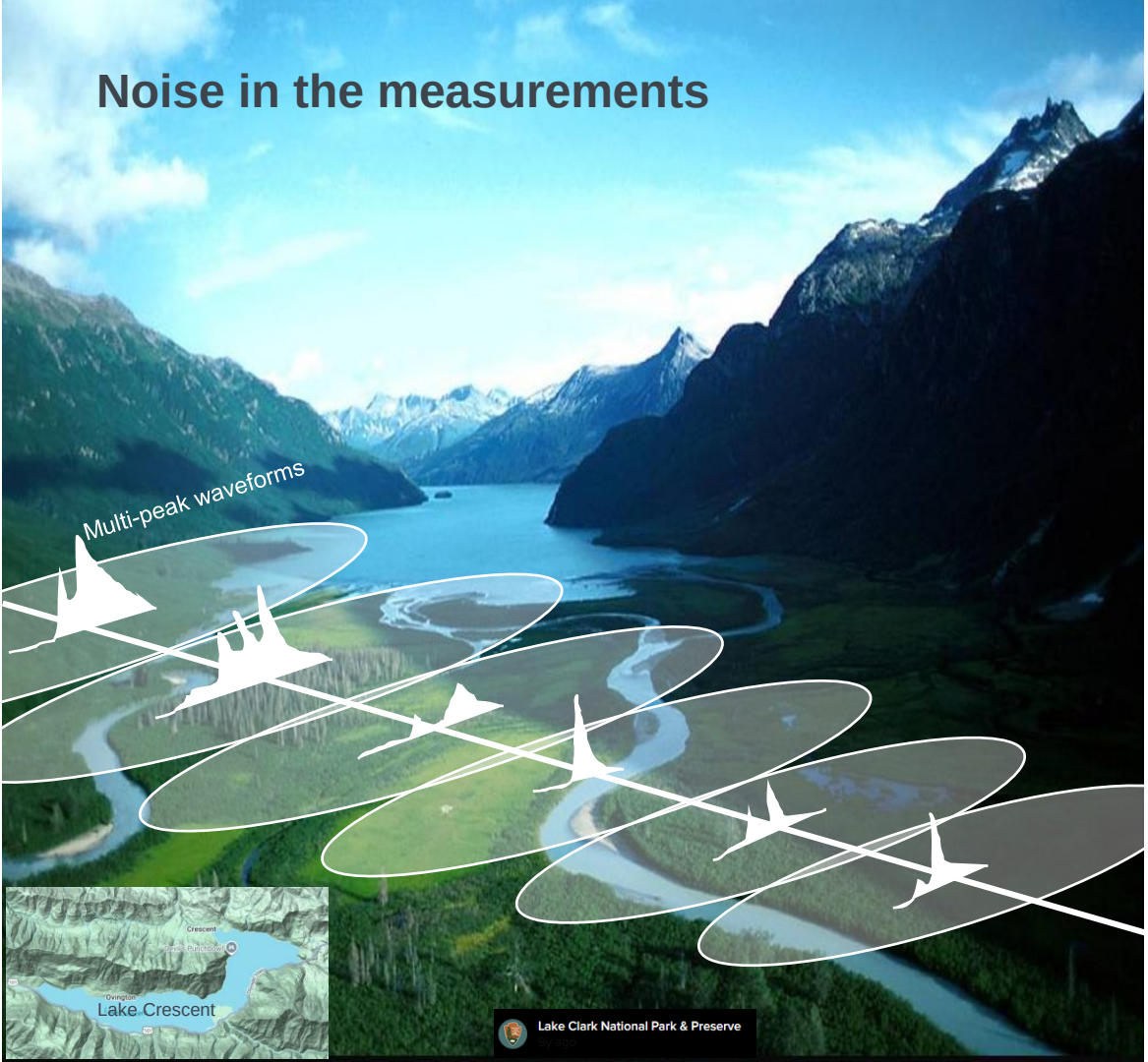
Table 1: Comparison of beam-limited, pulse-limited, and SAR altimetry missions

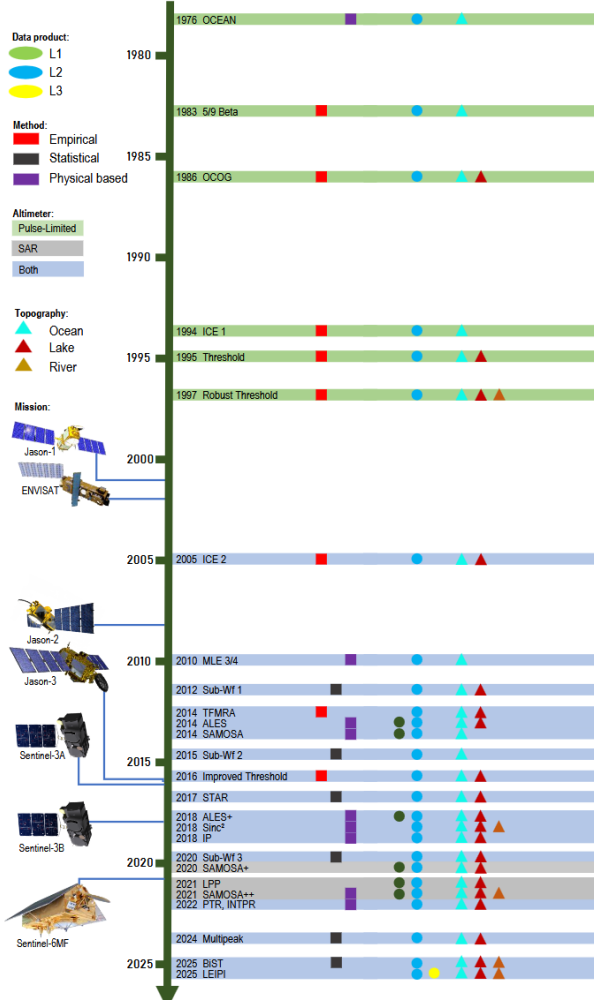
Parameter	**SEASAT**	**ERS-1&2**	**TOPEX, Jason-1/2/3**	**Sentinel-3**	**Sentinel-6**
Altimetry concept	Beam-limited	Pulse-limited (early)	Pulse-limited	SAR	SAR
Orbit altitude h [km]	~800	~780	1336	815	1336
Ground velocity v [km s^{-1}]	~7.4	~7.4	~7.0	~7.4	~7.0
Radar band	Ku	Ku	Ku	Ku	Ku
Carrier frequency f [GHz]	13.5	13.8	13.6	13.575	13.575
Wavelength λ [cm]	~2.22	~2.17	~2.21	~2.21	~2.21
Antenna beamwidth θ [deg]	~1.6	~1.3	~1.3	~1.3	~1.3
PRF [kHz]	~0.6	~1.0	~2–4	~17.8	~9.2
Bandwidth B [MHz]	~20	~80	320	320	320
Pulse duration τ [ns]	~50	~12	~3.1	~3.1	~3.1
SAR coherent pulses N	–	–	–	64	64
Coherent integration time [ms]	–	–	–	~3.6	~7.0
Footprint control	Beamwidth	Pulse length	Pulse length	Pulse + Doppler	Pulse + Doppler
Pulse-limited footprint radius [km]	~15–20	~2–3	~2.0	~1.5	~2.0
Along-track resolution [km]	~15–20	~7–10	~5–7	~0.3	~0.3

