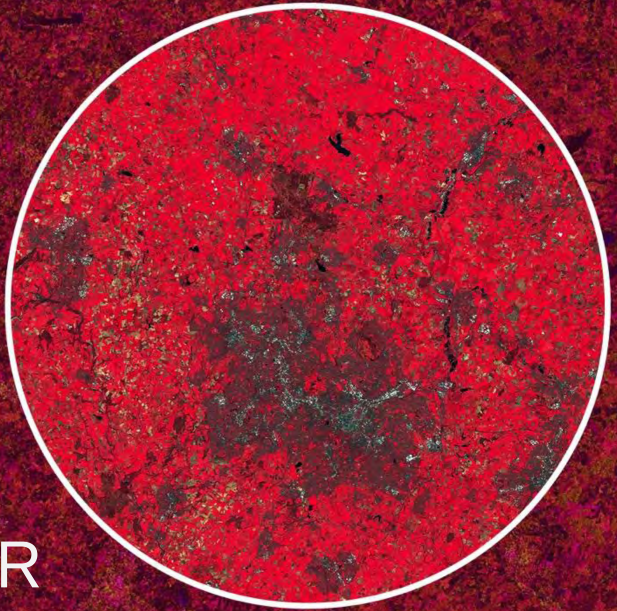
→ 8th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

10–14 September 2018
University of Leicester | United Kingdom



RIVER DISCHARGE AND LAKE VOLUME VARIATION USING RADAR ALTIMETRY AND IMAGING SENSORS

Angelica Tarpanelli & Jérôme Benveniste

Summary

- ***Satellite data: Radar altimetry***
  - ***Principles***
  - ***Missions and technologies***
  - ***Data access and toolboxes***

- ***Satellite data: Optical and multispectral sensors***
  - ***Missions and technologies***
  - ***Data access***

- ***Hydrological Applications***
  - ***River Discharge (from altimetry, from multispectral sensors, from multi-mission)***
  - ***Lake Volume variation (from multi-mission)***

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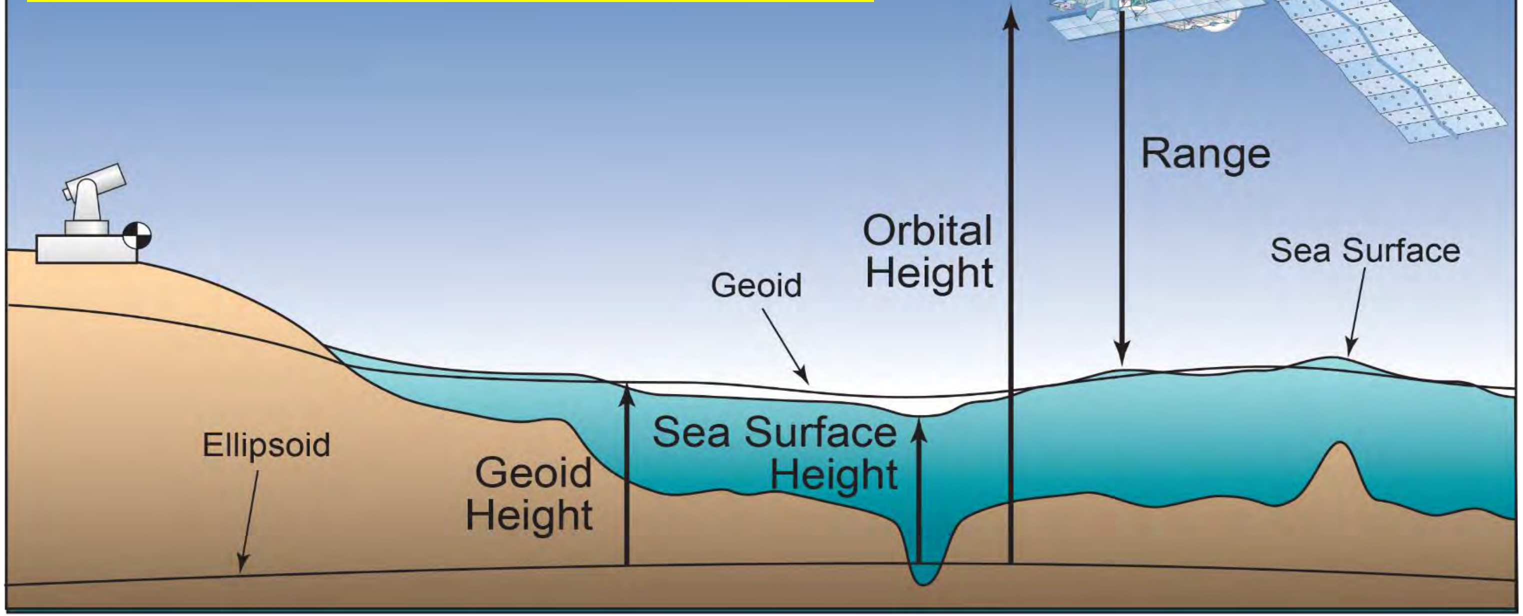
Radar altimetry principles

Altimeters measure the **range** between the **satellite** and **the surface** observed at nadir.



Radar altimetry principles

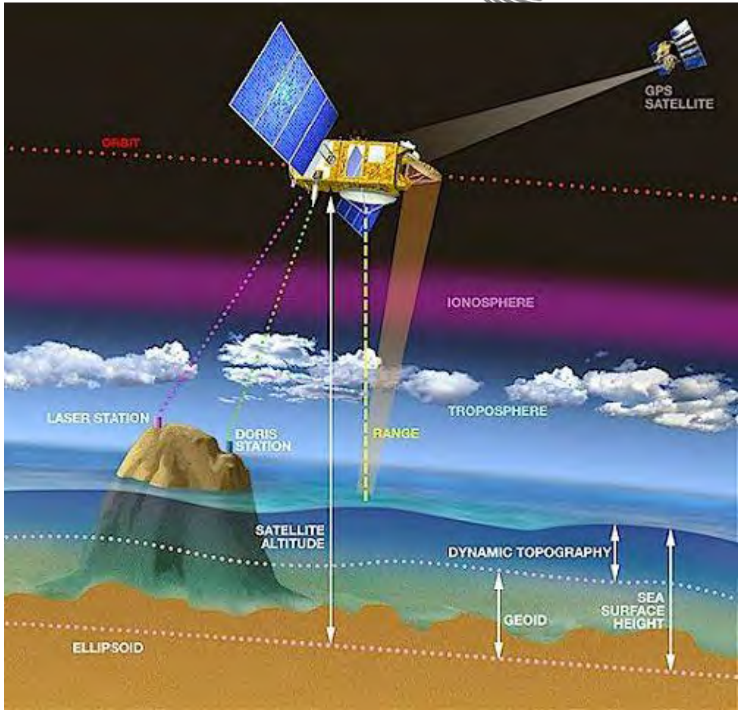
- The **orbit** is typically determined with an accuracy (radial orbit error) of <2 cm (NTC products) by using SLR, GPS (20,180 km orbit) and DORIS data (10-100 m in '50s-'60s with optical data, 5-10 cm in NRT/STC L2 products).

