Applications de la mission « Surface Water and Ocean Topography » (SWOT) en hydrologie continentale

Sylvain BIANCAMARIA (LEGOS), Jean-François CRETAUX (LEGOS), Hind OUBANAS (INRAE), Delphine LEROUX (CNES), Daniel MOREIRA (CPRM), Fabrice PAPA (LEGOS), Jida WANG (Univ. Of Illinois), Steve COSS (Ohio State Univ.), Claire POTTIER (CNES), Mélanie TRUDEL (Univ. Sherbrooke), Gabriela SILES (Univ. Laval), SWOT Science Team et beaucoup d'autres…

17 January 2025

Outline

1. **Context and need for the SWOT mission**

2. **Princip of the SWOT mission**

3. **Example of scientific studies with SWOT**

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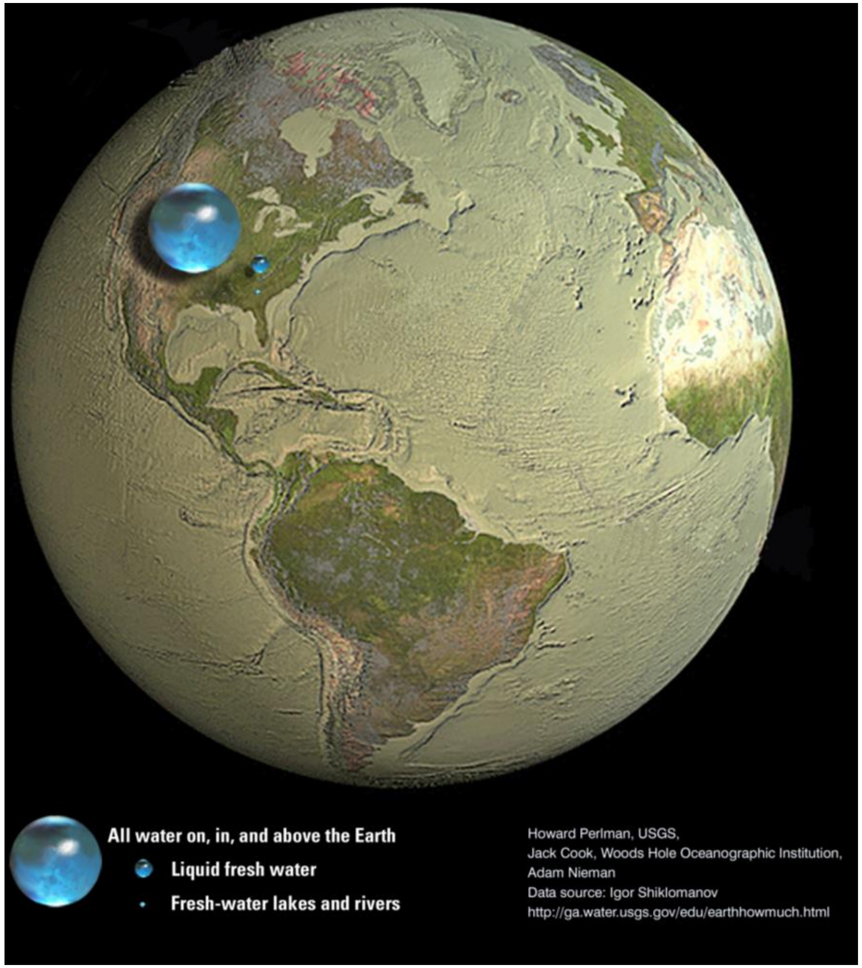
1. **Context and need for the SWOT mission**

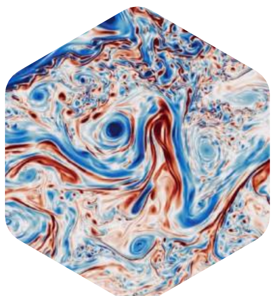
2. **Princip of the SWOT mission**

3. **Example of scientific studies with SWOT**

Why Surface Water and Ocean Topography (SWOT) mission?

- Science objectives for SWOT:
  - Understand the oceanic mechanisms of small mesoscale eddies, ocean/atmosphere couplings (climate issues) and ocean biology/dynamics.
  - Understand hydrological processes to determine water flows and stocks on continents
- Significant social benefits:
  - Predicting our environment over the next few days/weeks
  - Predict and manage extreme events
  - Understand and manage our food and water needs

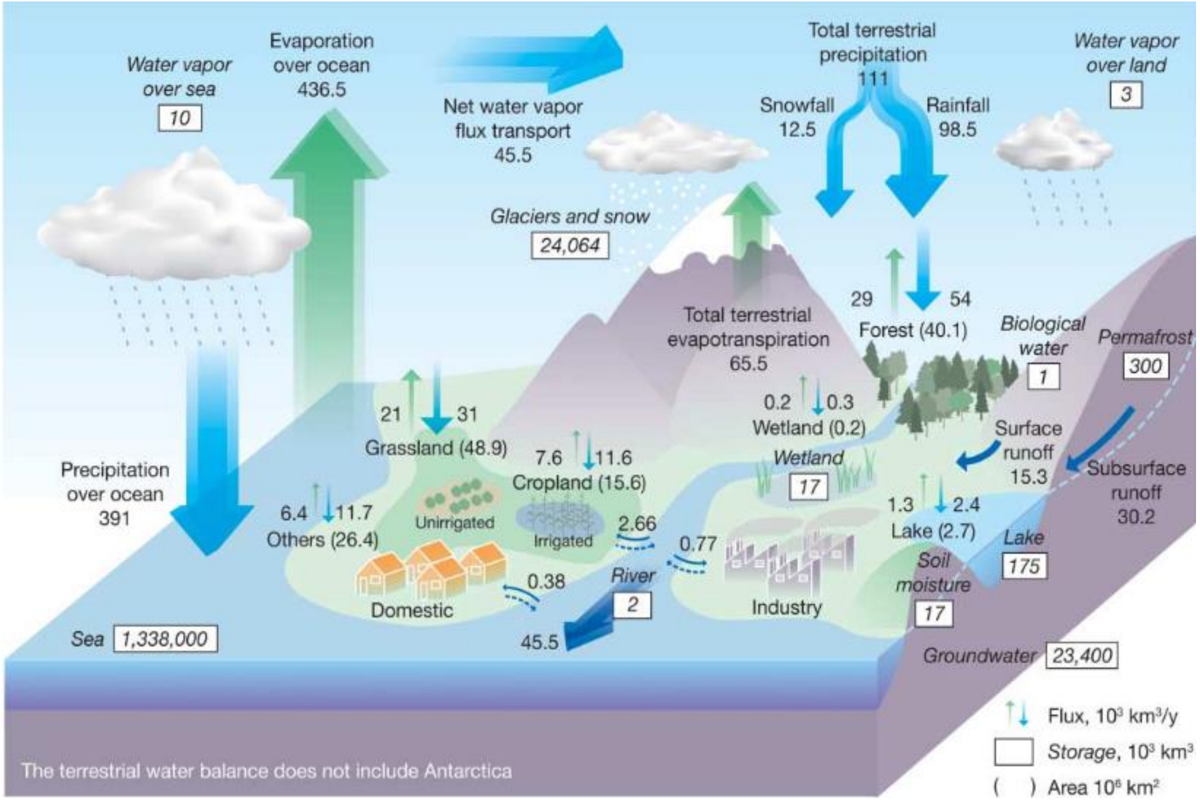




From D. Leroux

Open surface waters over continents

- Open surface waters: rivers, lakes, reservoirs, floodplains

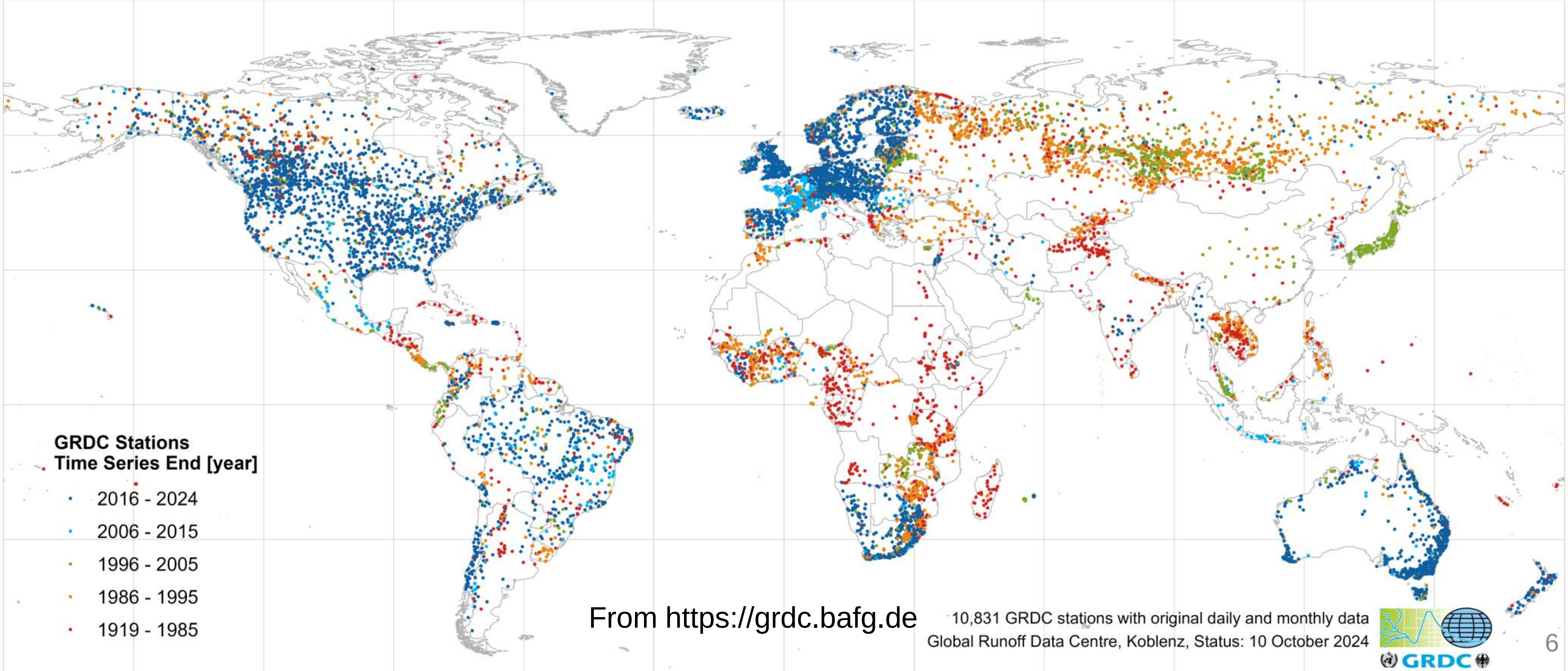


From T. Oki, 2006

- Only 3% of Earth water corresponds to freshwater:
  - 68% as solid water (glaciers & icesheets)
  - 31% as ground water
  - 0.3% as surface water (rivers, lakes, reservoirs, wetlands…)
- Surface waters store few water mass but corresponds to important water fluxes => need to observe surface waters fluxes

How to observe open surface waters? In situ data

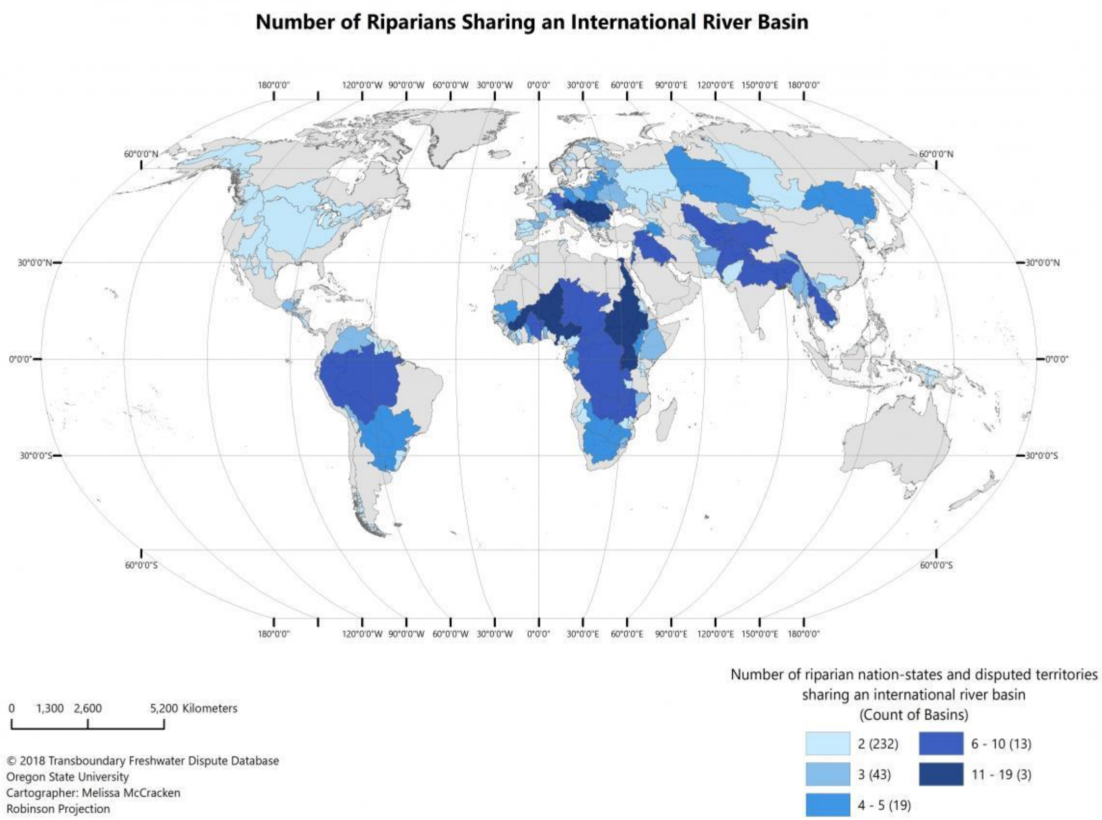
- In situ measurements (on the ground) are the most accurate and can measure directly physical variables of interest (water level, discharge)
- However, in situ data at global scale are heterogeneous in space and time, example of river discharge data:



From https://grdc.bafg.de

How to observe open surface waters? In situ data

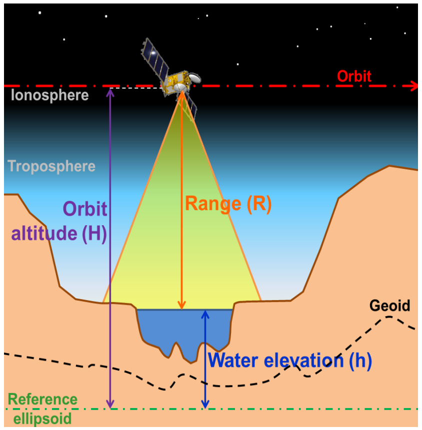
- Why in situ obs. Are not available everywhere? Main causes:
  - Economic issues (in situ network not funded)
  - Some remote locations difficult to access, no people to maintain network, no interest by national agencies to monitor such locations
  - Data could be considered strategic and are not shared publicly (ex.: reservoirs data not shared because electricity production could be derived from these data)
  - Impossibility to have a large coverage from the ground
- Difficulties to get data for some transboundary basins (i.e. shared by multiple countries; ~40% continental surfaces):



From the Register of International River Basins, OSU, https://transboundarywaters.science.oregonstate.edu

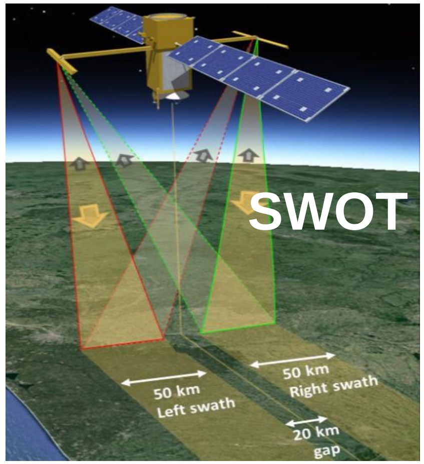
How to observe water mass balance? Satellite data