Altimetry missions from 1985

Mission	Operated by	Lifetime / data period	Height [km]	Incl. [°]	Rev. / repeat [days]	Altimeter / mode	OLTC	Frequency
Geosat	US Navy / NOAA	03.1985–09.1989	785	108.0	244 / 17	LRM	—	Ku: 13.5 GHz
ERS-1	ESA	07.1991–03.1996	785	98.5	501 / 35[1]	LRM	—	Ku: 13.8 GHz
TOPEX/Poseidon	CNES / NASA	09.1992–01.2006	1,336	66.0	127 / 10	LRM	—	Ku/C: 13.6 / 5.3 GHz
ERS-2	ESA	04.1995–09.2011	785	98.5	501 / 35	LRM	—	Ku: 13.8 GHz
GFO	US Navy / NOAA	02.1998–11.2008	~800	108.0	244 / 17	LRM	—	Ku: 13.5 GHz
Jason-1	CNES / NASA	12.2001–06.2013	1,336	66.0	127 / 10	LRM	—	Ku/C: 13.6 / 5.3 GHz
Envisat	ESA	03.2002–04.2012	~800	98.5	501 / 35	LRM	—	Ku/S: 13.575 / 3.2 GHz
ICESat	NASA	2003–2009	~600	94.0	2,723 / 183[2]	**Laser**	n/a	1064 / 532 nm
Jason-2 / OSTM	CNES / NASA / NOAA / EUMETSAT	06.2008–10.2019	1,336	66.0	127 / 10	LRM	✓[3]	Ku/C: 13.575 / 5.3 GHz
CryoSat-2	ESA	04.2010–present	~719	92.0	5,344 / 369	**LRM / SAR / SARIn**	—[4]	Ku: 13.575 GHz
HY-2A	CNSA / NSOAS	08.2011–2020	~971	99.3	193 / 14	LRM	—	Ku/C: 13.58 / 5.25 GHz
SARAL/AltiKa	ISRO / CNES	02.2013–present[5]	~800	98.55	501 / 35[5]	LRM	✓[3]	Ka: 35.75 GHz
Jason-3	CNES / NASA / NOAA / EUMETSAT	01.2016–present	1,336	66.0	127 / 10	LRM	✓	Ku/C: 13.575 / 5.3 GHz
Sentinel-3A	ESA / EUMETSAT	02.2016–present	~815	98.65	385 / 27	**SAR**	✓	Ku/C: 13.575 / 5.41 GHz
Sentinel-3B	ESA / EUMETSAT	04.2018–present	~815	98.65	385 / 27	**SAR**	✓	Ku/C: 13.575 / 5.41 GHz
ICESat-2	NASA	10.2018–present	~496	92.0	1,387 / 91	**Photon-counting laser**	n/a	532 nm
HY-2B	CNSA / NSOAS	10.2018–present	~971	99.3	193 / 14	LRM	—	Ku/C: 13.58 / 5.25 GHz
Sentinel-6 Michael Freilich	EUMETSAT / ESA / NASA / NOAA / CNES	11.2020–present	1,336	66.0	127 / 10	**SAR (HR) + LRM**	✓	Ku/C: 13.575 / 5.41 GHz
SWOT	NASA / CNES / CSA / UKSA	12.2022–present[6]	~891	77.6	292 / 21	KaRIn + **LRM nadir**	✓[7]	Ka: 35.75 GHz; Ku/C nadir: 13.575 / 5.3 GHz
Sentinel-6B	EUMETSAT / ESA / NASA / NOAA / CNES	11.2025–present	1,336	66.0	127 / 10	**SAR (HR) + LRM**	✓	Ku/C: 13.575 / 5.41 GHz