- **Geoids** (i.e. the ocean surface excluding the influence of wind and tides) are obtained from geodetic or gravity missions (e.g. CHAMP, GRACE, GOCE and including Starlette/Stella, LAGEOS-1/2 data).

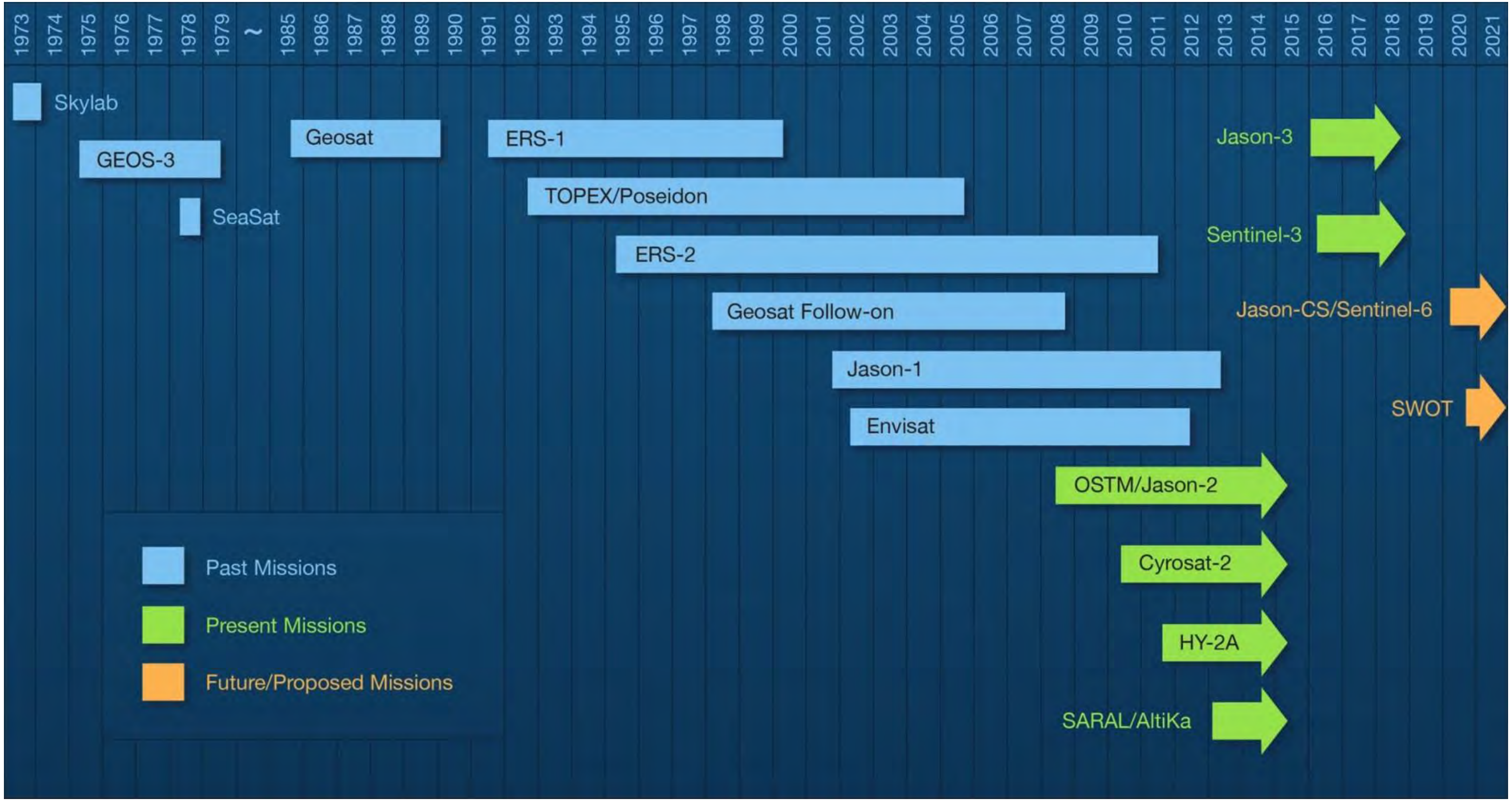
- A reference **ellipsoid** shall be considered as baseline Datum (e.g., WGS84). It is an arbitrary smooth surface designed to be close to the Earth's surface.

- The **range** measurement shall be corrected for a series of effects related to both the propagation into the **Ionosphere/Troposphere**, the **reflection** and **geophysical forcing** on the ocean.

SSH = ORBIT – (RANGE – CORRECTIONS)



Radar altimetry principles



Radar altimetry missions

Satellite	Agency	Launch	Altitude	Altimeter	Frequency (band)	Revisit Time (days)	Inter track (km)	Inclination
Skylab	NASA	1973	435 km	S193	-	-		50°
GEOS 3	NASA	1974	845 km	ALT	-	-		115°
Seasat	NASA	1978	800 km	ALT	Ku	17	165	108°
Geosat	US Navy	1985	800 km		Ku	17	165	108°
ERS-1	ESA	1991	785 km	RA	Ku	35	80	98.5°
Topex/ Poseidon	NASA /CNES	1992	1336 km	Topex	Ku and C	10	315	66°
				Poseidon-1	Ku			
ERS-2	ESA	1995	785 km	RA	Ku	35	80	98.5°
GFO	US Navy /NOAA	1998	800 km	GFO-RA	Ku	17		108°
Jason-1	CNES /NASA	2001	1336 km	Poseidon-2	Ku and C	10	315	66°
Envisat	ESA	2002	800 km	RA-2	Ku and S	35	80	98.5°
Jason-2	CNES /NASA/ Eumetsat/NOAA	2008	1336 km	Poseidon-3	Ku and C	10	315	66°
CryoSat	ESA	2010	720 km	SIRAL	Ku	369	7	92°
Saral	ISRO/CNES	2009	800 km	AltiKa	Ka	35	90	92°
HY-2	China	2010	963 km		Ku and C	14	200	99.3°
Sentinel-3 A/B/C/D	ESA	2016 (A)	814 km	SRAL	Ku and C	27	52 (A+B)	98.5°
Jason-3	CNES /NASA/ Eumetsat/NOAA	2016	1336 km	Poseidon-3B	Ku and C	10	315	66°
SWOT	NASA	2021	970 km	KaRIn	Ka	22	120	78°