- Remote sensing data = drone, airborne, balloon, satellite… data -> only satellite data will be considered in this course
- Satellite data are used to complement in situ observation:
  - pros: cover more areas than in situ network, are not country-dependent, provide data/variables not available from the ground (e.g. river discharge)
  - cons: often less accurate than in situ, rough time/space sampling, usually does not measure directly the physical variable of interest
- For water storage and fluxes: radar altimetry are used to compute water surface elevation



Since 1992 = Nadir radar altimetry
(measerements only along the satellite track)

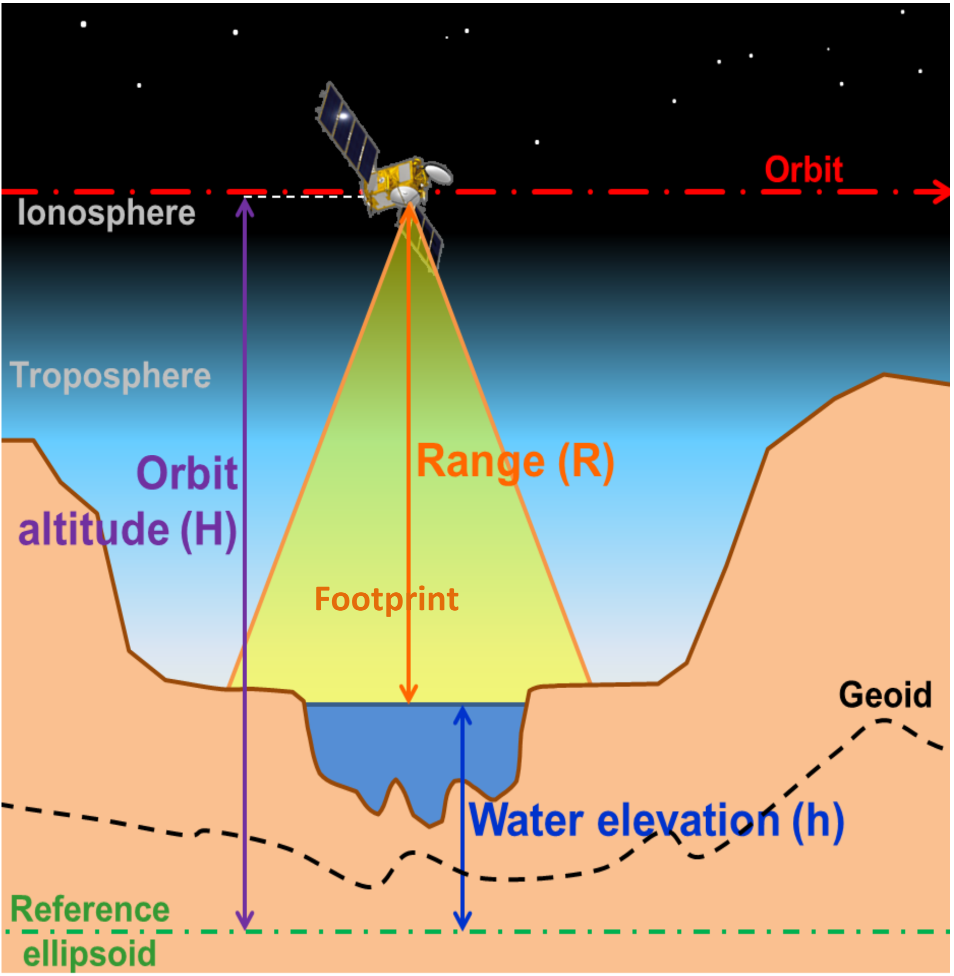
To overcome nadir altimetry limitations



Since 2023, wide swath radar altimetry
(images of water surface elevation, WSE)

Before SWOT: nadir radar altimeter

- Conceived to measure ocean surface topography
- Used opportunistically to estimate Water Surface Elevation (WSE) for continental open waters

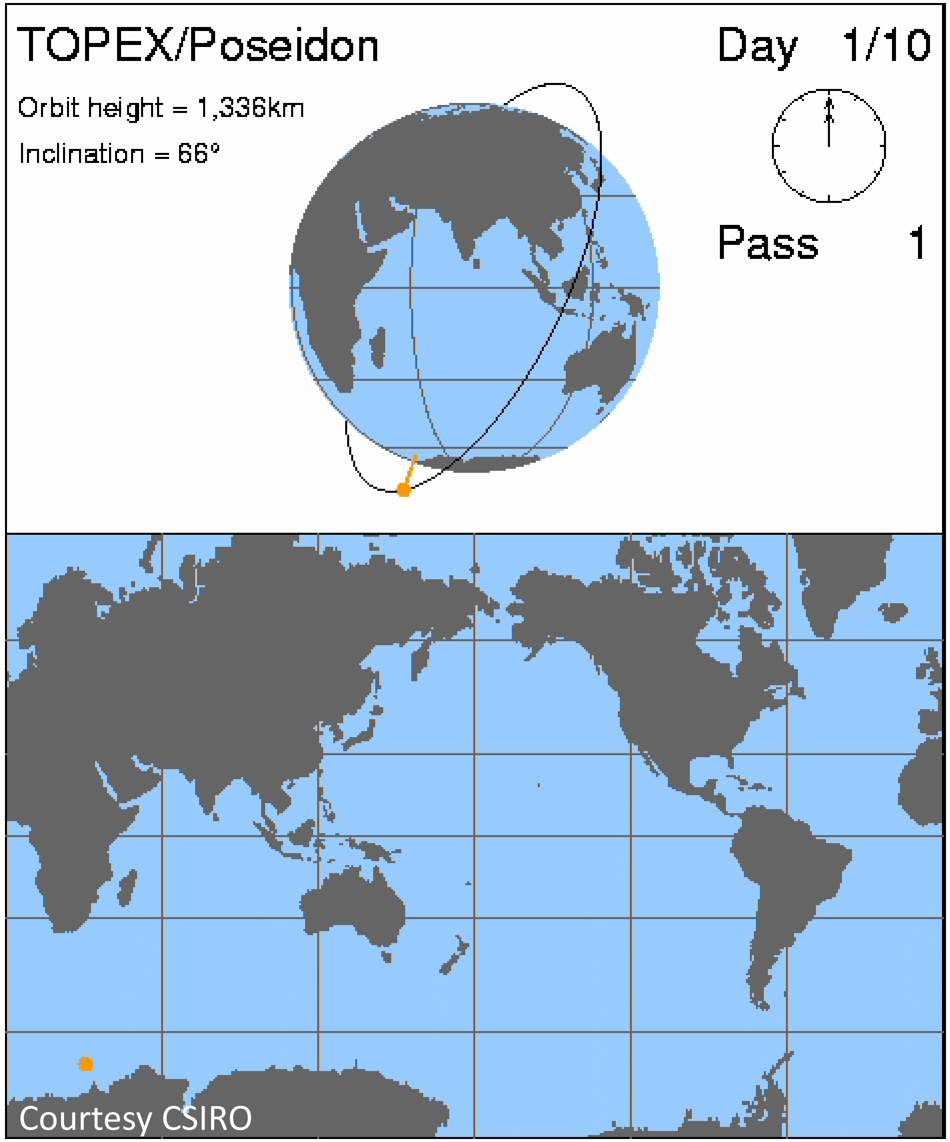


- Radar (active instrument) = measurements for all weather (not affected by clouds or rain) and all time (day/night)
- Principle: measures time (Δt) signal backscattered to satellite -> R=c*Δt/2 (c= speed of light)
- WSE (h) from: h = H - (R + ΣΔR)
- ΣΔR = corrections :
  - Electromagnetic waves slow down by ionosphere, dry and wet troposphere,
  - Pole and solid Earth tides movements (=generated from small perturbations of the Earth rotation axis) need to be corrected

Space and time samplings

- Altimeter instrument provides data "along-track", on a narrow thread of measurements just beneath the satellite

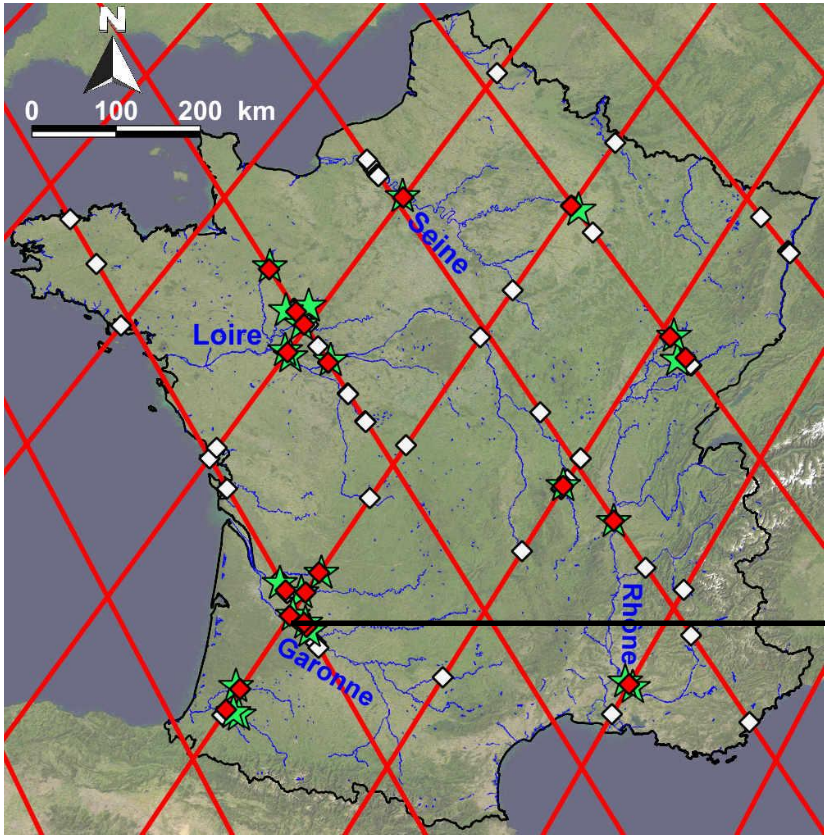
from https://www.aviso.altimetry.fr/fr/multimedia/education/cours-daltimetrie.html

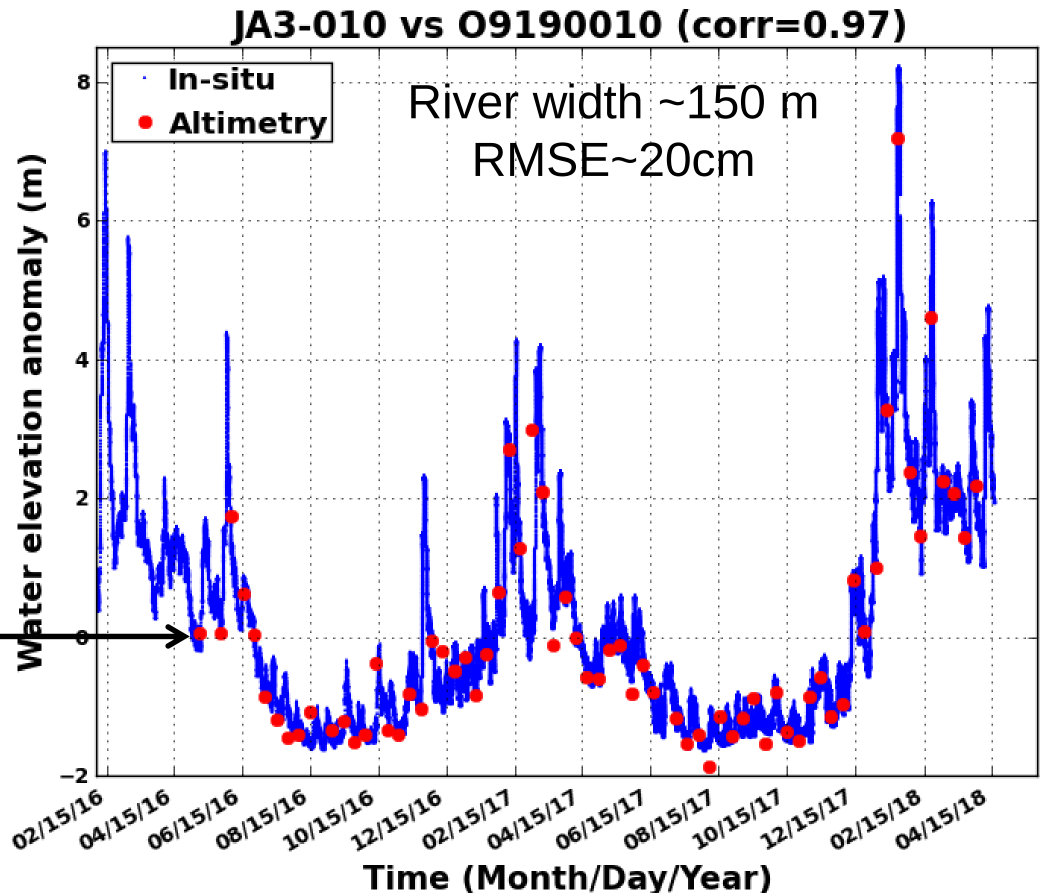


Courtesy CSIRO

Example of nadir altimeter data validation

- Which accuracy can be expected from nadir altimeter? It depends! For example:
  - Root mean square error (RMSE) without temporal mean over river ~20 cm to >1m
  - RMSE over big lakes/reservoirs ~ few cm to 30 cm
  - RMSE more dependent of the observed scene than just river width or water body size

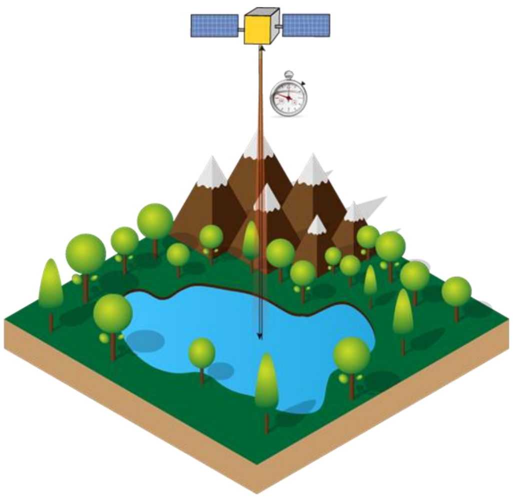




Need for wide swath altimetry

- Main limitations of nadir radar altimetry = time and space samplings, no extent
- Wide swath radar altimetry = images of water topography (from 1D to 2D) -> overcome the space sampling issue

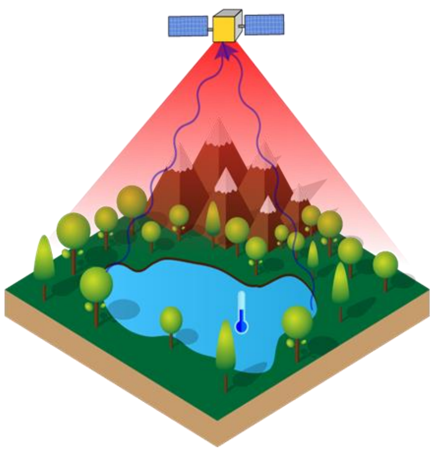
Water Level



Radar altimetry (active sensor)

- Repetitive
- Independent to cloud cover
- Only large lakes and rivers
- Mono variable

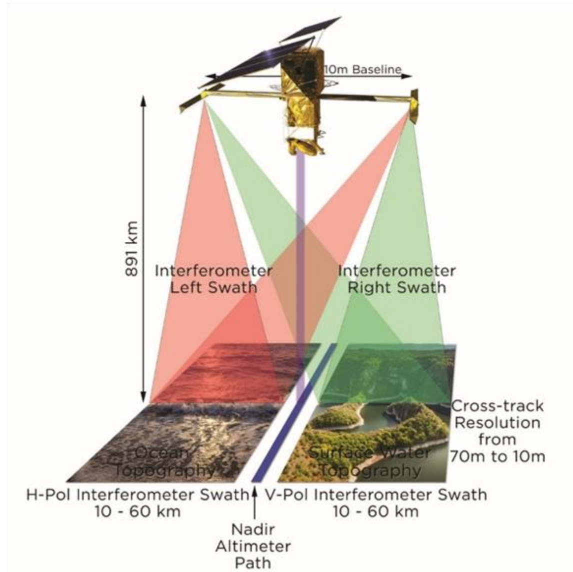
Water extent



Optical imagery (passive sensors)