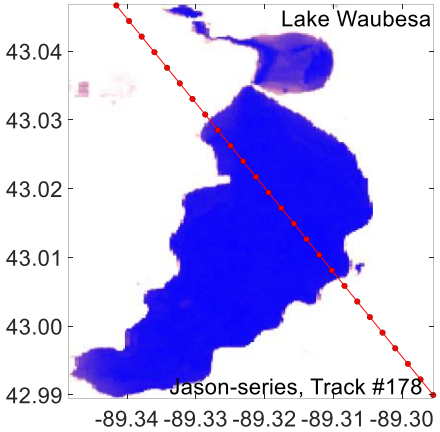
Noise in the measurements

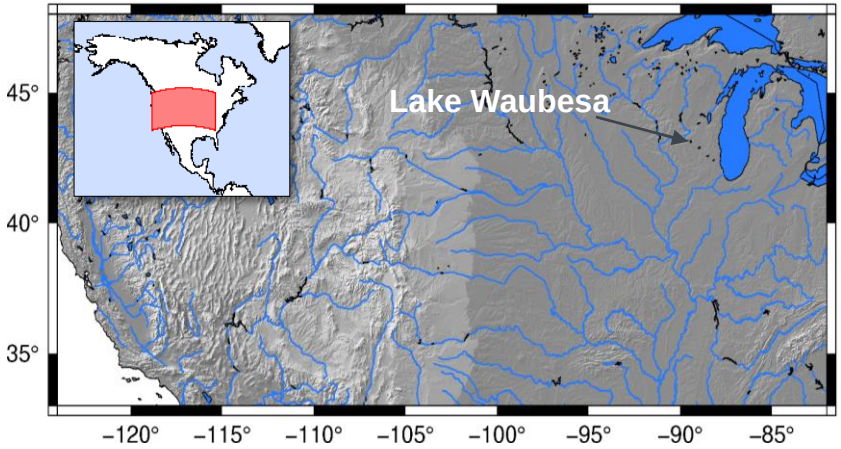


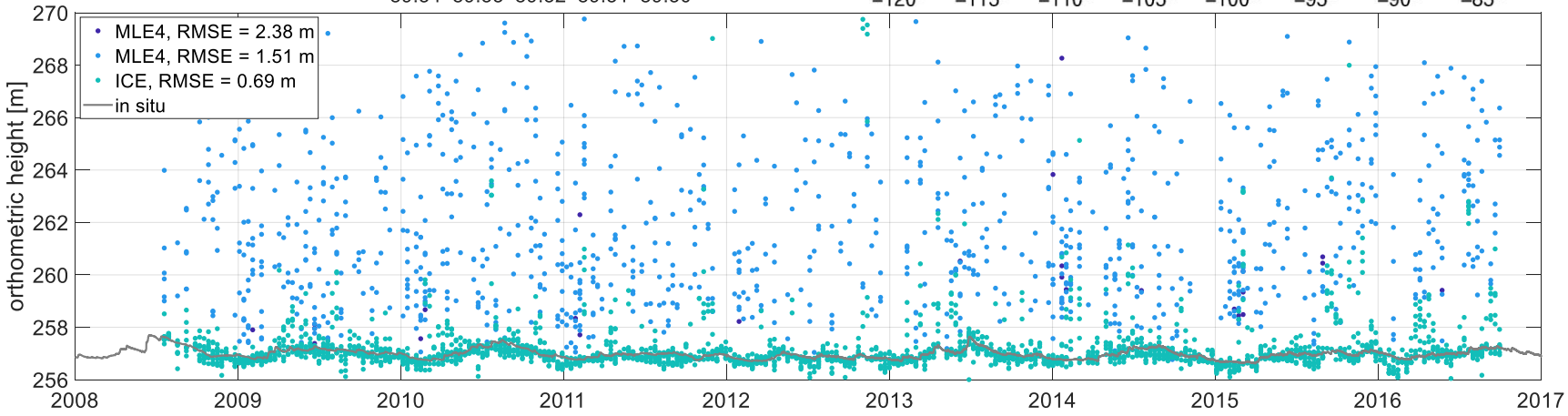


Khalili S., Tourian MJ, et al. (2026). **Advances in Retracking Techniques for Satellite Altimetry: A Survey of Methods and Performance**. *Under preparation*