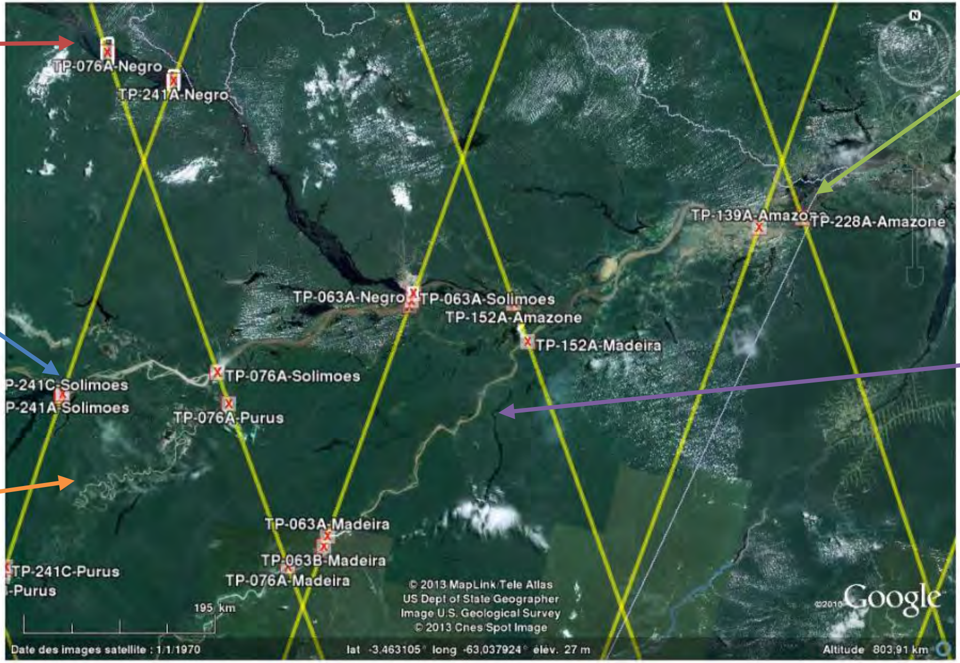
Radar altimetry missions

Topex/Poseidon . . . Jason-3 : 315 km– 10 days

3 VSs in Negro river

4 VSs in Solimoes river

2 VSs in Purus river



3 VSs in Amazon river

4 VSs in Madeira river

The virtual station, VS, is the location where the radar satellite track intersects the river reach

Radar altimetry missions

ERS, ENVISAT, SARAL : 80 km– 35 days

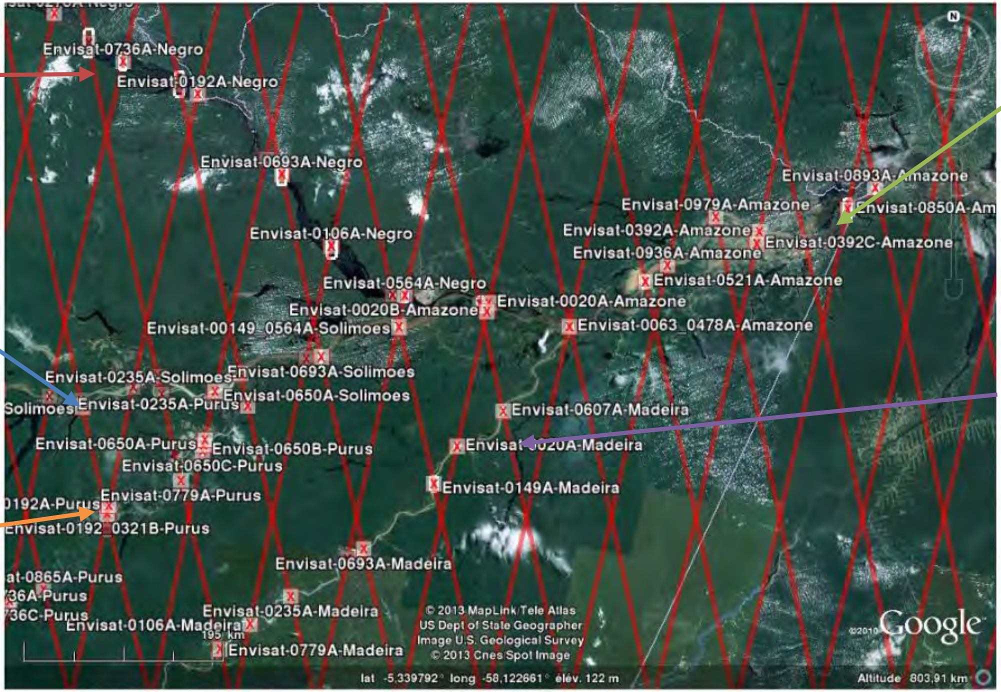
10 VSs in Negro river

9 VSs in Solimoes river

8 VSs in Purus river

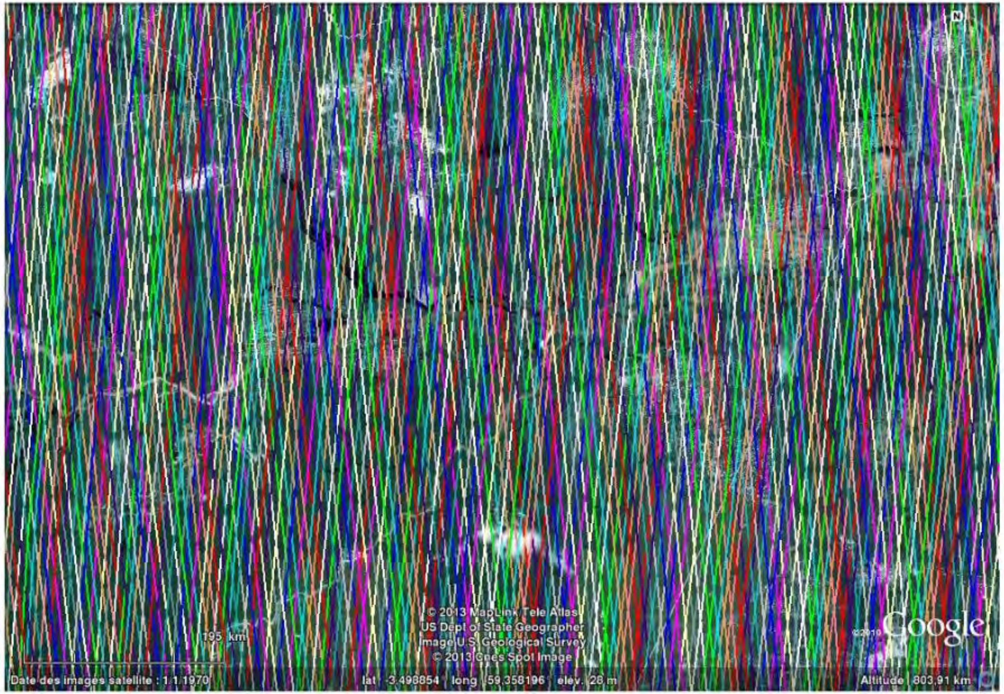
13 VSs in Amazon river

8 VSs in Madeira river



Radar altimetry missions

CryoSat-2 : 7 km– 369 days (colours : "12.7 subcycles")