- Repetitive
- Cloud dependent
- Mulitple size lakes and rivers
- Mono variable

Water level, extent and volume changes



Radar interferometry (active sensors)

- Repetitive
- Independent to cloud cover
- Mulitple size lakes and rivers
- Multi-variables

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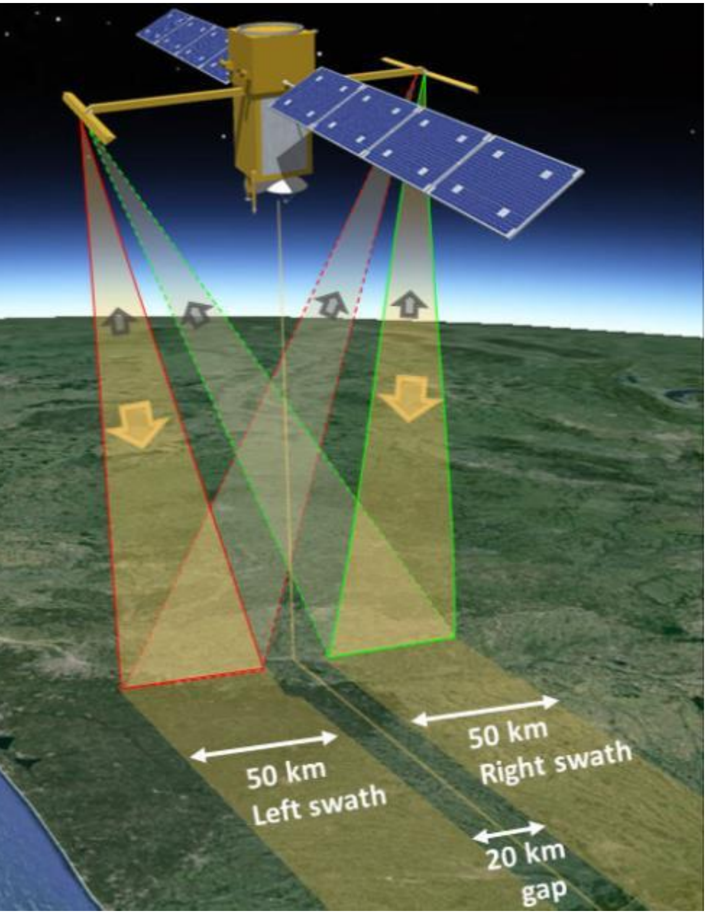
Surface Water and Ocean Topography (SWOT)



Biancamaria et al. (2016)

- Open surface water topography (ocean+continents)
- Nominal mission lifetime: 3 years to 5 years
- Wide swath altimeter + nadir altimeter
- Launched 16 December 2022
- SWOT was first on a 1-day orbit, from January to July 2023, then on its nominal 21-day science orbit (77.6° inclination, 890.56 km altitude)
- Measurement requirements over continents:
  - Water elevations for river wider than 100m, accuracy < 10 cm after aggregation over 1 km^2 of water
  - Water mask, with accuracy < 25%
  - River slope, with accuracy < 1.7 cm/km
- Other added value products over continents:
  - Lakes/reservoirs water volume change
  - Discharge product based on simple Manning equation – steady flow – and bayesian approach to infer unknown parameters (friction coef. and unobserved river cross-section area)

Global lakes and rivers survey from SWOT

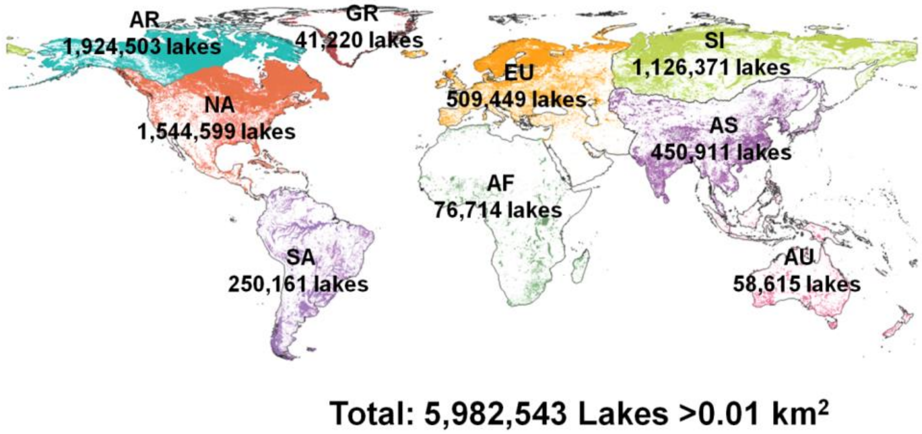
SWOT measurements and products

- **Lakes**

Height, extent & volume changes on lakes larger than 250 m x 250 m (~1.8 M lakes worldwide)

⇒ **Allow water storage changes computation**

⇒ **Understand role of lake in water cycle**



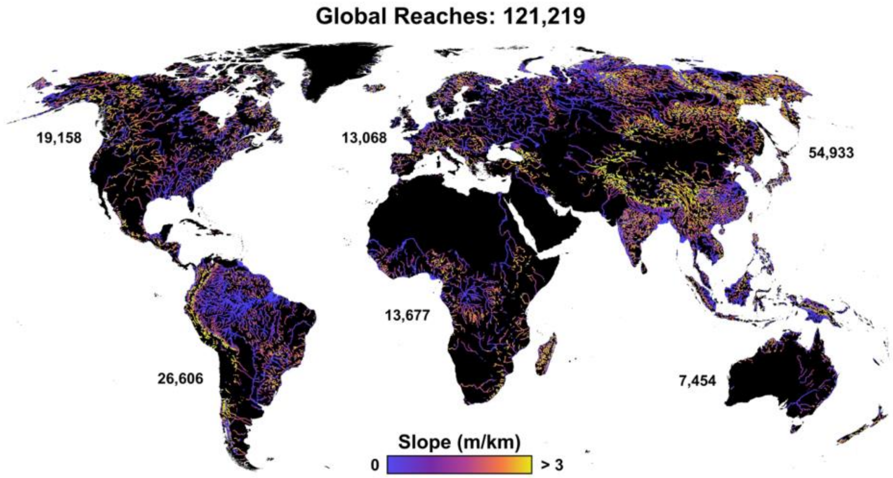
- **Rivers**

Height, slope & width of rivers larger than 100 m

⇒ **Allow discharges computation along pre-defined reaches of 10 km**

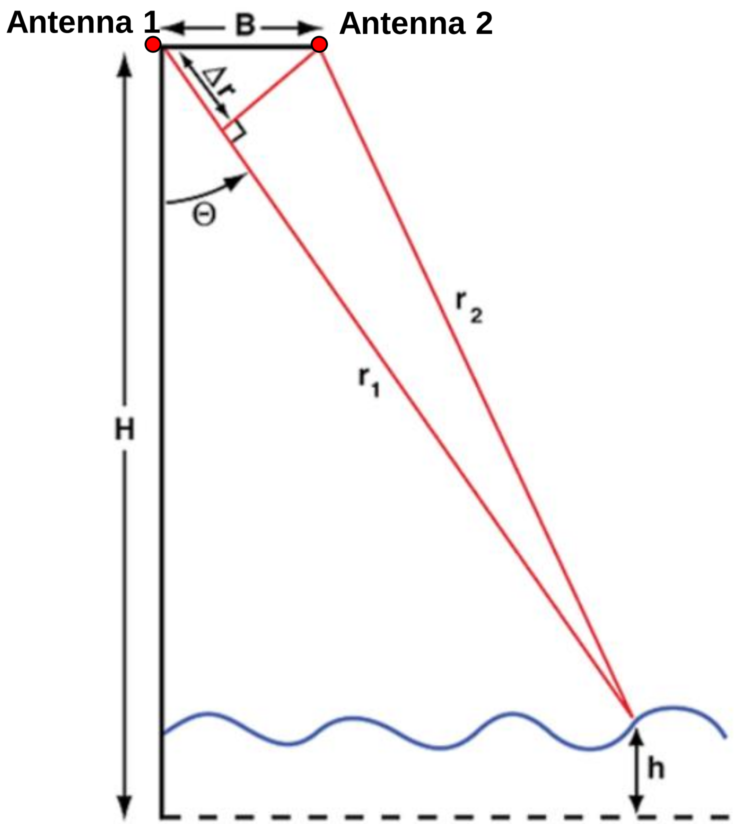
⇒ **Understand role of rivers in water cycle**

⇒ **Understand interaction with floodplain and groundwater dynamics at basin scale**



Principle of wide swath altimetry

- Conceptual view of radar interferometry at near nadir look angles (reality is much more complex!):



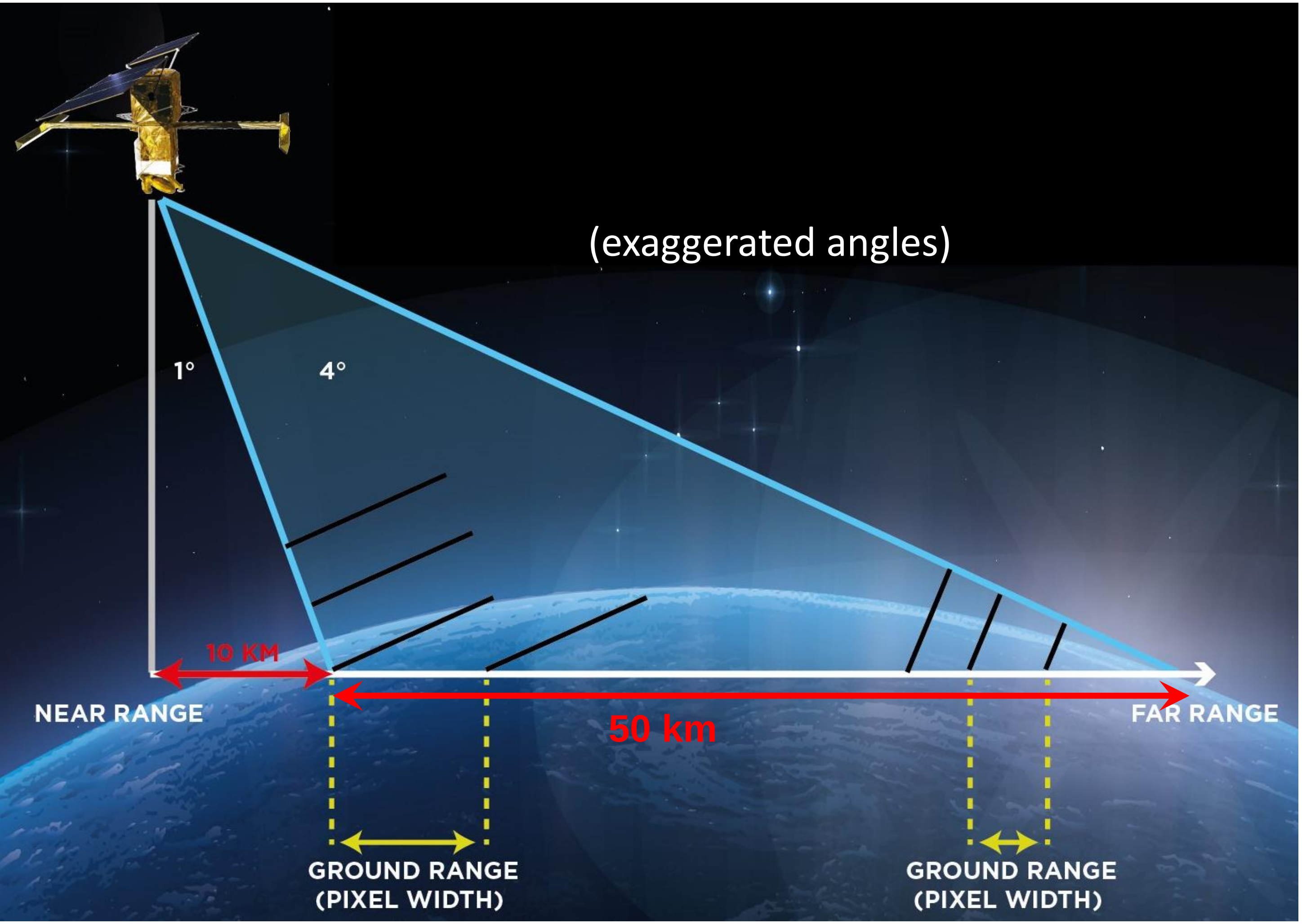
from SWOT Science Document

- Antenna 1 send electromagnetic signal and backscattered signal recorded by antennas 1 and 2
- r_1 is measured by the system timing measurements (~nadir altimeter)
- Θ is estimated by computing the phase difference (δϕ) btw the two electromagnetic signal recorded by antennas 1 and 2 (B = interferometric baseline):

$$\delta\phi = 2.\pi.\Delta r/\lambda = 2.\pi.B.\sin(\Theta)/\lambda \Rightarrow \sin(\Theta) = \lambda.\delta\phi/(2\pi.B)$$

- h is estimated with: $h = H - r_1.\cos(\Theta)$
- These equations assume a flat earth, does not take into account complexity to process SAR images… see Rosen et al. (2000) for the theoretical basis of SAR interferometry

SWOT swath and pixel geometry (side view)

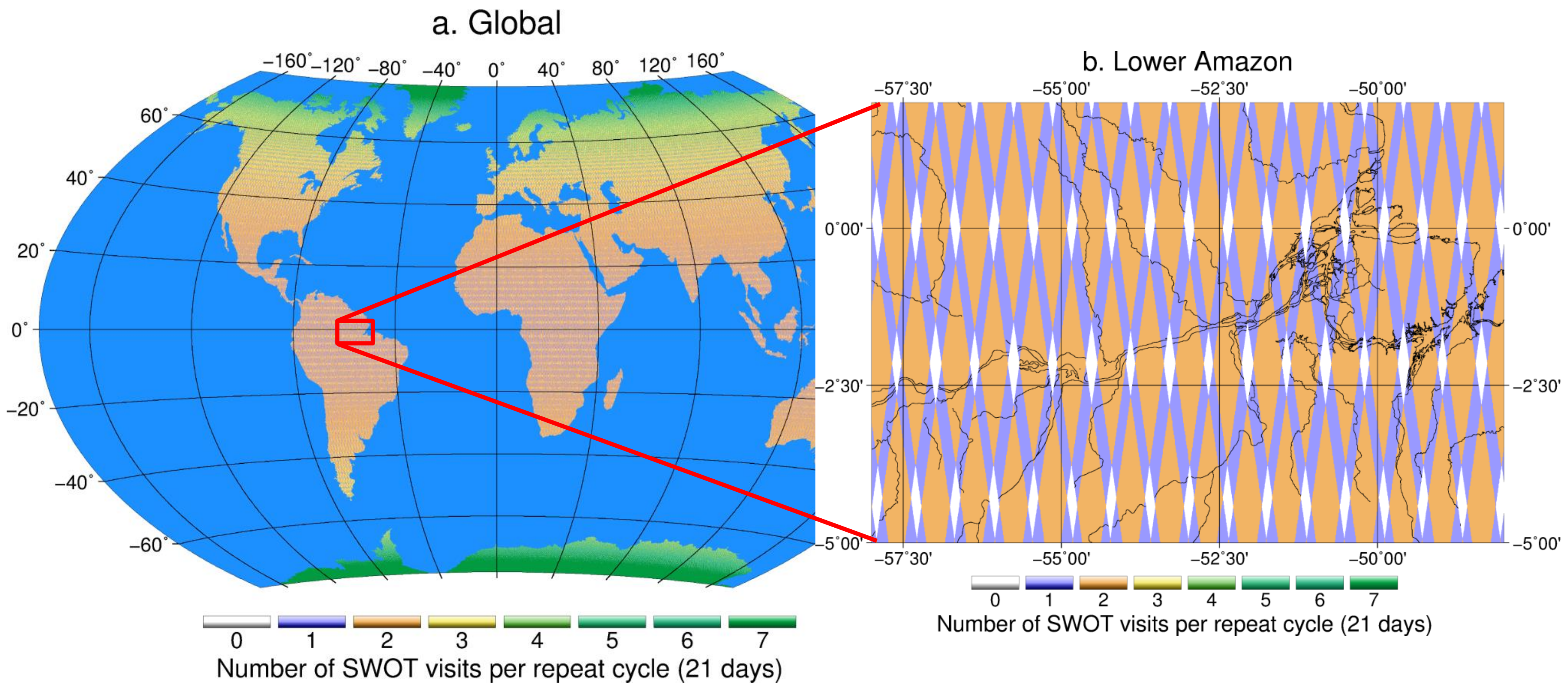


- ± 10 km blind zone around nadir
- 2 swaths of 50 km each
- Thanks to the 2 swaths -> almost global coverage <78°N (3% of continents not observed)