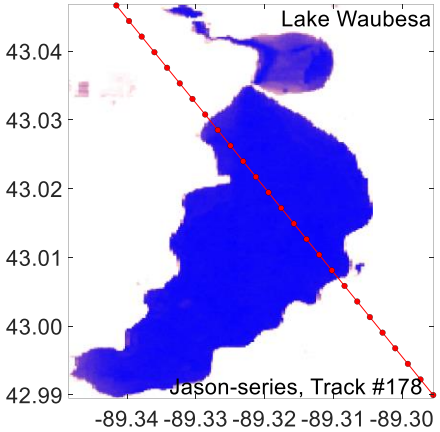
Noise in the measurements

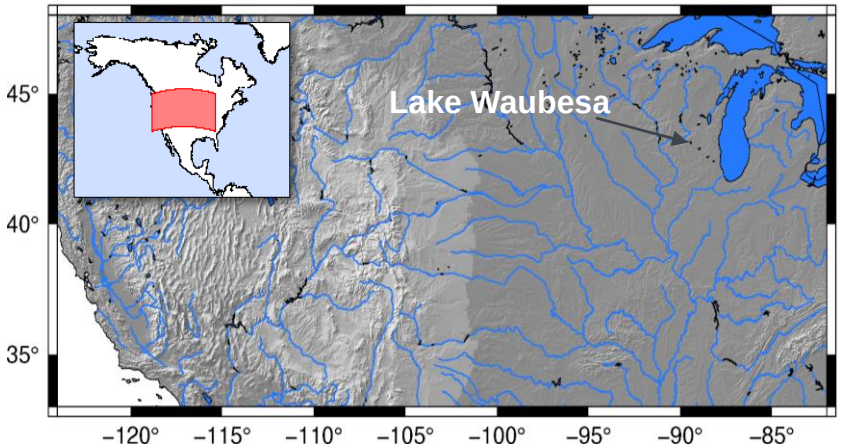


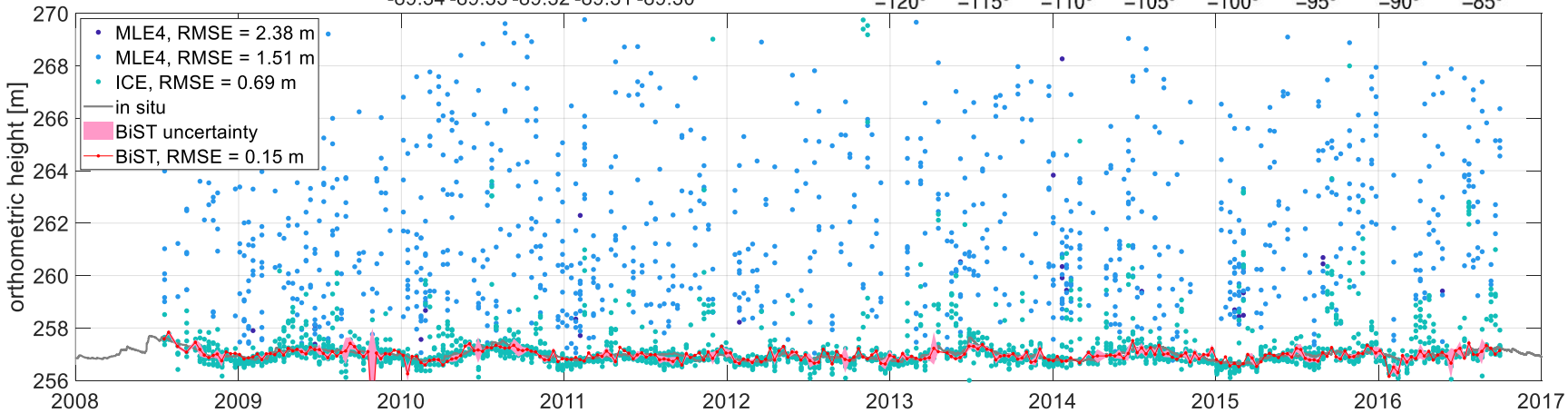




Improved water level time series







Tourian, M. J., Elmi, O., Khalili, S., & Engels, J. (2025**). Improving inland water altimetry through Bin-Space-Time (BiST) retracking: A Bayesian approach to incorporate spatio-temporal information**. *IEEE Transactions on Geoscience and Remote Sensing*.

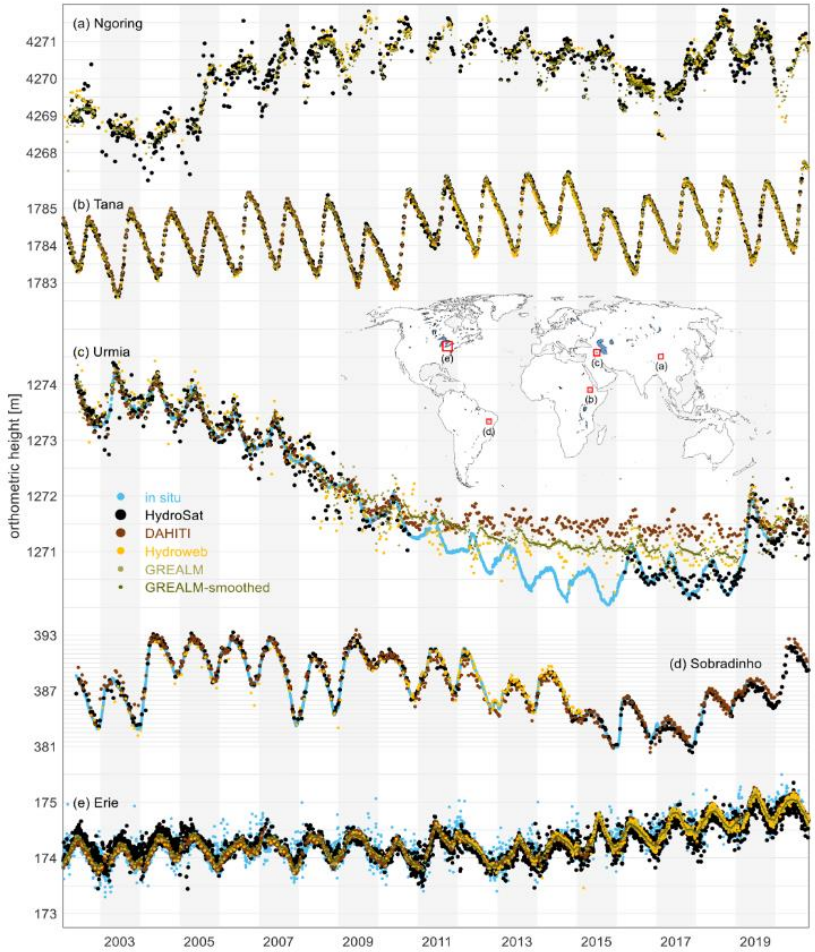
Satellite altimetry data

Level	Dataset	Resolution / Coverage	Comment
Level-1A	**Raw / Telemetry Data**	Full instrument sampling; mission-dependent	Raw radar measurements after telemetry decoding and time ordering. Contains instrument counts and housekeeping information; generally not directly usable for geophysical applications.
Level-1B	**High-Resolution Waveform (L1B)**	~20 Hz (≈350 m along-track)	Calibrated radar echo power per range gate after instrument corrections and geolocation. Contains the waveform used for retracking; mission-specific format.
Level-2	**Geophysical Data Record (GDR)**	~20 Hz (≈350 m)	Geophysical parameters and surface-height/range estimates with associated corrections (wet/dry troposphere, ionosphere, tides, etc.). Distributed through mission data centers such as AVISO+, Copernicus, or PO.DAAC.
Level-2	**Enhanced / Sensor GDR (EGDR/SGDR)**	~20–40 Hz; mission-dependent	Includes additional high-rate parameters, waveform/retracking information, sigma-0, and retracked range/height estimates useful for inland-water processing.
Level-3	**Water-Level Time Series / Virtual Stations**	Temporal: typically repeat cycle (~10–35 days); spatial: individual satellite–water-body crossings	Processed, quality-controlled, and often multi-mission water-level time series for rivers, lakes, and reservoirs.