Typical altimeter technologies

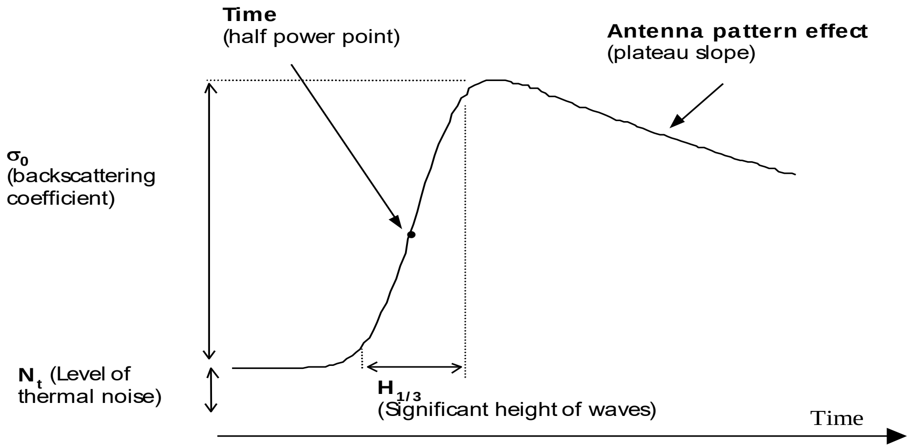
Low Resolution Mode

- **Envisat**: (pulse-limited altimeter: 8 Km along track resolution by averaging 20 measurements acquired every 400 m), Ku Band (13.6 GHz), vertical resolution of 0.5, 2 or 8 m (adaptable to the scenario, 320 MHz, 80 MHz, 20 MHz). 800 km orbit.
- **SARAL/AltiKa**: Single Antenna, Ka band (35.75 GHz), 0.3 m vertical resolution (500 MHz chirp bandwidth). Smaller footprint than Ku band due to higher frequency. 800 km orbit (same as Envisat). (classical pulse-limited altimeter)

Typical altimeter technologies

Processing schemes: Low Resolution Mode

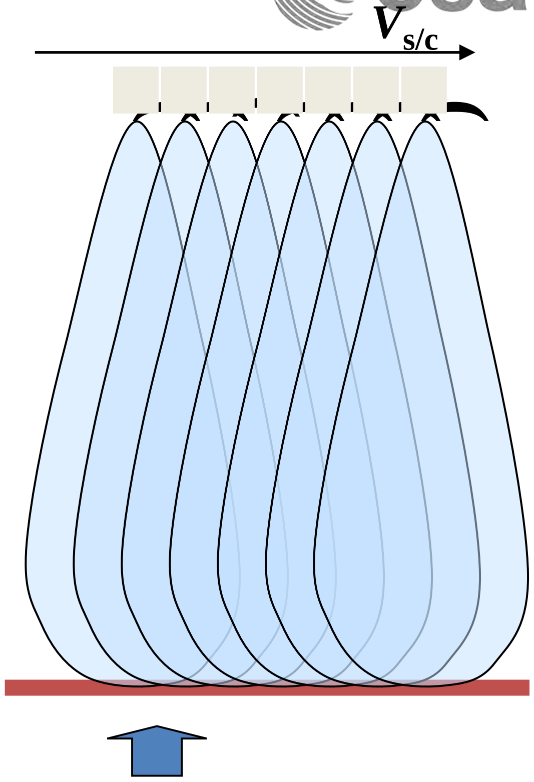
The radar altimeter transmits a short pulse of microwave radiation with pre-defined power toward the target surface. The pulse interacts with the rough surface and part of the incident radiation reflects back to the altimeter.



Animation by Keith Raney

1800-2000 Pulses Transmitted per second

After averaging all the measured ranges over 1/20 second (90 - 100 looks), we have the Brown's Echo over ocean.

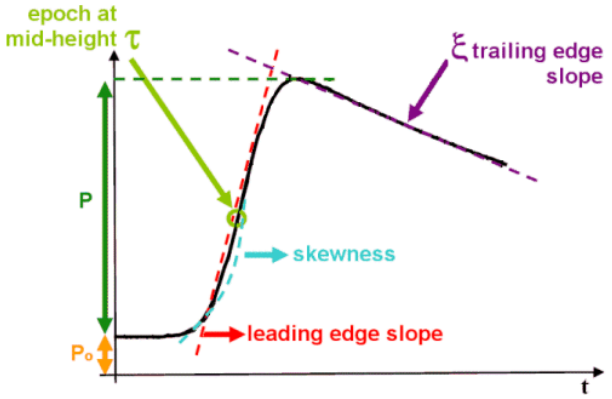


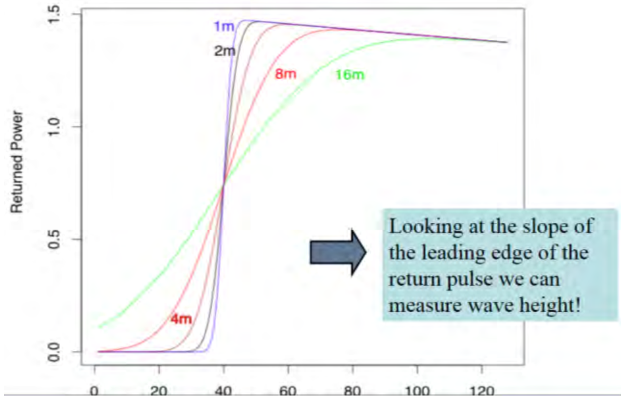
Ground Resolution Cell (around 3-5 km)

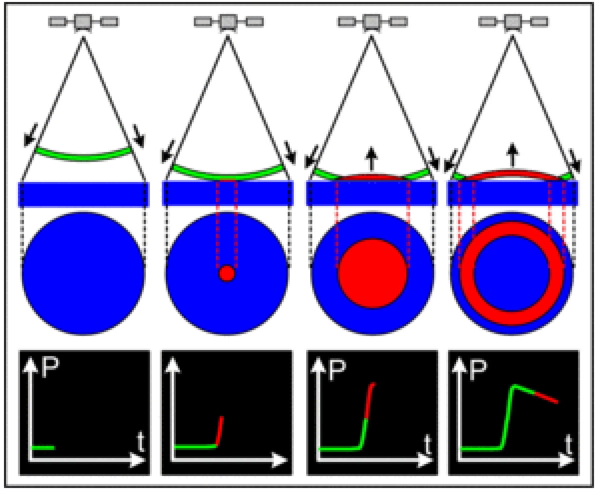
Typical altimeter technologies

Processing schemes: Low Resolution Mode

When the incident pulse strikes the surface, it illuminates a circular region that increases linearly with time. Correspondingly, a linear increase in the leading edge of the return waveform occurs. The signal reaches the water surface, and it keeps increasing, until power becomes maximum value.
After the trailing edge of the pulse has intersected the surface, the region back-scattering energy to the satellite becomes an expanding annulus of constant area.







The one way travelling time of signal is actually the mid-point of leading edge.

Observed parameters: Range, Significant Wave Height (SWH), Wind Speed

Typical altimeter technologies

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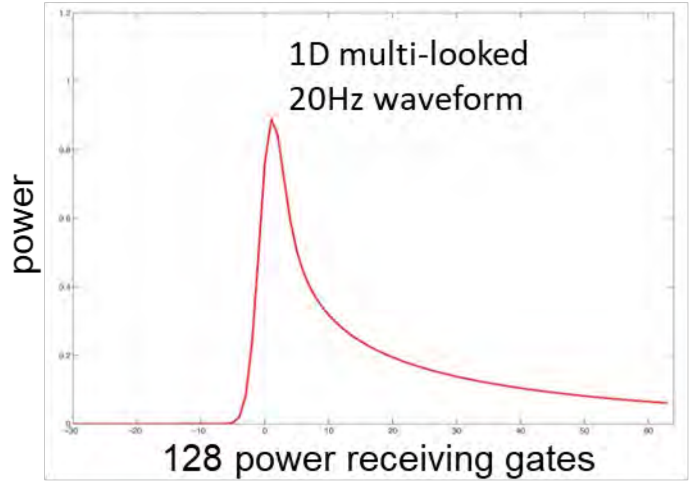
❑ Unfocused Delay/Doppler

- **Sentinel-3** (SRAL): **SAR Processor** (spatial resolution of 250 m in the along-track direction), Onboard Radiometer, vertical resolution of 0.4 m (350 MHz bandwidth). 814.5 km Orbit .
- **CryoSat-2**: 2 Antennas, **LRM/SAR/SARin Processors** (spatial resolution of 250 m in the along-track direction), No Onboard Radiometer. Vertical resolution of 0.47 m (320 MHz bandwidth). 732 km orbit (high latitude coverage: 88°).