from Jean-François Crétaux

Space and time samplings

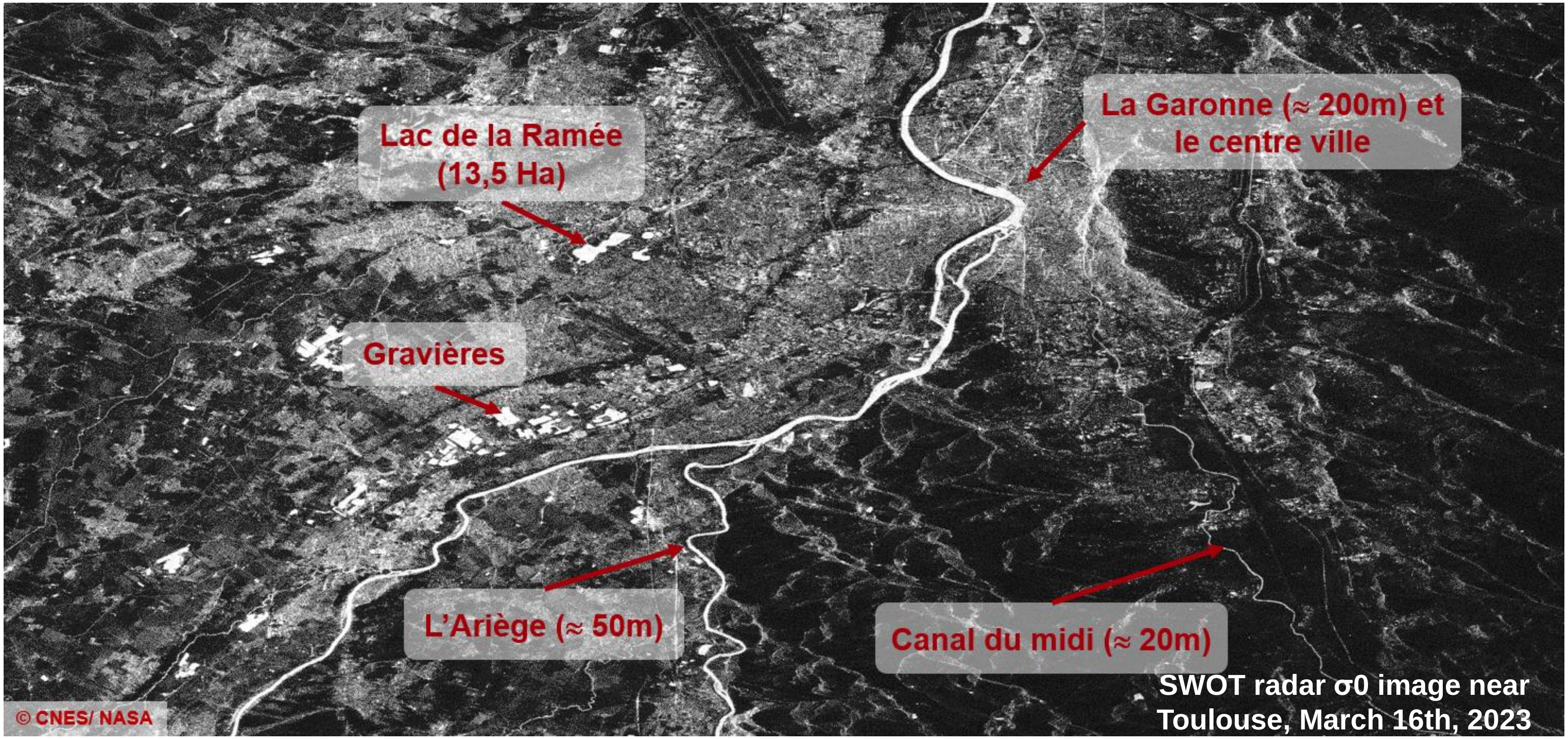
- Environ 0 à 2 obs./21 jours à l'équateur, > 4 obs. au-dessus de 60°N
- 3.6% des surfaces continentales entre 78°S-78°N jamais observées



Biancamaria et al. (2016)

Characterisitcs of SWOT measurements

- SWOT look angle (0.6° to 3.9°) = near-nadir -> water area send back much more energy than other type of soil (contrarily to SAR sensors with higher look angles, e.g. Sentinel-1):



SWOT hydrology error budget over 1 km^2 of water area

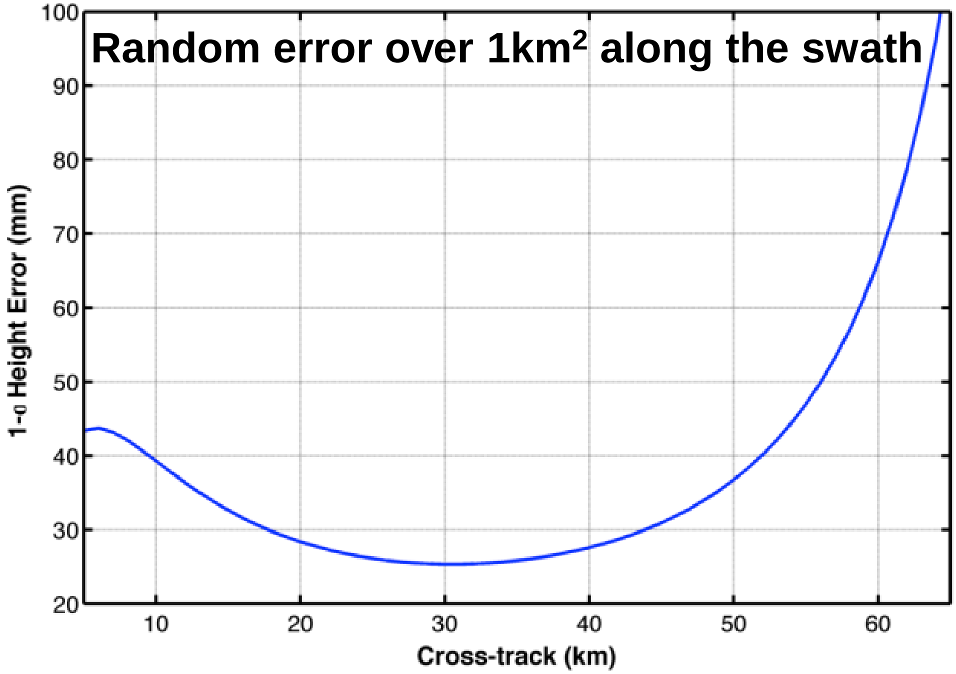
Hydrology Error Component	Height Error [cm]	Slope Error [μrad]
Ionosphere signal	0.8	0.1
Dry Troposphere Signal	0.7	0.1
Wet Troposphere Signal	4.0	1.5
Radial Component	1.62	0.5
KaRIn Random and Systematic Errors after Cross-Over Correction	8.9	15.5
Motion errors	0.8	1.6
Total Allocation (RSS)	**9.98**	**15.7**
Unallocated margin RSS/SUM	0.65 / 0.02	6.6 / 1.3
Total (RSS) Error	**10**	**17**

KaRIn Hydrology Error Component	Height Error [cm]	Slope Error [μrad]
KaRIn Random	4.4	15.3
KaRIn Systematic cross-track errors after cross-over correction	7.4	1.7
KaRIn Systematic along-track height bias error	1.5	0.08
High Frequency errors	1.15	0.5
(Unallocated margin, RSS)	1.23	1.75
Total (RSS) Error Requirement[1]	**8.9**	**15.5**

from SWOT mission performance and error budget document

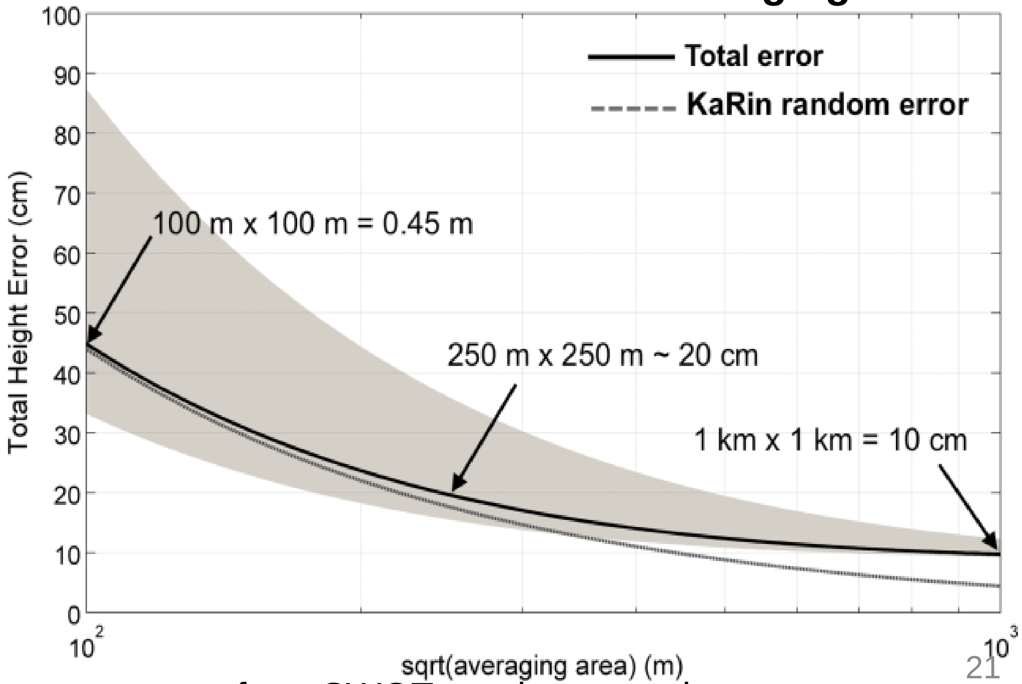
KaRIn random errors

- ‘errors related to the variance of the height (or phase) measurements […], as well as other destructive errors that increase the variance, and which cannot be corrected on the ground’ (from SWOT mission performance and error budget document)
- Decrease when averaging radar pixels (‘destructive errors’)
- Depends of KaRIn signal-to-noise ratio (SNR), the interferometric baseline, and the processing algorithm



from SWOT mission performance and error budget document

KaRIn total error vs water averaging area

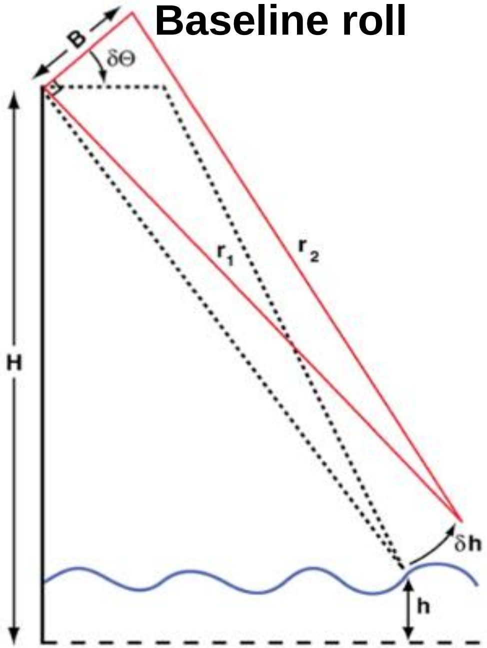


from SWOT requirements document

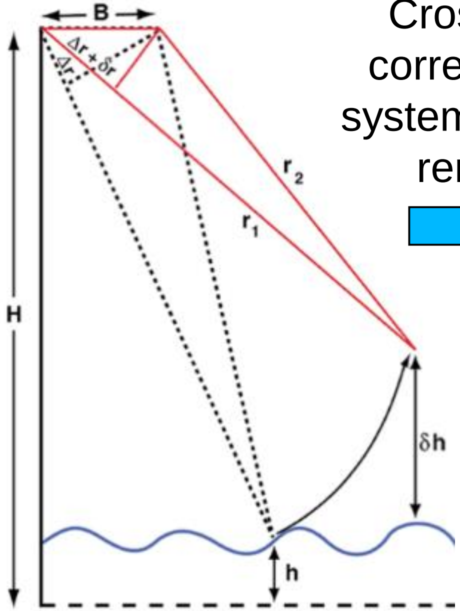
KaRIn systematic errors

- ‘non-destructive errors typically associated with drifts or range variations that end up introducing bias in the measured heights, and which could be corrected if known’ (from SWOT mission performance and error budget document)
- ‘associated with baseline roll, a change in the baseline length, and to range (or timing) and phase drift errors’

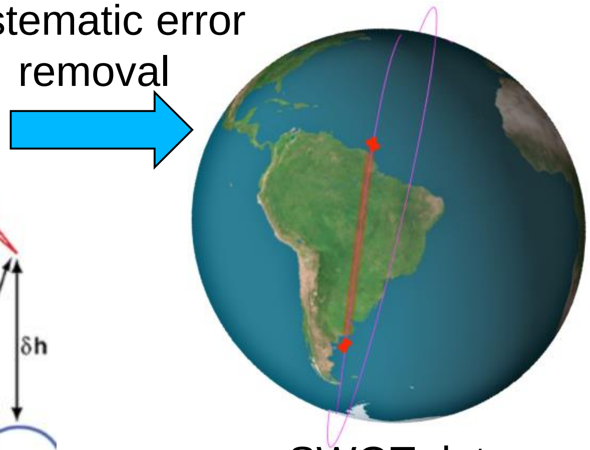
Baseline roll

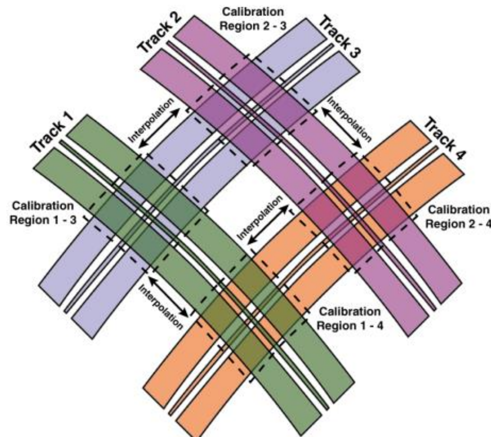


Phase drift



Cross-over correction for systematic error removal



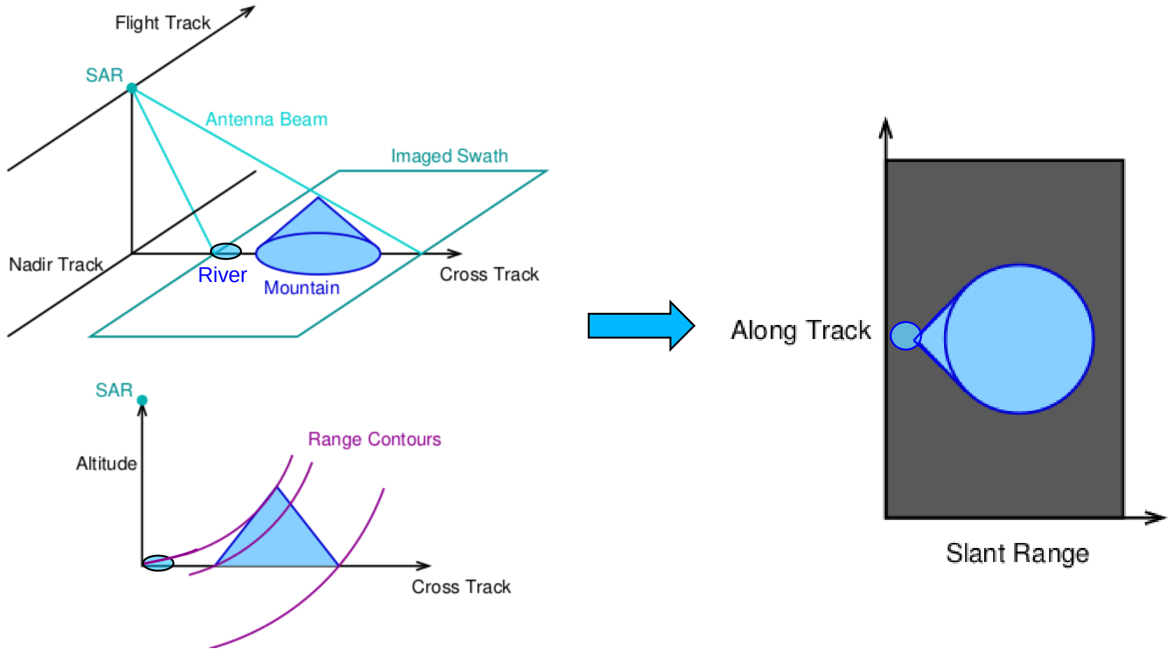


SWOT data over ocean between two different tracks are compared at cross-ovser to correct systematic errors -> correction interpolated