Level 3 datasets

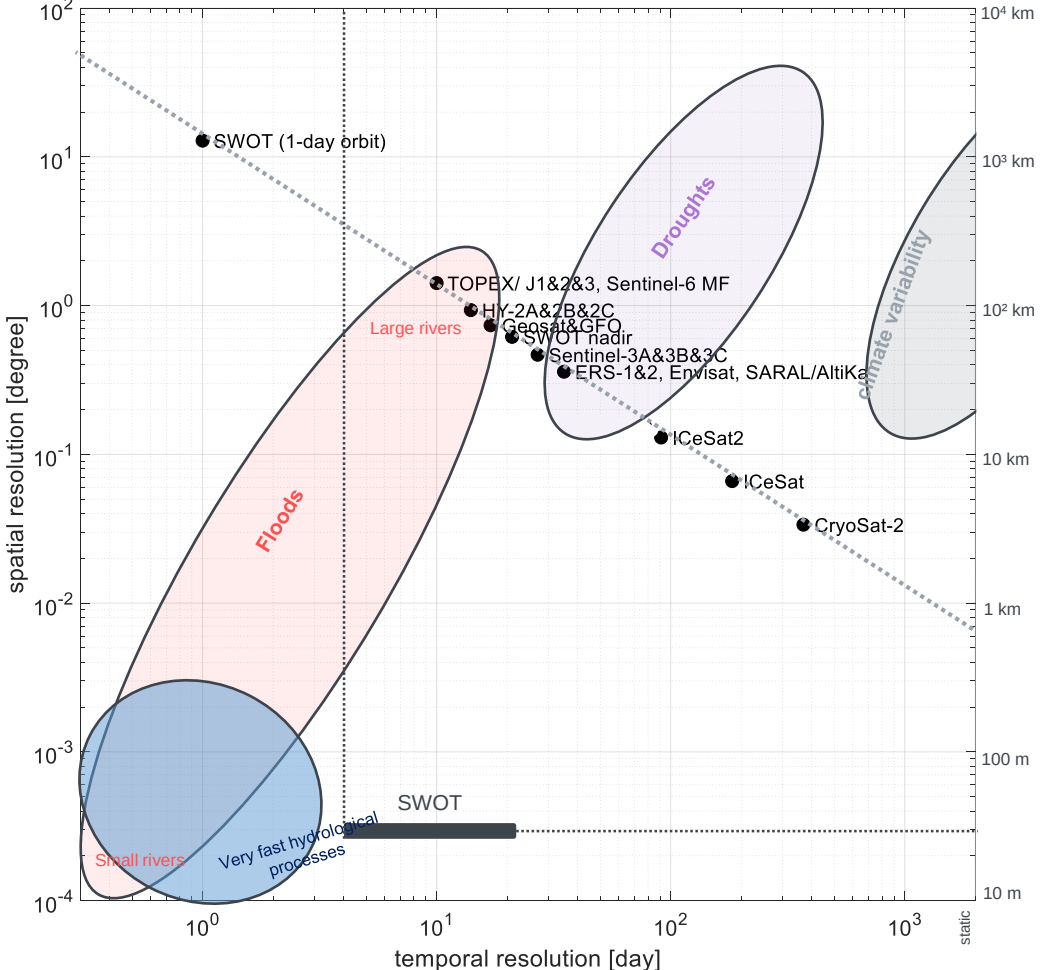
Product / database	Provider	Coverage
Hydroweb.next	CNES / LEGOS / CLS / Theia	Global rivers, lakes & reservoirs
DAHITI	DGFI-TUM	Global rivers, lakes, reservoirs & wetlands
HydroSat	University of Stuttgart	Global rivers & lakes
G-REALM	USDA-FAS / NASA	Global large lakes & reservoirs
GRRATS	Ohio State University / NASA	Large rivers globally
C3S Lake Water Level	Copernicus / CLS	Selected lakes globally
Regional/research products	Various	Selected basins

M. J. Tourian et al.: HydroSat



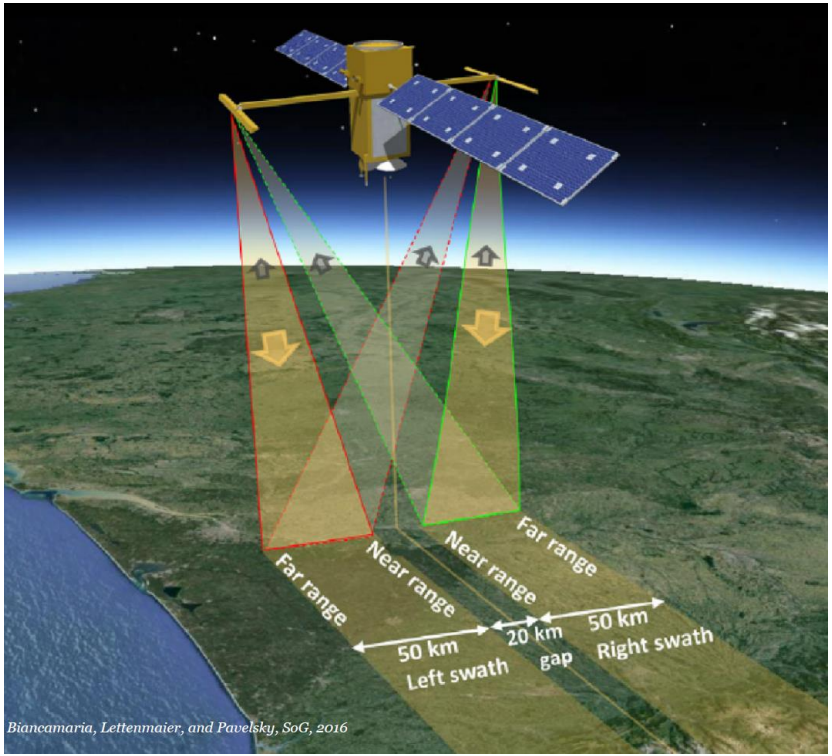
Swath altimetry

Spatio-temporal resolution/coverage: A challenge



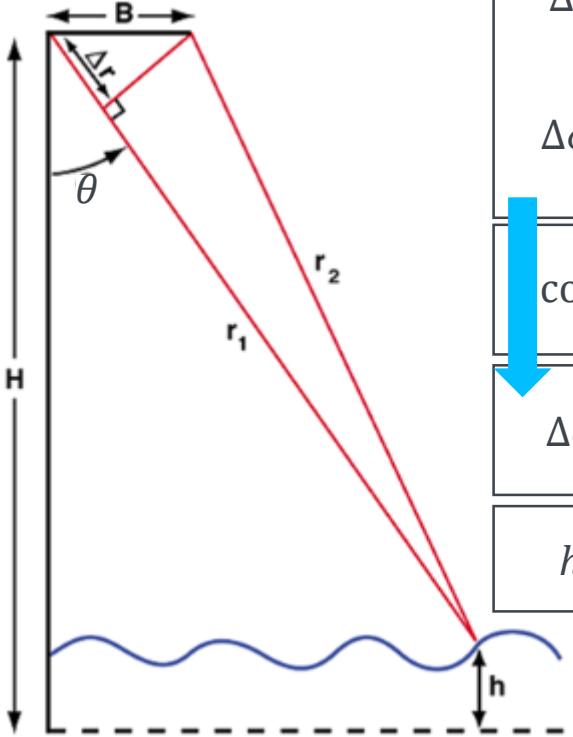
The Surface Water and Ocean Topography Mission