Typical altimeter technologies

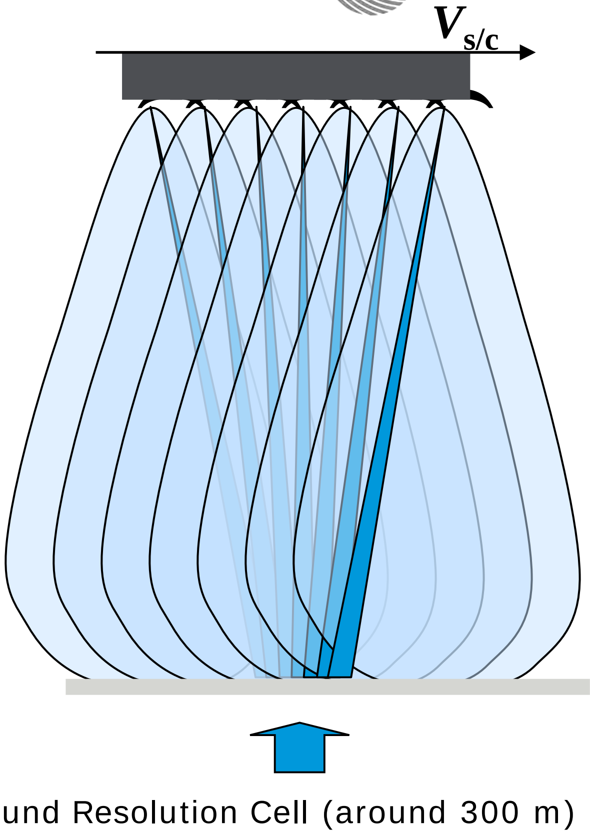
Processing schemes: Unfocused Delay-Doppler

Delay-Doppler / SAR altimeter stares at each resolved along-track cell as the radar passes overhead for as long as that particular cell is illuminated. Each cell is viewed over a larger fraction of the antenna beam than the pulse-limited. Thus more data is gathered, which leads to substantial benefits (it uses most of the power received).



In SAR Altimetry, we average around 250 looks whereas in pulse limited we average around 90 looks: that makes SAR altimetry more precise than classic altimetry

Pulses Transmitted in a Burst @ 17.8 kHz

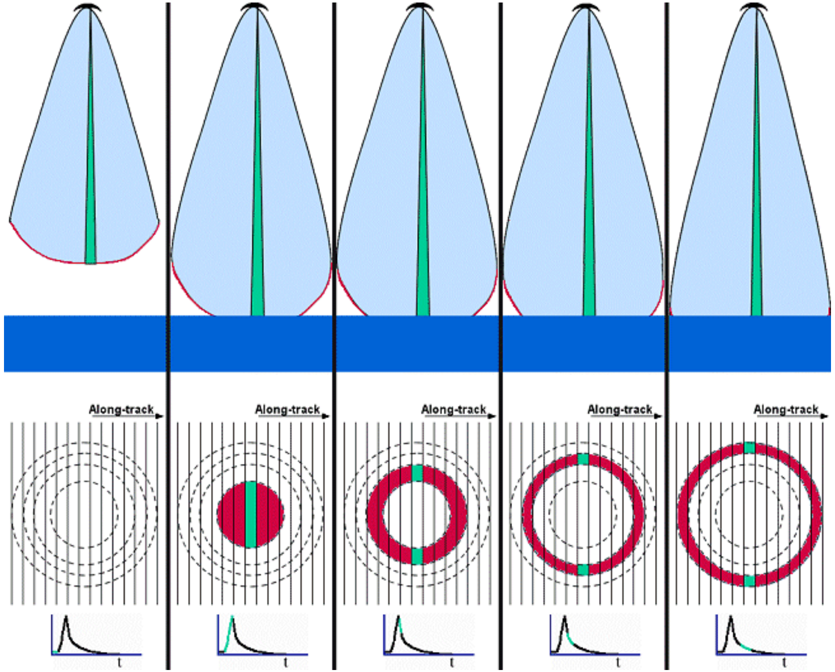


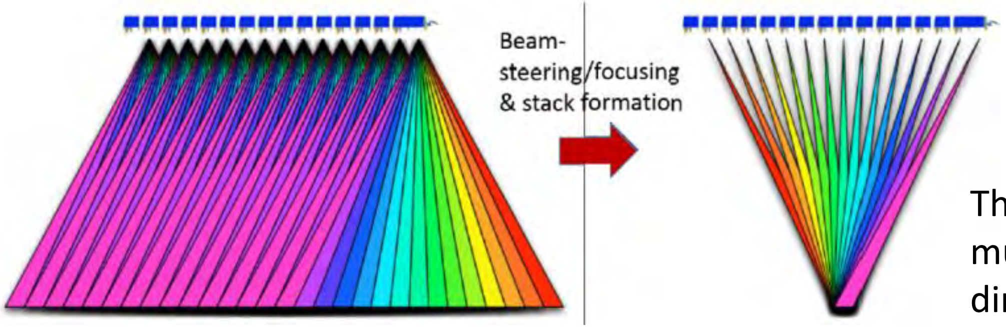
Typical altimeter technologies

Processing schemes: Unfocused Delay-Doppler

Contrary to the classical altimeter, the lighted area is not a surface-constant ring, but only part of it, which explain the peakier shape of the echo. This makes the footprint for each waveform significantly smaller. Consequently, land contamination is avoided or, at least, reduced.

The Delay-Doppler / SAR altimetry processes the data such that they could be seen as having been acquired from a synthetic aperture antenna.





This processing increases resolution and offers a multilook processing with the two independent dimensions: along-track and across-track.