from SWOT mission performance and error budget document

Layover issue

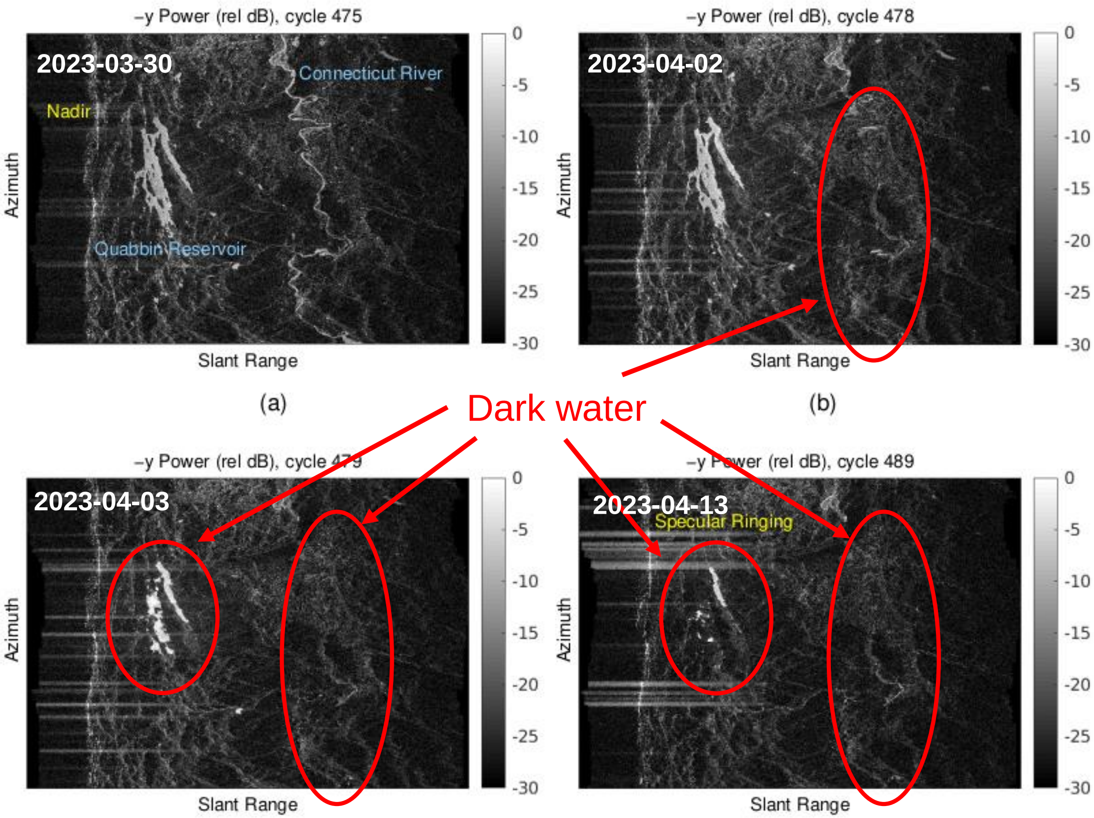
- Layover: land region (e.g. mountain) at same distance of the antenna than water body => they are mixed in the SAR image => error on δφ
- Layover more important at near nadir look angles than higher look angles
- Land-land layover could be falsely detected as water, land-water layover could impact water elevation accuracy, water-water layover lead to even higher errors



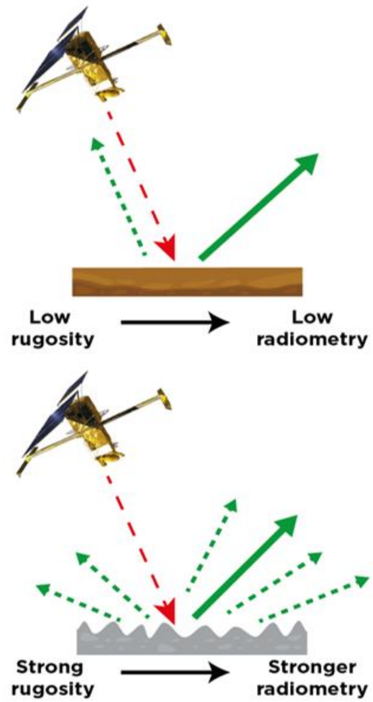
from SWOT Science Data Products User Handbook

Dark water

- '"dark water" refers to water pixels that are believed to be water but that are too unreflective ("dark") to be classified as water by the reflectivity-based detection algorithm' (from SWOT mission performance and error budget document)
- It could be due to rain attenuation or very flat water (i.e. specular) surface



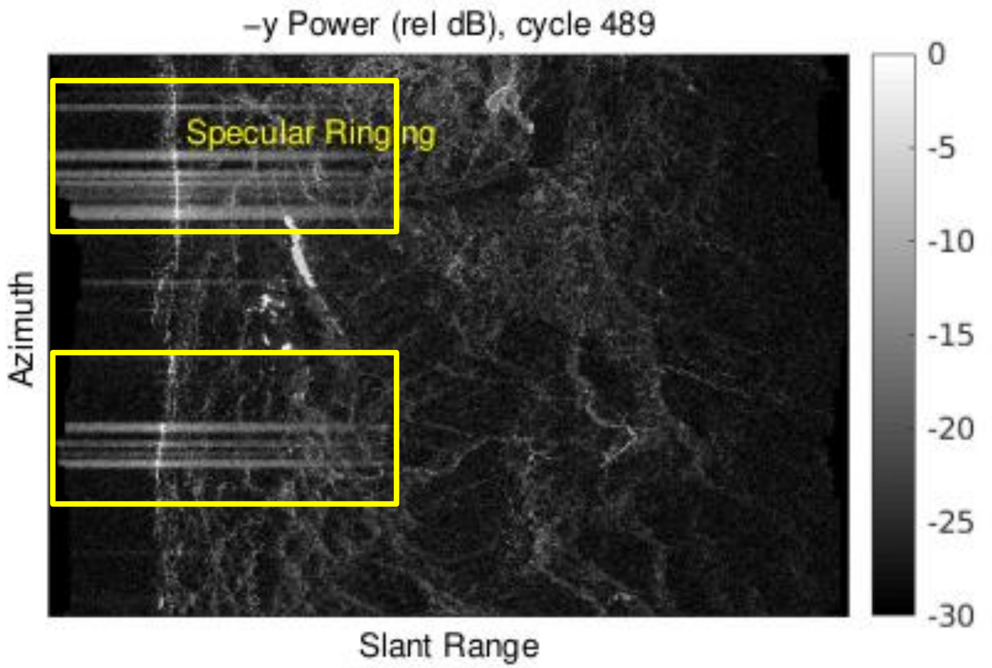
- Water mask badly impacted by dark water effect for some cycles



from SWOT Science Data Products User Handbook

Specular ringing

- 'Occurs when the range side-lobes of bright, specular targets near nadir are strong enough to contaminate other targets in the swath' (from SWOT Science Data Products User Handbook)

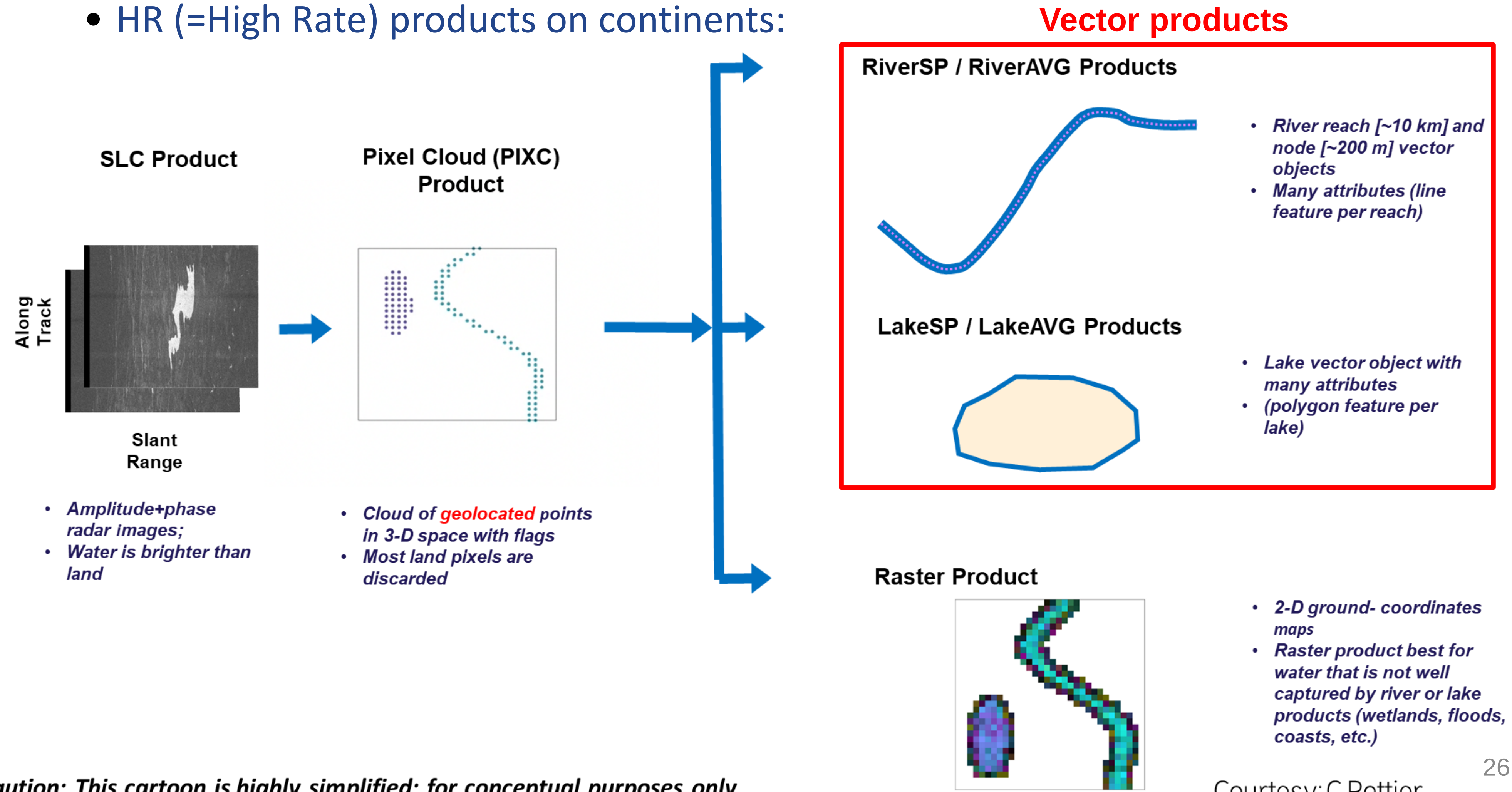


- Specular ringing vary in time
- Affect WSE and water mask (zone affected by specular ringing will be detected as water)
- New processing chain helps to mitigate this issue

from SWOT Science Data Products User Handbook

SWOT products

- Product version C (Since November 2024 = PIC2, PIC0 before)
- LR (=Low Rate) products = ocean products
- HR (=High Rate) products on continents:



Caution: This cartoon is highly simplified; for conceptual purposes only

Courtesy: C.Pottier

Lakes volume change from SWOT in SWOT products

Objectives: Investigating errors expected from the SWOT products (the volume changes) & applications on several cases studies (Sahelian pounds, Brazilian reservoirs, Canadian & French lakes) have been done using simulations.

Algorithm proposed has been implemented on the LOCNES processing chain for operational production

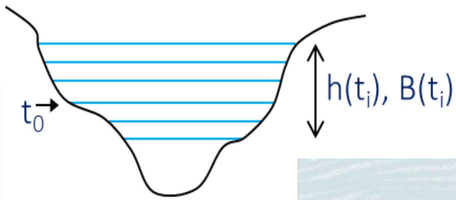
$$\Delta V\left(\frac{t_i}{t_0}\right) = \Delta V\left(\frac{t_{i-1}}{t_0}\right) + \frac{[B(t_i)+B(t_{i-1})+\sqrt{B(t_i)*B(t_{i-1})}]}{3}.[h(t_i)-h(t_{i-1})]$$

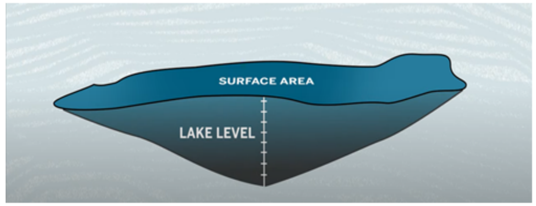
(quadratic case)

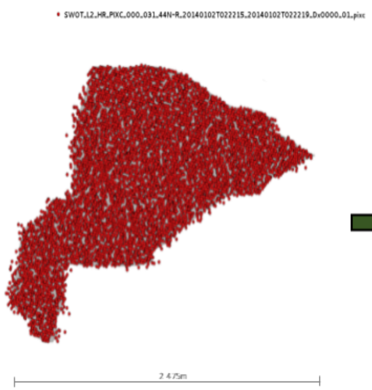
$$\Delta V\left(\frac{t_i}{t_0}\right) = \Delta V\left(\frac{t_{i-1}}{t_0}\right) + \frac{[B(t_i)+B(t_{i-1})]}{2}.[h(t_i)-h(t_{i-1})]$$

(Linear case)

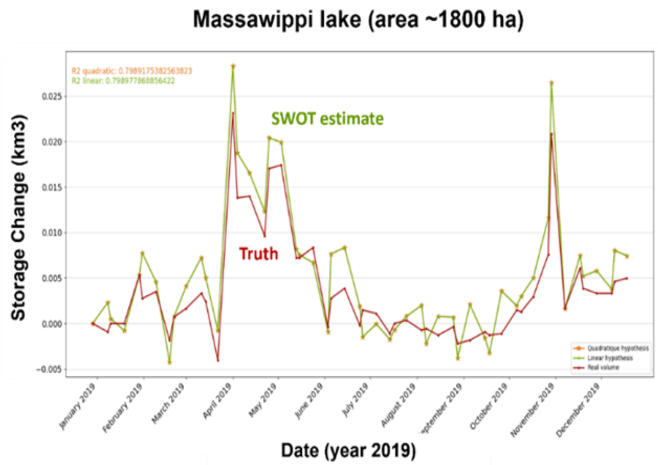
$$\sigma(Me) = \sqrt{\sigma(H1)^2\left(\frac{\partial\Delta V}{\partial H1}\right)^2 + \sigma(H2)^2\left(\frac{\partial\Delta V}{\partial H2}\right)^2 + \sigma(A1)^2\left(\frac{\partial\Delta V}{\partial A1}\right)^2 + \sigma(A2)^2\left(\frac{\partial\Delta V}{\partial A2}\right)^2}$$