- The principal payload on SWOT is a Ka-band radar interferometer (KaRIn) at 8.6 mm wavelength with twin 50 km swaths pointing 1-4.5° off nadir
- 21 day repeat orbit at 890 km
- Launched in December 2022
- 3 year nominal mission lifetime
- Simultaneously measures inundation extent and water surface elevation
- Total budget: ~$1.1 B
- Partnership between NASA, CNES, Canadian Space Agency, and UK Space Agency





Interferometric measurement concept



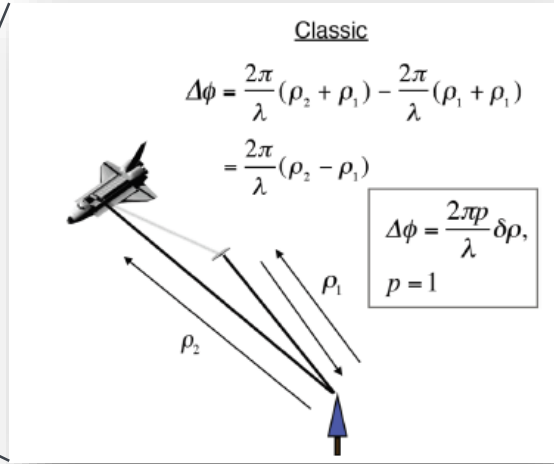
$$\Delta\varphi = \frac{2\pi}{\lambda}(r_2 + r_1) - \frac{2\pi}{\lambda}(r_2 + r_2)$$

$$\Delta\varphi = \frac{2\pi}{\lambda}(r_1 - r_2) = \frac{2\pi}{\lambda}\Delta r$$

$$\cos(90 - \theta) = \frac{\Delta r}{B}$$

$$\Delta\varphi = \frac{2\pi}{\lambda} B \sin\theta$$

$$h = H - r_1 \cos\theta$$



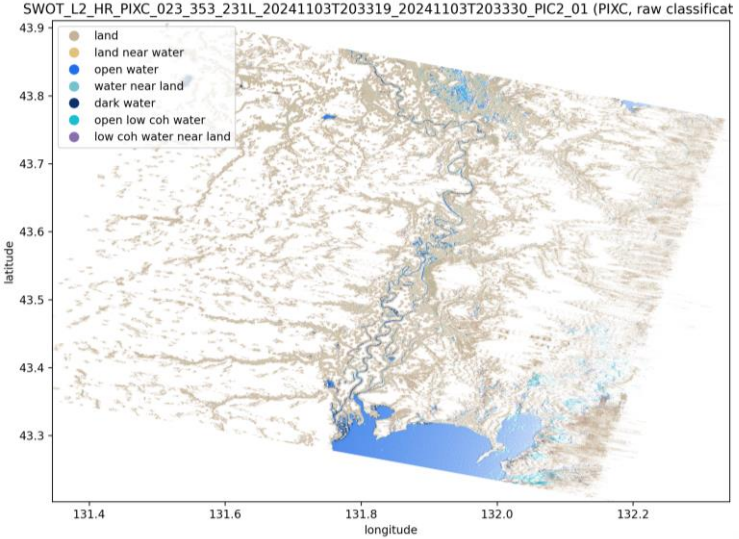






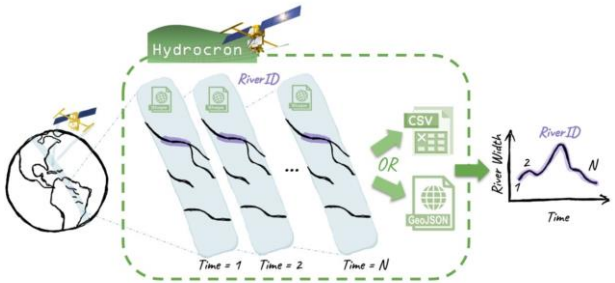
SWOT data

Level	Dataset	Resolution
Level-1B	HR Single Look Complex	Half swath 64 km² 3 m × 0.75 m
Level-2	Pixel Cloud	20–60 m
	Pixel Cloud Vector	20–60 m
Level-2	Raster	100 m & 250 m

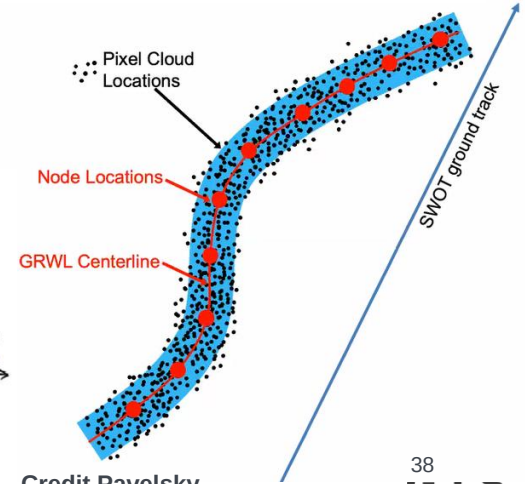


Sources for data access

- NASA PO.DAAC
- AVISO+ Data Portal
- Hydroweb.next Portal
- NASA Earthdata
- Hydrocron

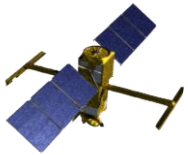


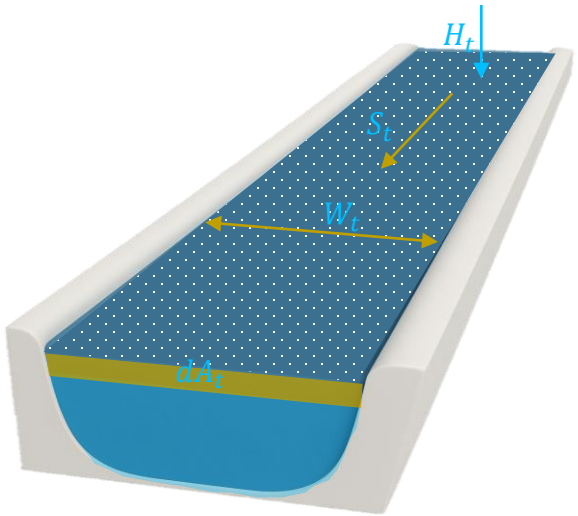
Credit: NASA JPL.