Typical altimeter technologies

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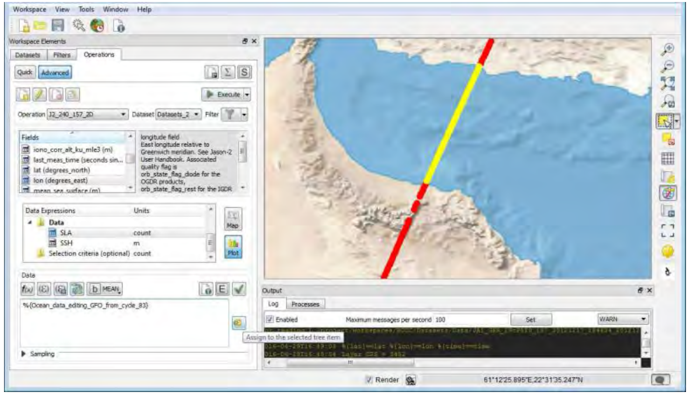
Interferometric Delay/Doppler

- **SWOT (Surface Water Ocean Topography):** two dimensional swath, Ka band

Broadview Radar Altimetry Toolbox (BRAT)

- BRAT is a collection of tools and tutorial documents designed to facilitate the reading, manipulation and visualization of radar altimetry data.
- It can read all altimetry missions' data, from ERS-1 (1991) to Sentinel-3 (2016).
- BRAT can be used in conjunction with MATLAB/IDL or C/C++/Python/Fortran, allowing users to obtain the desired data, bypassing the data-formatting hassle.
- BRAT is available at **http://www.altimetry.info/toolbox**: installers for Windows, macOS and Linux.
- BRAT is open-source: released under the GNU Lesser General Public License (LGPL).
- The source code is available at **https://github.com/BRAT-DEV/main**, where users can submit bug reports, requests for features or even contribute to the development.
- Easy access to altimeter data from RADS (**http://rads.tudelft.nl/rads**) and display of RADS variables included in BRAT.

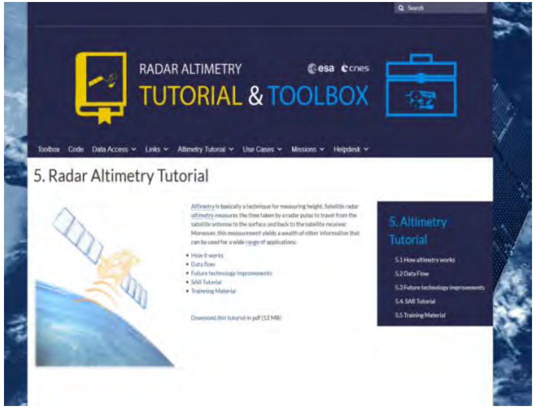


Broadview Radar Altimetry Toolbox (BRAT)

- BRAT also includes the Radar Altimeter Tutorial, which contains an extensive introduction to altimetry. As part of it, you can find:

  - Examples of usages of altimetry data
    http://www.altimetry.info/thematic-use-cases
  - Didactic material
    http://www.altimetry.info/radar-altimetry-tutorial/training-material
  - Community forum
    http://www.altimetry.info/?forum=altimetry-forum-2
  - Step-by-step instructional videos
    http://bit.ly/bratvideo

www.altimetry.info



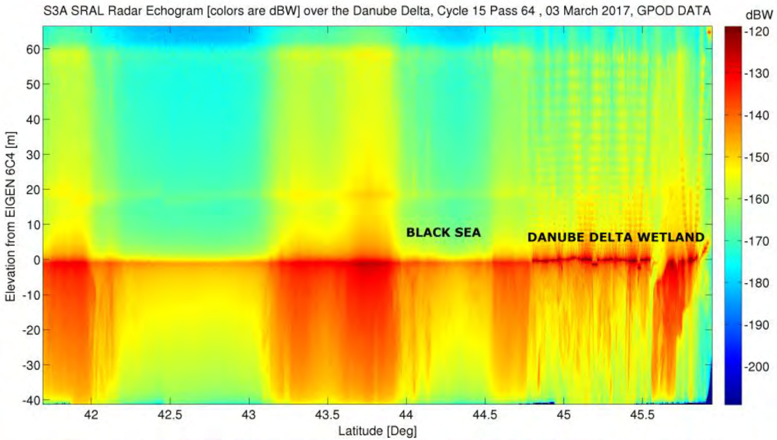
SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation (SARvatore)

- SARvatore is a SAR and SARin altimeter data processing on demand service available on the ESA-RSS processing platform (**G-POD**).
- Users can process, on line and on demand, low-level CryoSat-2 and Sentinel-3 Altimetry data products (FBR, Level-1A) up to Level-2 geophysical products.
- The service provides self-customised options, which are not available in the default processing of CryoSat-2 and Sentinel-3 Ground Segments.
- As one of the options for Level-2 processing, users can choose SAMOSA+, a SAMOSA2 model tailored for inland water, sea ice and coastal zone domain.
- SARvatore for Sentinel-3 provides default profiles with the most suitable processing options for **inland water**.

http://gpod.eo.esa.int/services/SENTINEL3_SAR/

http://gpod.eo.esa.int/services/CRYOSAT_SAR/

http://gpod.eo.esa.int/services/CRYOSAT_SARIN/



Altimetry data download

Alti-Hydro portals:

- River&Lake (**http://tethys.eaprs.cse.dmu.ac.uk/RiverLake**)
- HydroWeb (**http://hydroweb.theia-land.fr**)
- Theia (**http://hydroweb.theia-land.fr/**)
- G-REALM (**https://ipad.fas.usda.gov/cropexplorer/global_reservoir/**)
- HydroSat (**http://hydrosat.gis.uni-stuttgart.de**)
- DAHITI (**http://dahiti.dgfi.tum.de**)
- PODAAC (**https://podaac.jpl.nasa.gov/node/749**)
- AltWater (**https://github.com/cavios/tshydro**)

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  - Lake Volume variation (from multi-mission)

Optical and multispectral sensors

Multispectral remote sensing is generally based on acquisition of image data of Earth's surface **simultaneously in multiple wavelengths**. As different types of surfaces reflect the light of different wavelengths with various intensity, different spectral behavior is leading to detailed classification of specific types of land surfaces (depending on the spatial, spectral and radiometric resolution of the used sensor).

Optical and multispectral sensors

Nowadays, there are many systems for the acquisition of multispectral image data:

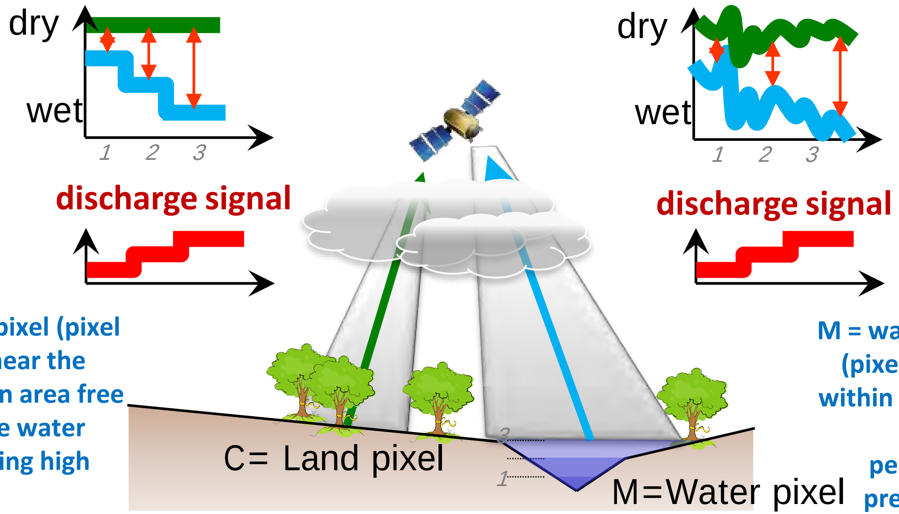
- meteorological satellites with **low spatial resolution** (e.g. Meteosat, NOAA, GOES) used in particular for global analysis at the level of entire countries or continents,
- **medium resolution** data (e.g. Landsat, SPOT, ASTER, MERIS, MODIS, OLCI) used especially for studies at the regional level,

  - visible bands (RGB)
  - near Infra-Red (NIR)
  - shortwave Infra-Red (SWIR)
  - thermal Infra-Red (TIR)

- **very high spatial resolution** data (e.g. Quickbird, Ikonos, WorldView, GeoEye and Rapid Eye), characterized by a spatial resolution of about 0.5 - 1 m, used for detailed local studies.