PixC product



Vector product:
H,E,dV/dt

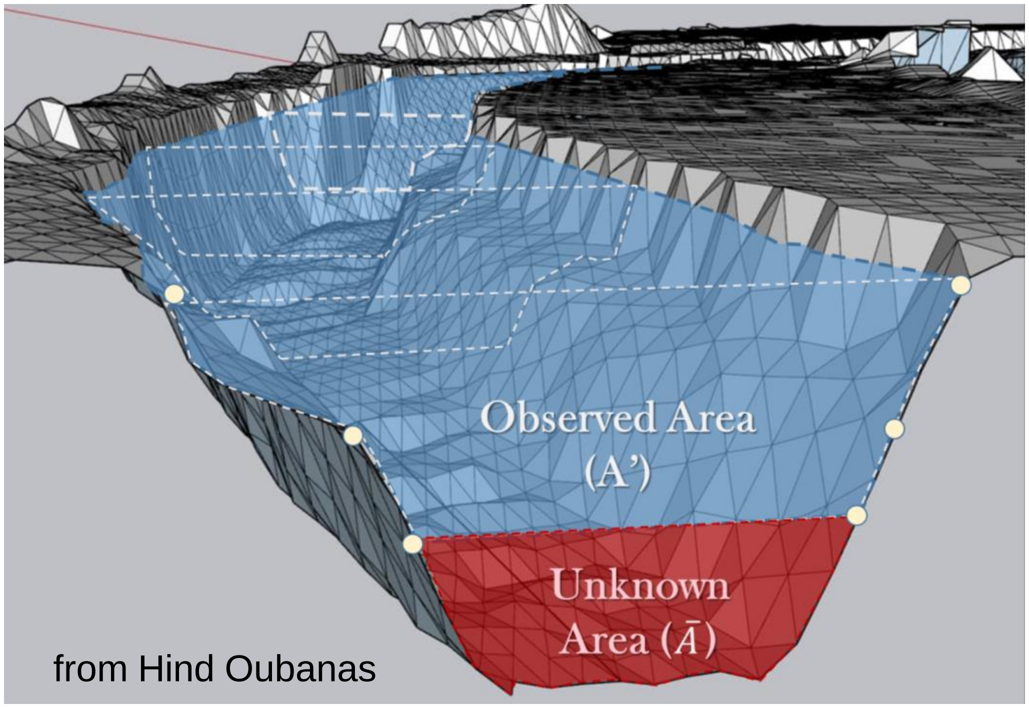
Simulations were done on dozen of lakes of different size and shape
Errors never exceeded 10% (in rare cases) of the real volume changes

from Jean-François Crétaux

SWOT river discharge product

- 6 river discharge algorithms applied at global scale using SWOT river WSE, slope and width have been developed to infer river discharge, friction coefficient and unobserved bathymetry, available in RiverSP Reach products
- Most of them are based on simplified diffusive approximation to the shallow water equations or Manning equation (for more info, see Durand et al., 2023)

$$Q = \underbrace{\frac{1}{n}}_{\text{Inferred from SWOT discharge algo.}}(\bar{A} + \underbrace{A')^{5/3}W^{-2/3}S^{-1/2}}_{\text{from SWOT measurements}}$$



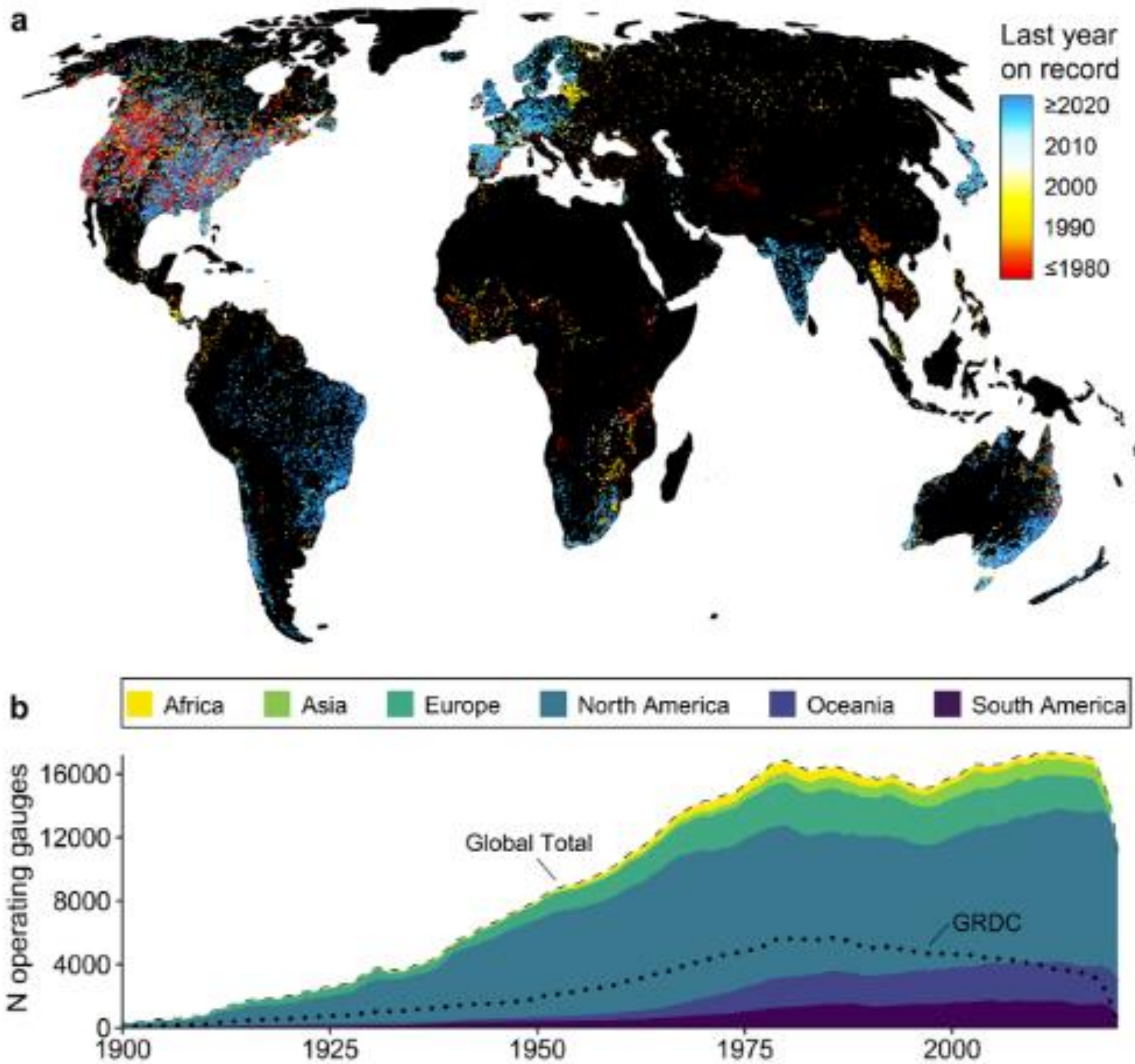
from Hind Oubanas

SWOT validation and complementarity with in situ network

- Validation based on specific in situ campaign + operational WSE and Q in situ network (but does not cover all regions).

- SWOT will not (and never) replace these gauges (which measure every 15 minutes and direct measurement of discharge!)

- But will complement in situ network: having discharge every 1-2 weeks all over the globe would be revolutionary! + global inventory of lakes (not possible on ground)



Riggs et al., 2023

SWOT products

- SWOT HR products could be downloaded at:
  - https://search.earthdata.nasa.gov/search?fpj=SWOT (NASA)
  - https://hydroweb.next.theia-land.fr/ (CNES)
  - Visualization: https://swotvis.cuahsi.io
  - Tools to get river/lake time series from vector products: https://podaac.github.io/hydrocron/intro.html#
  - To search and download data, you will need to get SWOT tiles covering your sites -> get the kmz file (could be seen with Google Earth) https://archive.podaac.earthdata.nasa.gov/podaac-ops-cumulus-docs/web-misc/swot_mission_docs/swot_science_coverage_20240319.kmz
- Tutorials:
  - Cookbook: https://podaac.github.io/tutorials/quarto_text/SWOT.html
  - Doc on products: https://podaac.jpl.nasa.gov/SWOT?tab=datasets-information&sections=about%2Bdata%2Bresources
- Tips:
  - Read the doc (especially SWOT Science Products User Handbook)
  - Vector product are easier to use, but more difficult to analyze errors -> look at raster and Pixecl Cloud products

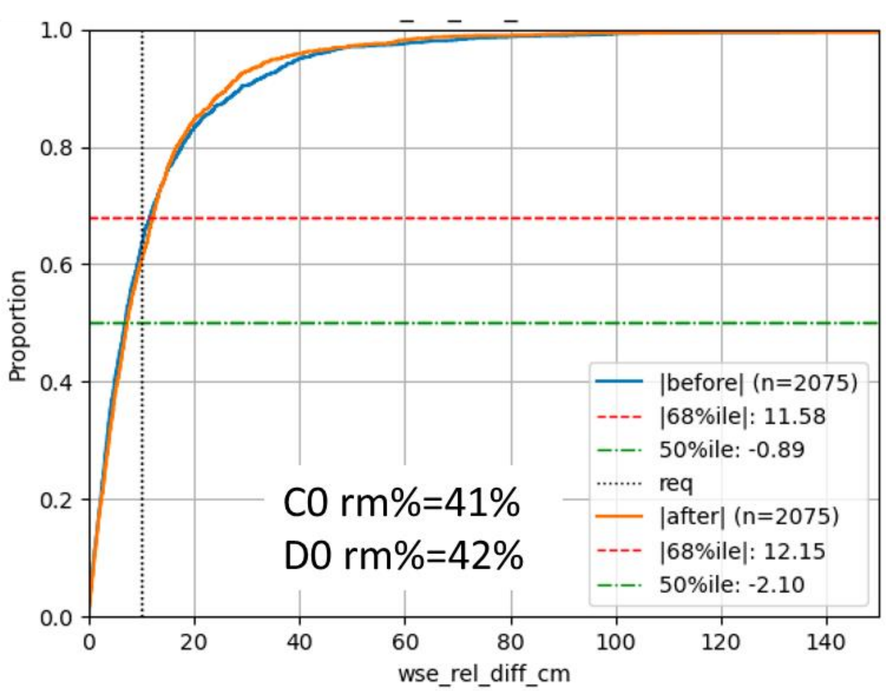
Outline

1. Context and need for the SWOT mission
2. Princip of the SWOT mission
3. **Example of scientific studies with SWOT**

Validation of SWOT WSE compared to in situ WSE

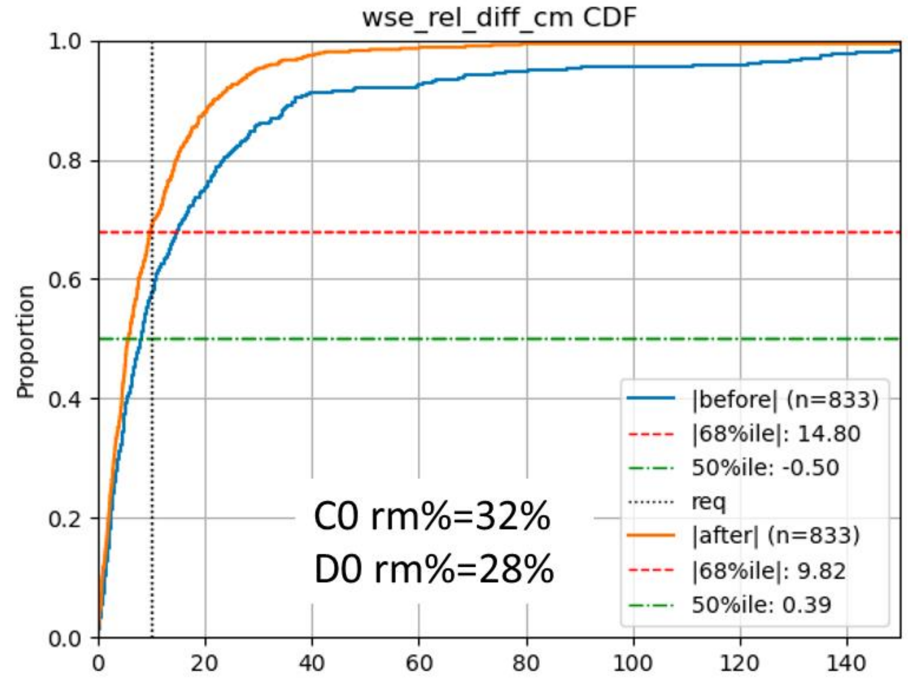
SWOT observations are generally quite accurate

Node Performance CDF with SWOT Qual Filters



River node WSE performance is astonishingly good relative to pre-launch expectations

Reach Performance CDF with SWOT Qual Filters

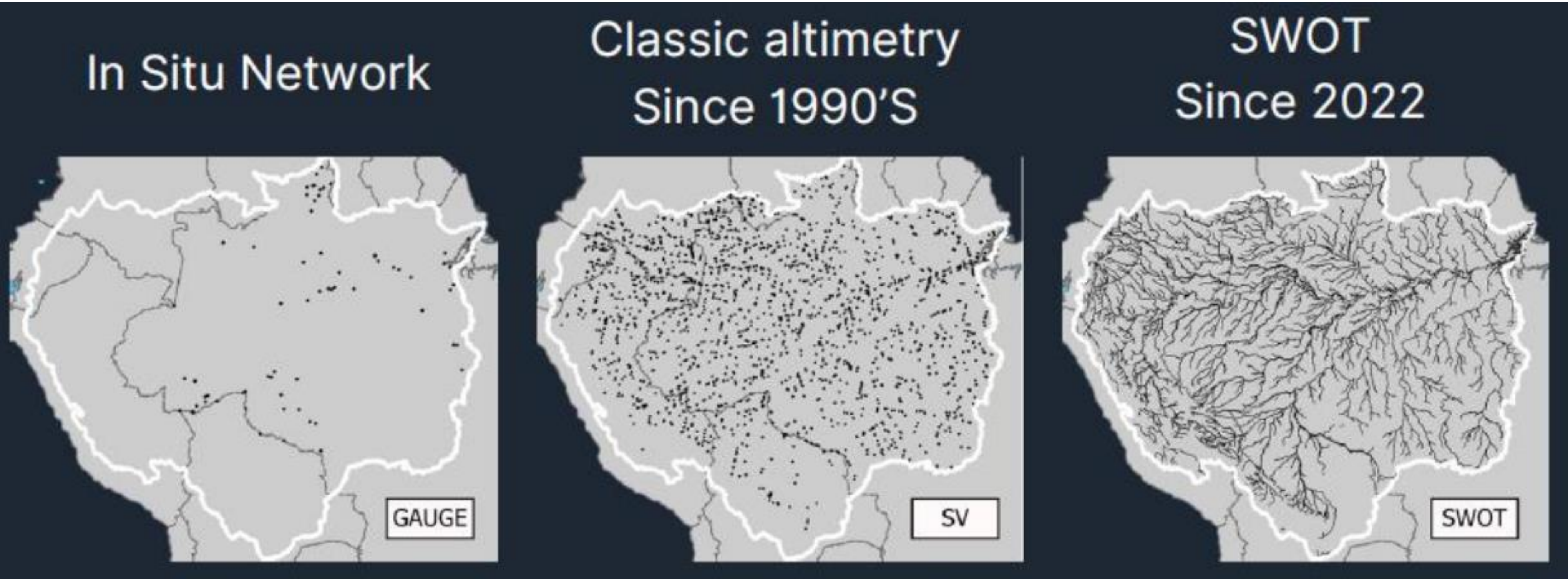


Reach WSE performance is continuing to improve with algorithm enhancements

Courtesy Cassie Stuurman, JPL

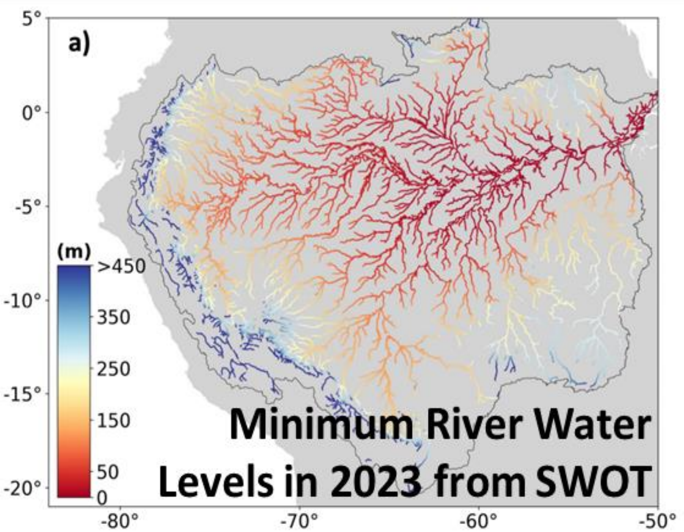
Amazon basin river elevation dynamic from SWOT