Credit Pavelsky

SWOT over rivers





SWOT monitores global rivers

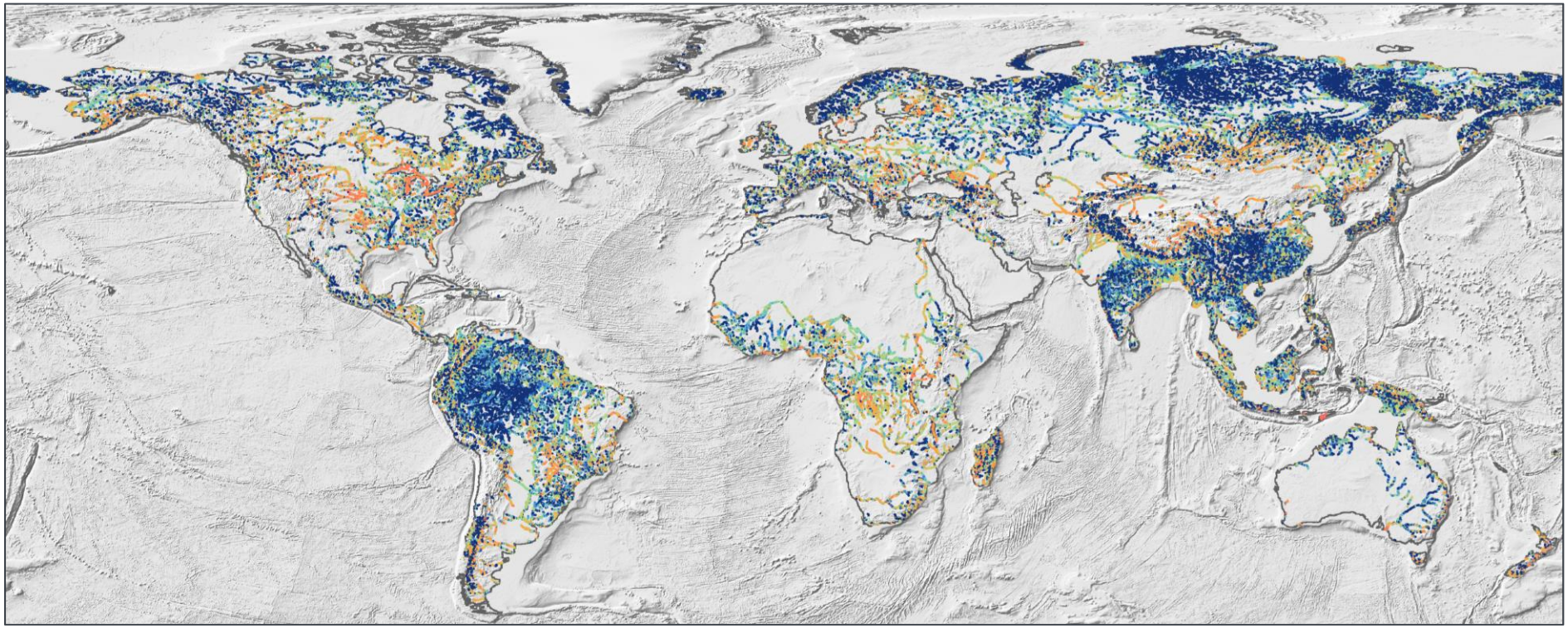


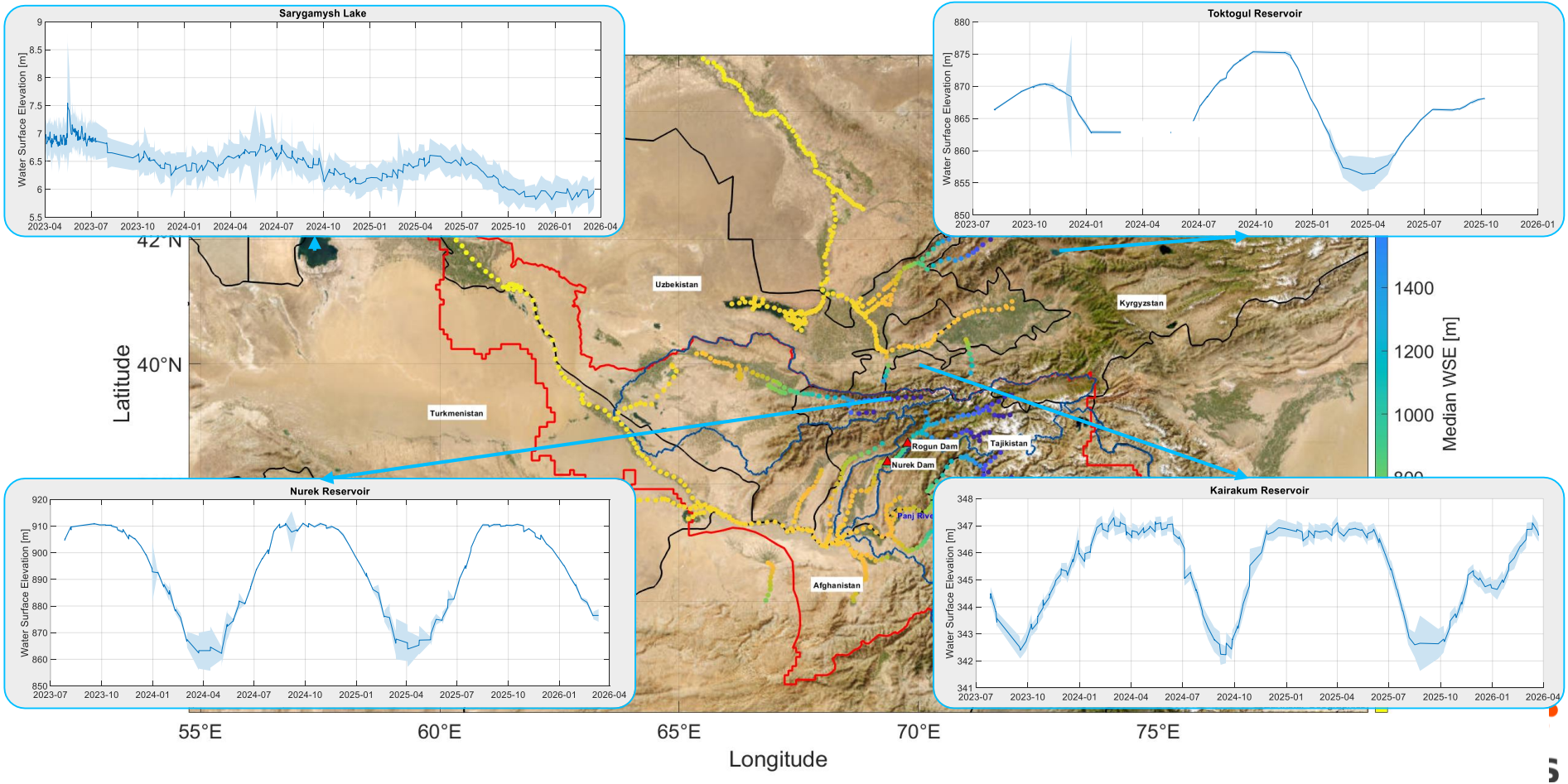
Figure courtesy of Peyman Saemain



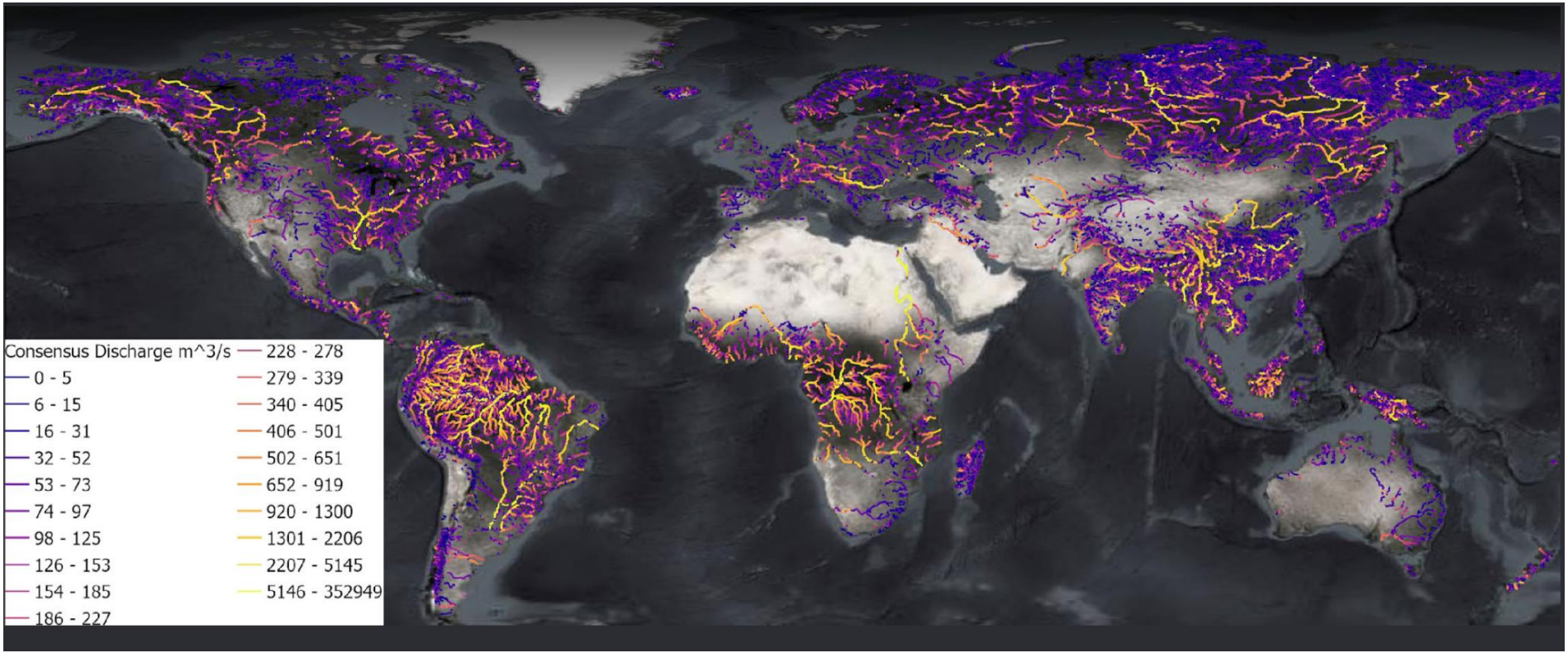
range of river water level variations [m]

measured by SWOT from April 2023 till June 2025