  - visible bands (RGB)
  - near Infra-Red (NIR) (sometimes)

Water signal by in NIR

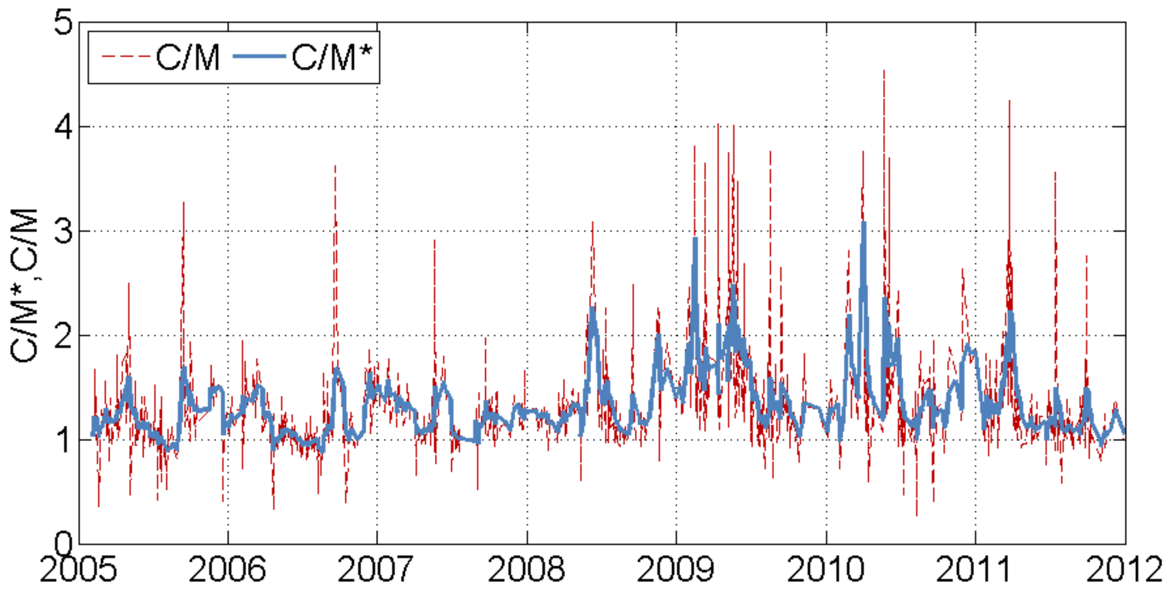


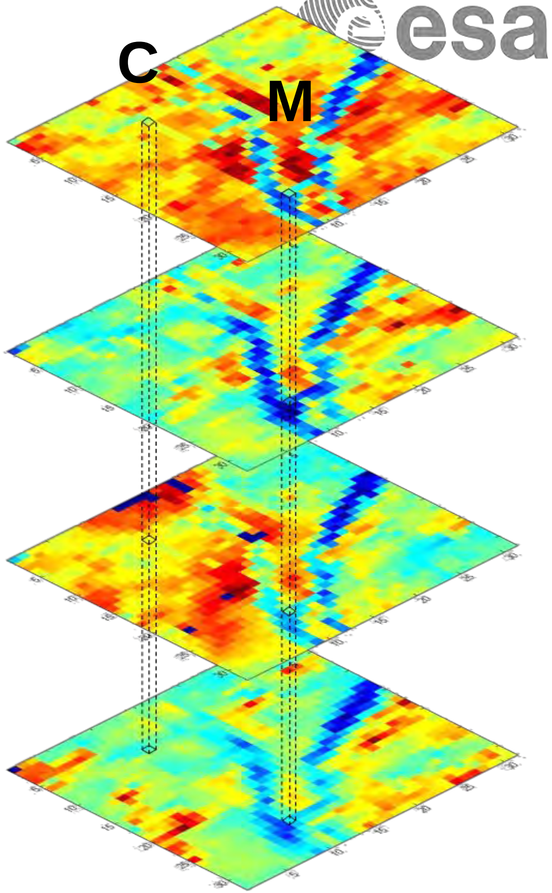
C = land pixel (pixel located near the river in an area free of surface water even during high floods)

M = water pixel (pixel located within the river with permanent presence of water)

Brakenridge, G.R., Nghiem, S.V., Anderson, E., Mic, R. (2007). Orbital microwave measurement of river discharge and ice status. *Water Resour. Res*. 43, W04405.

Water signal by in NIR





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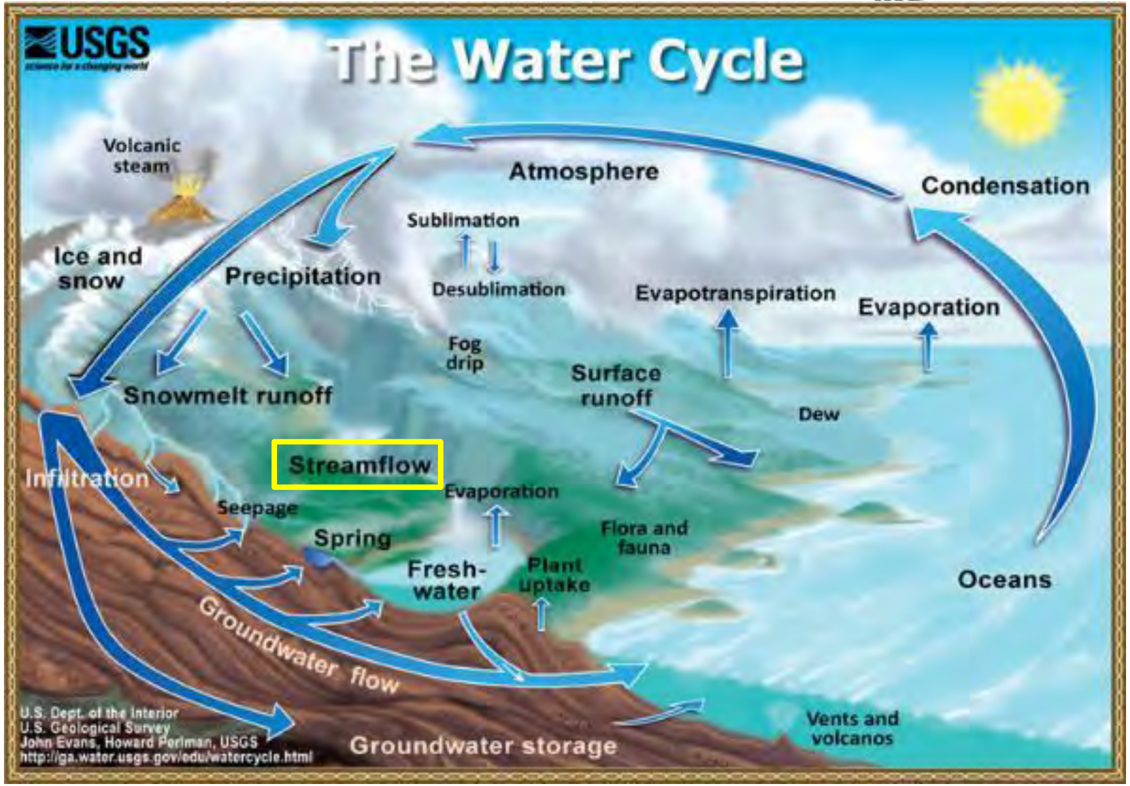
River Discharge Definition and Measurements

River discharge is one of ECVs selected by GCOS as an important variable in driving the climate system.