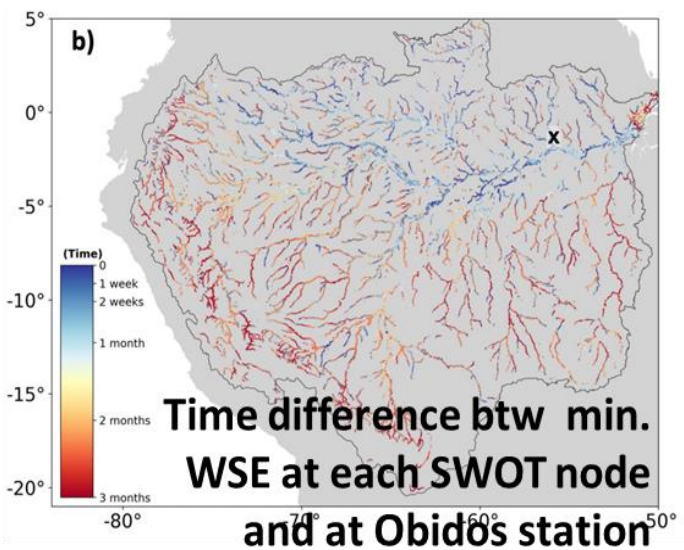
- Observation revolution from SWOT



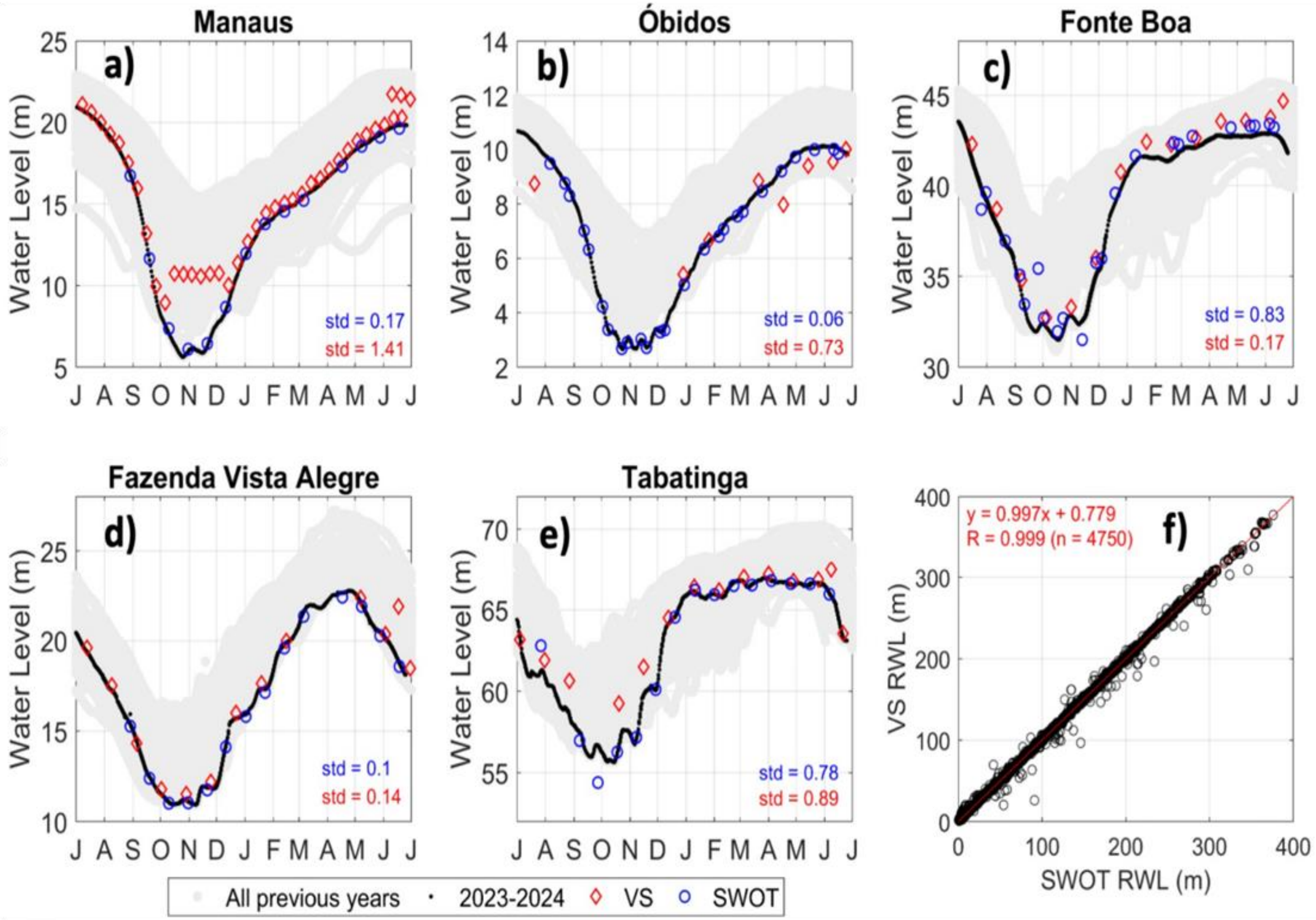
from Moreira et al. (2024), South America Water from Space symposium

Amazon river elevation dynamic from SWOT



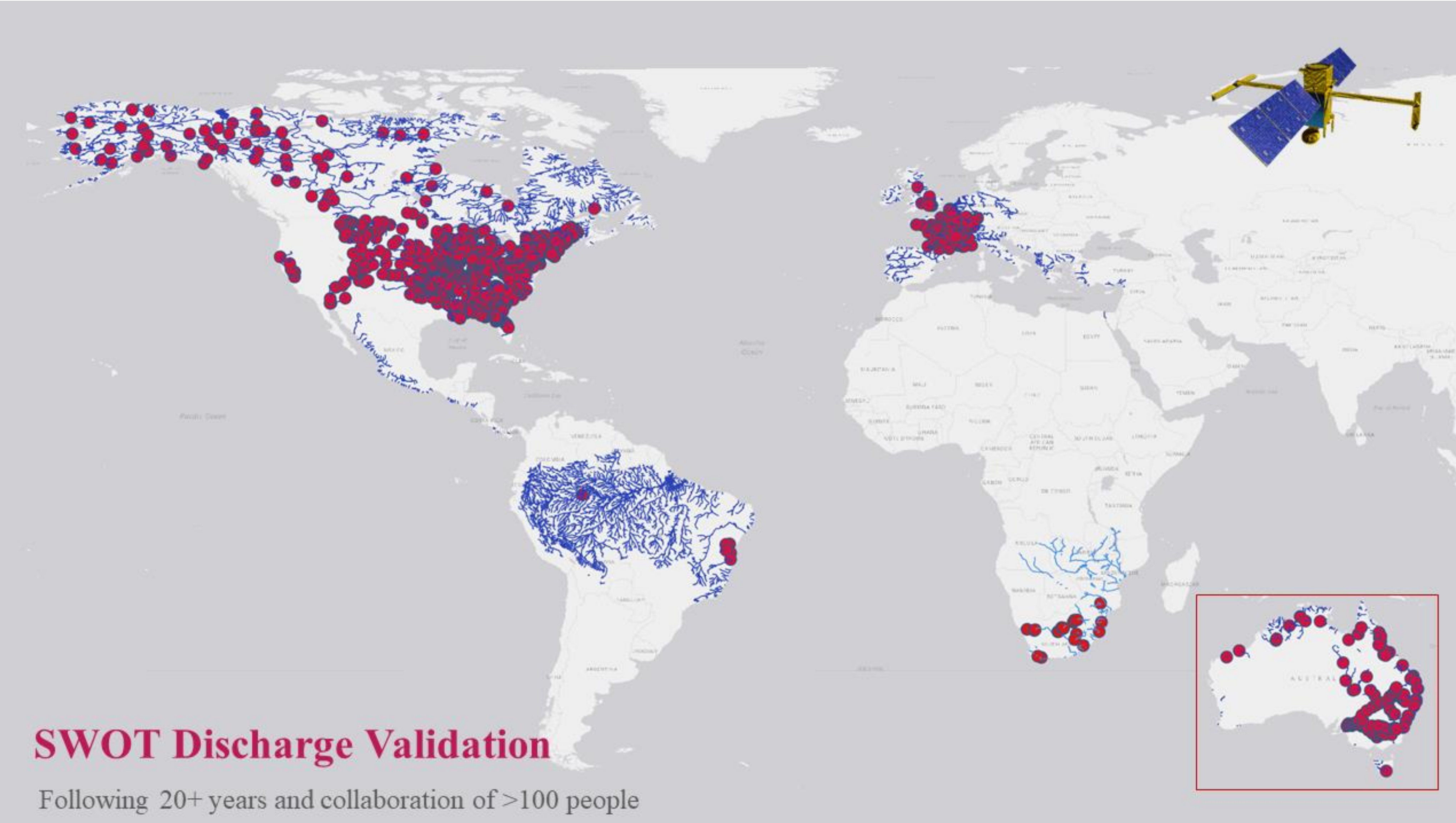


SWOT and nadir alti WSE validation at 5 gauge from July 2023 and June 2024



Moreira, Papa et al., 2024

SWOT discharge product validation

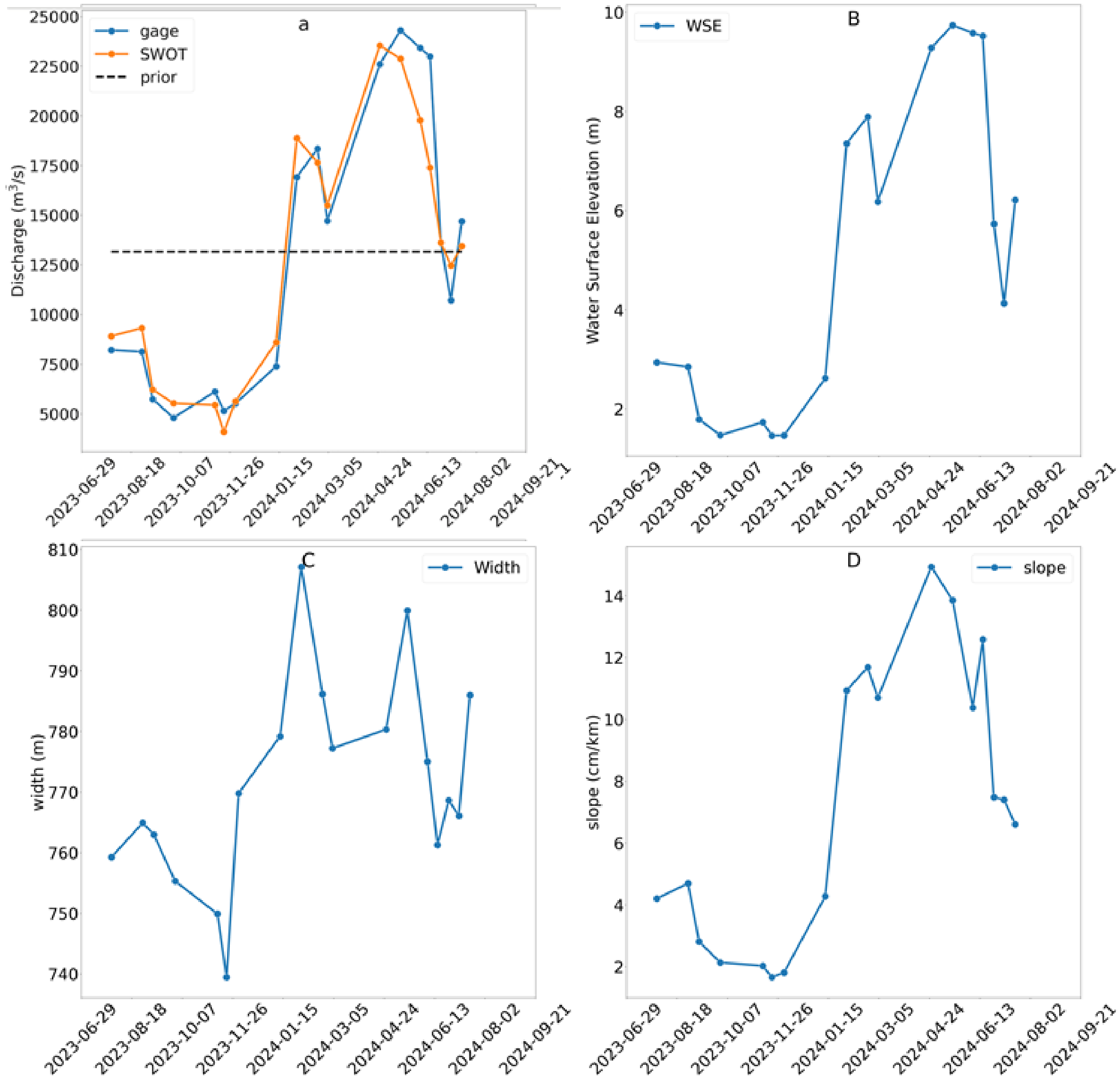


from DAWG

SWOT discharge product validation

SWOT discharge tracks discharge variations globally

- Global run of SWOT discharge retrievals track in situ gages where SWOT reach measurements pass rigorous filters
- Outstanding result (at right) shows promise; ongoing work addresses timeseries bias in other reaches
- Overall >11,000 reaches globally pass these filters, 5x more than global near-real-time gages on equivalent rivers