SWOT over Amu Darya, lakes and reservoirs

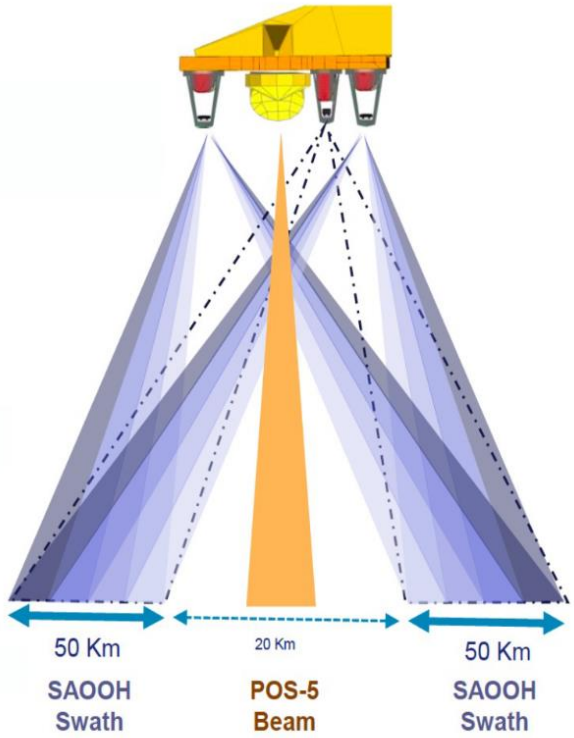


SWOT estimates global river discharge



Future swath altimetry missions, Sentinel 3NG

- SAHOO
- To be launched in 2033



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Vielen Dank!

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