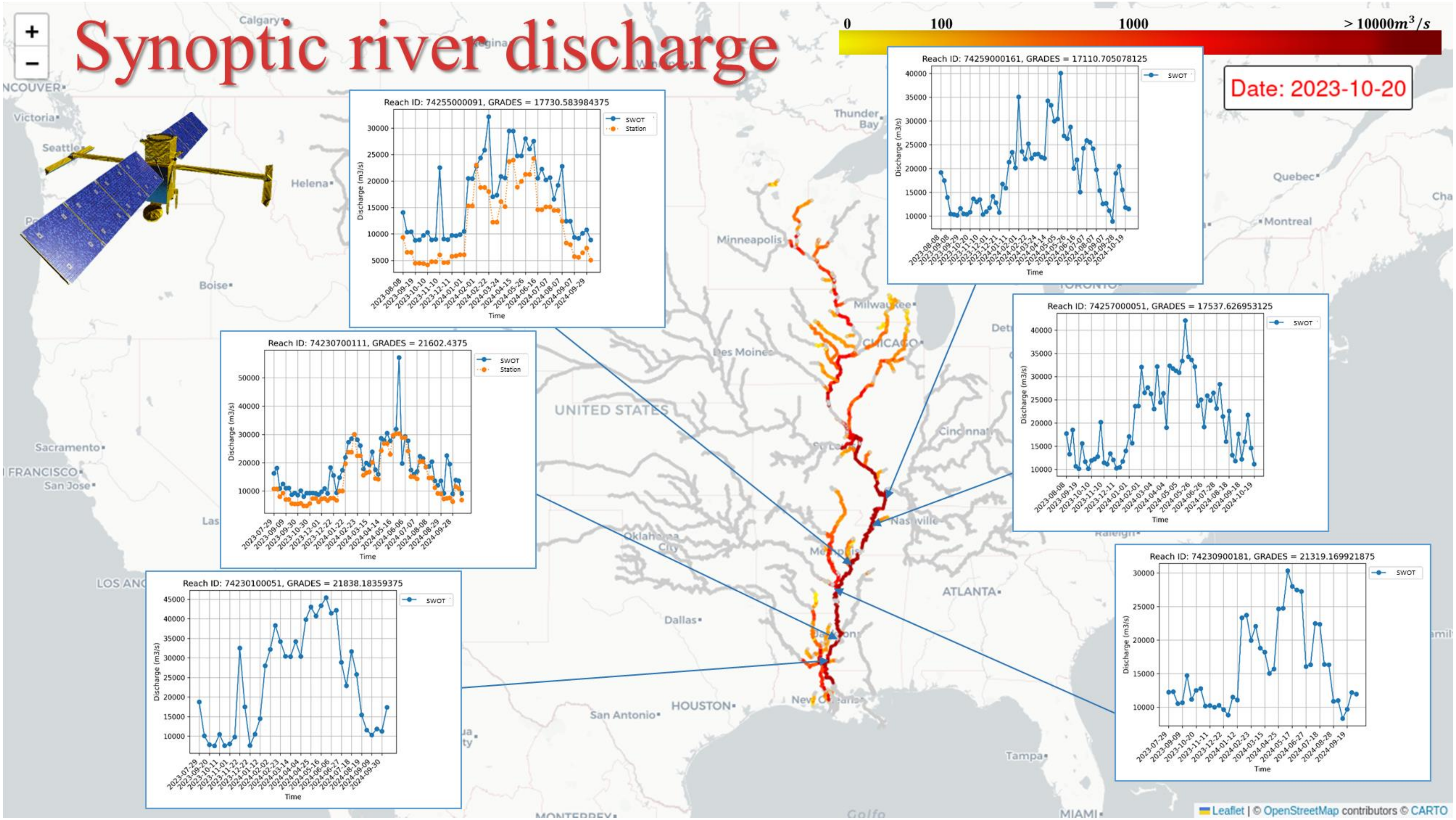


SWOT WSE, width and slope accurately predict river discharge on the Mississippi River.
Andreadis et al., in review at GRL

Courtesy the DAWG Team

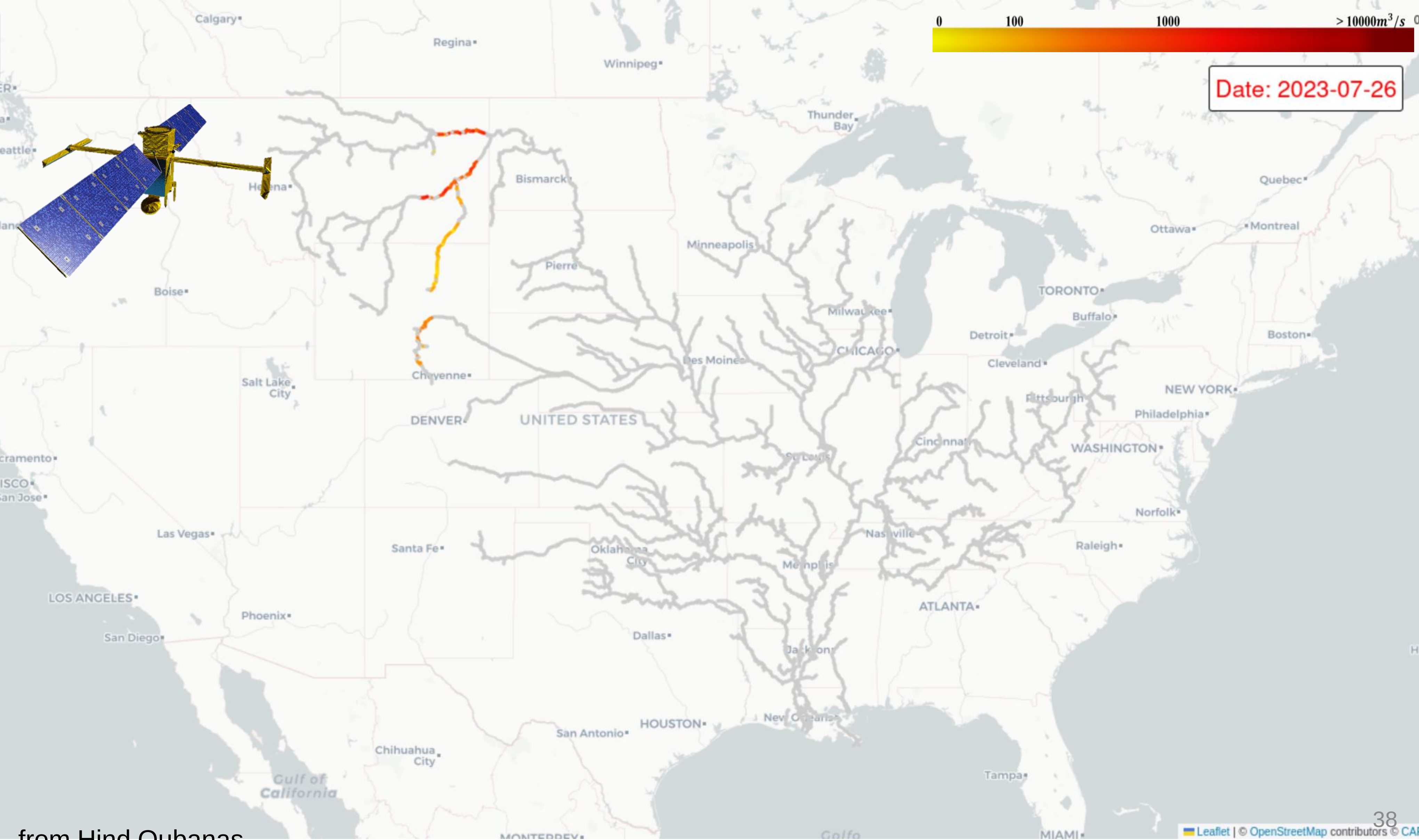
from Steve Coss, AGU 2024

SWOT discharge product validation



from DAWG

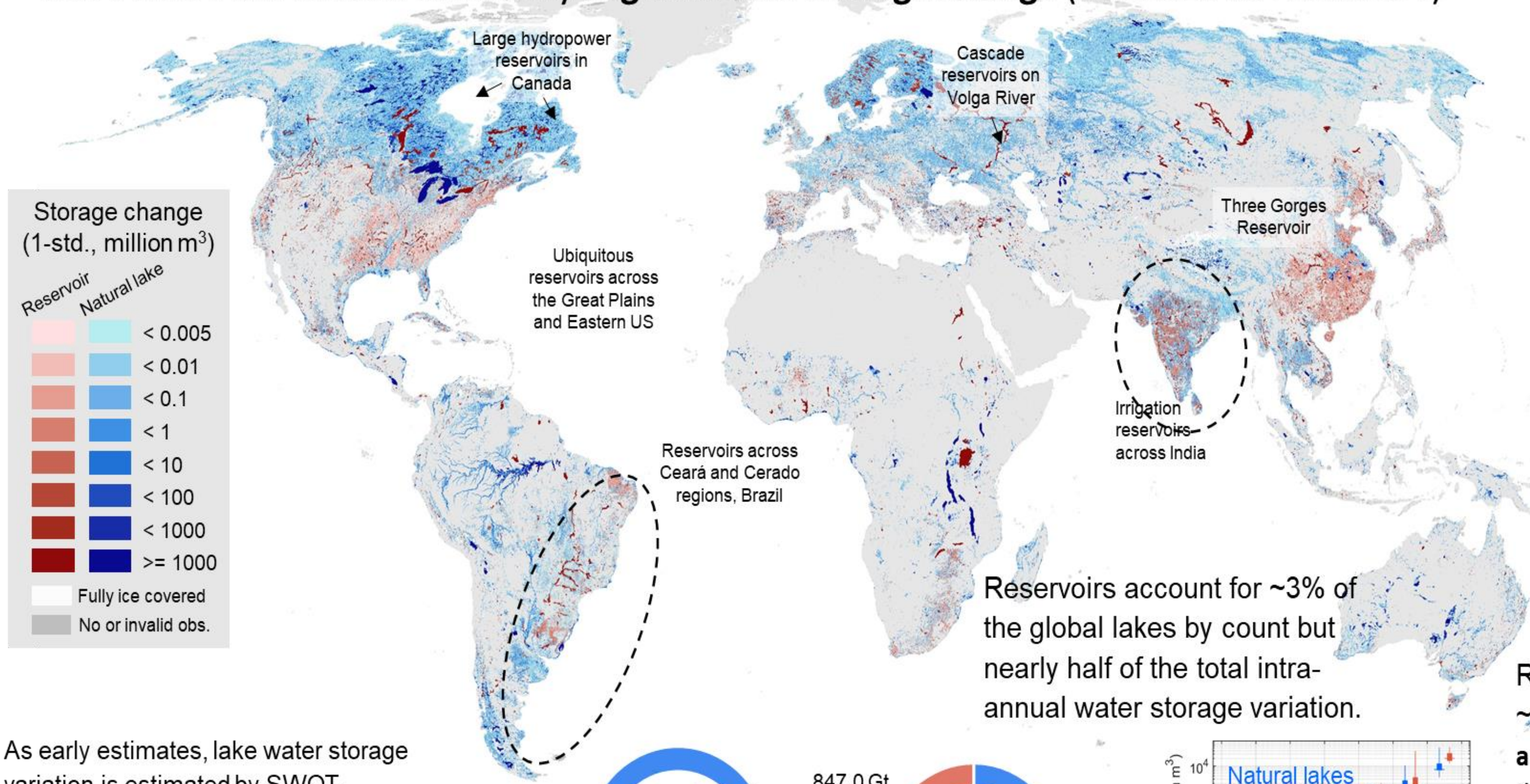
Example of SWOT discharge product in time



from Hind Oubanas

1st look at global lake storage change from SWOT (Jul. 2023 to Nov. 2024)

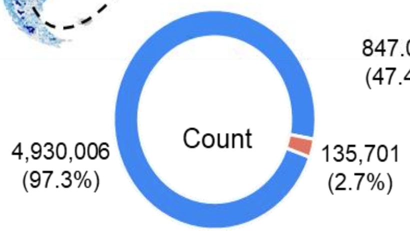
SWOT's first intra-annual variability in **global lake storage change** (Jul. 2023 to Nov. 2024)

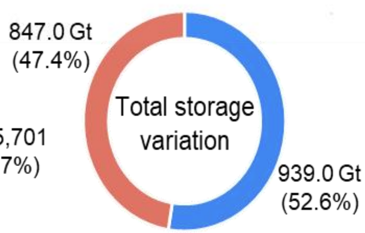


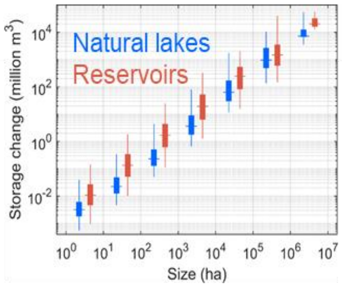
Reservoirs account for ~3% of the global lakes by count but nearly half of the total intra-annual water storage variation.

As early estimates, lake water storage variation is estimated by SWOT-measured WSE variation multiplied by the static prior lake area.

More accurate, realistic results will become available with the accumulation of SWOT data.





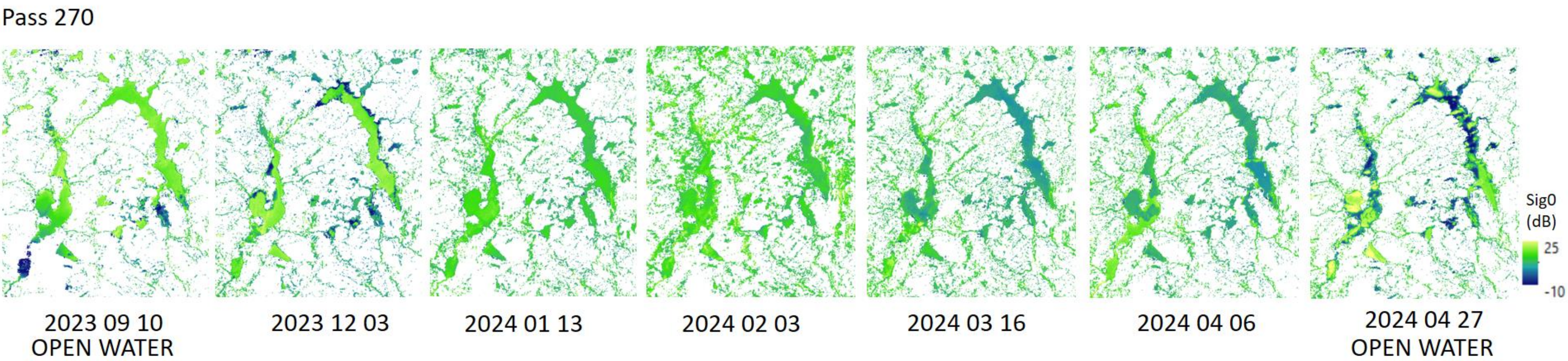


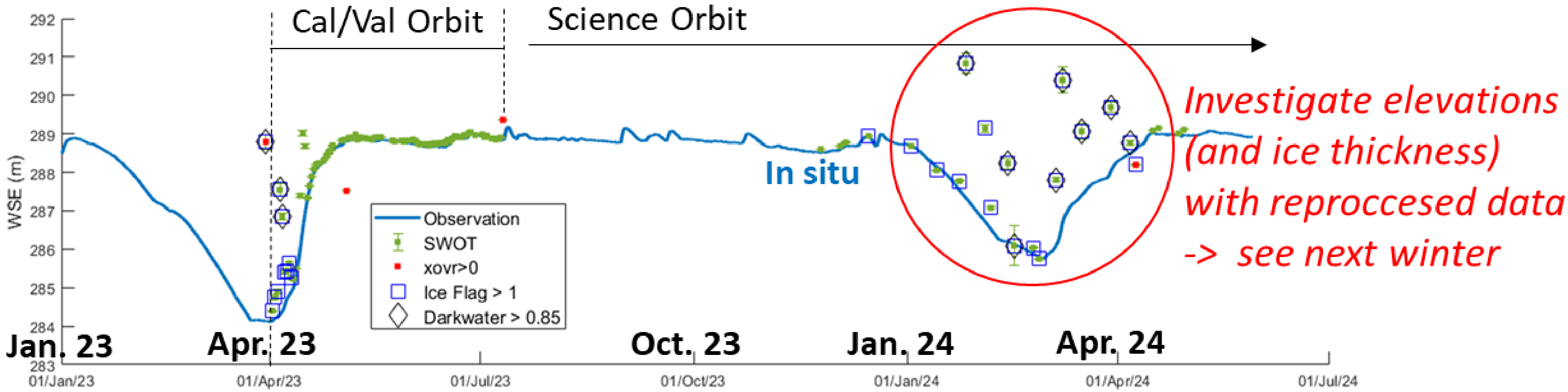
Lakes with only one measurement are excluded from change statistics.

Reservoirs experience ~54–620% **more intra-annual storage variation** than natural lakes due to direct human water management.

from Jida Wang (U. of Illinois) et al., in progress

Lake ice from SWOT





from Melanie Trudel, Gabriela Siles, Samuel Foucher (2024), in progress

Conclusions

- SWOT is a very promising and successful mission to observe continental open waters.
- SWOT requirements on WSE are met, SWOT random error seems lower than expected
- Because of specular ringing, lay over, but more importantly dark water, water mask (i.e. river width and lake extent) is sometimes underestimated (and could even be missed)
- Water bodies smaller than the requirements can be observed with SWOT
- Still need to better understand and process this new type of complex measurements -> many years of research!
- SWOT offer an new synoptic observation of rivers, canals, lakes, reservoirs, wetlands which will help to better understand and predict continental part of he water cycle!

For more information, you can contact SWOT French Hydrology Science PI (Hind OUBANAS, hind.oubanas@inrae.fr) or me (sylvain.biancamaria@univ-tlse3.fr)


Thank you!!!
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