- ❖ Key variable in the water cycle
- ❖ Essential for water resources management (floods and droughts)
- ❖ Necessary for the flood prediction (hydraulic risk)
- ❖ Help for identifying and adapting potential effects of climate change.
- ❖ Important for the reduction of the ocean salinity and the thermohaline circulation.

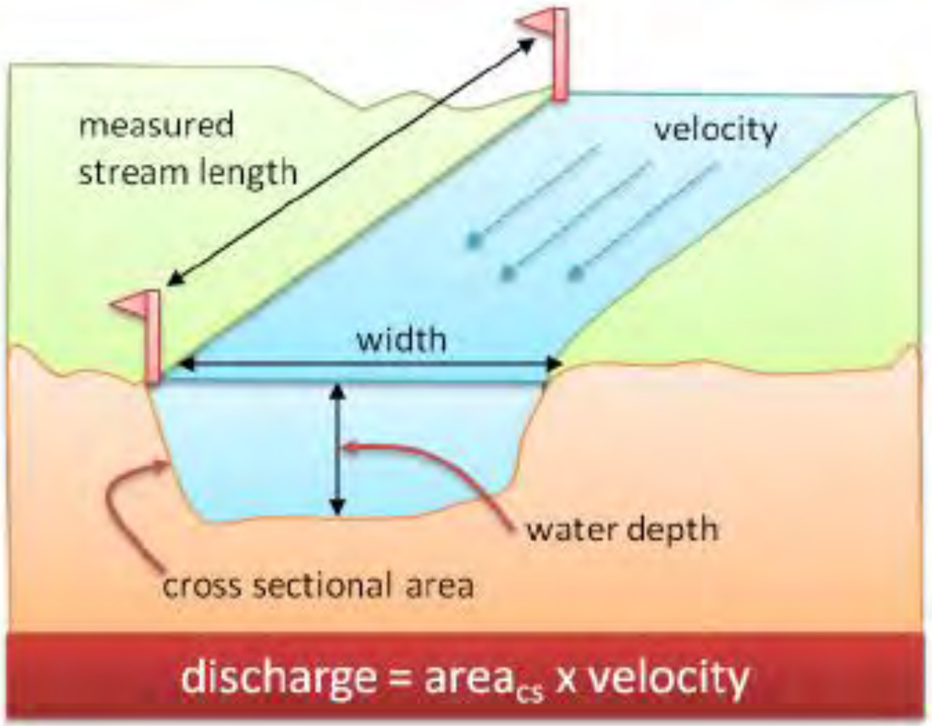


River Discharge Definition and Measurements

- **River discharge** is defined as the volume of water flowing through a river channel cross-section per unit of time.

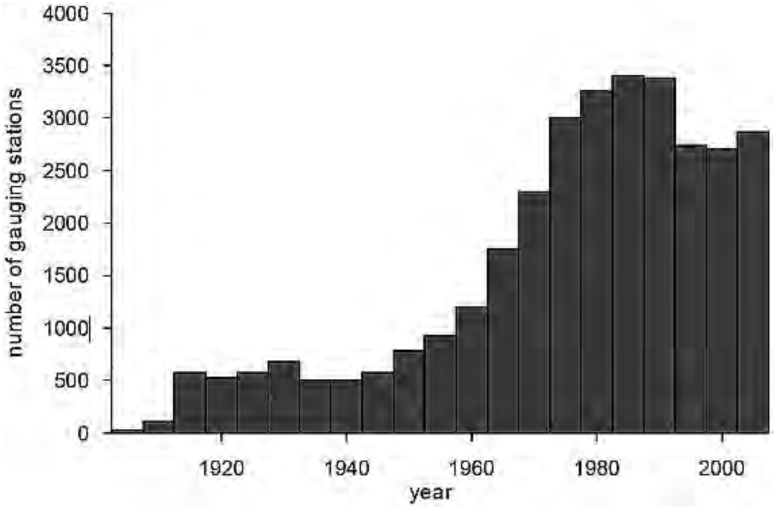
- It can also be expressed as the flow velocity times the cross-sectional flow area.

- Its estimation **is not direct** and, traditionally, it consists of in-situ measurements of water **flow velocity vertical profiles and depth**, at different measuring points across the river and the **water level**.

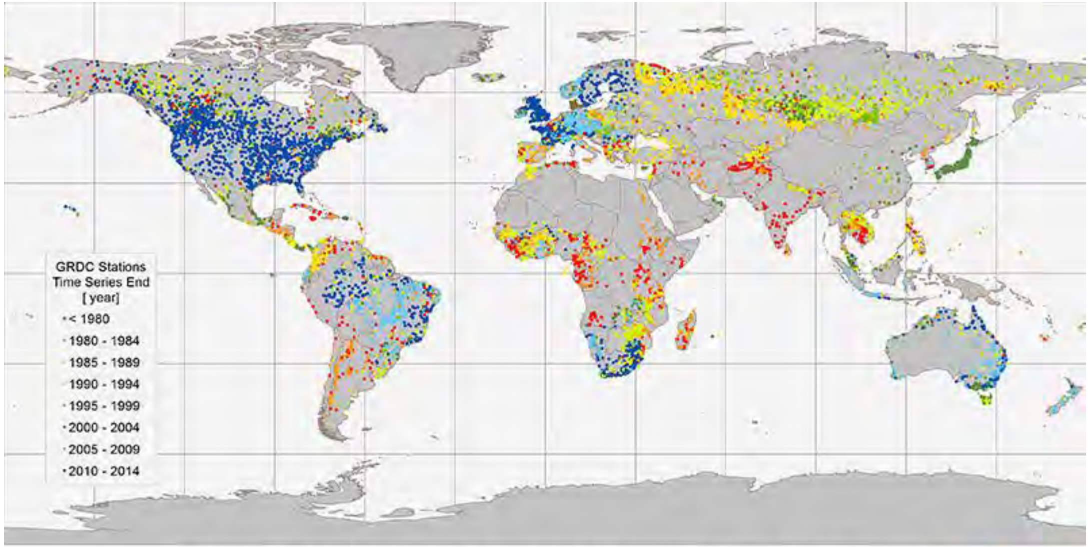


River Discharge Monitoring Network

- Not representative of the global water flow
- High costs of installation and maintenance
- Not uniformly distributed in the world
- Inaccessibility of many remote areas
- Problems of data sharing among neighbouring countries
- Reduction of hydrometric stations (Global Runoff Data Center)



Mishra and Coulibaly, 2009 Reviews of Geophysics



8962 stations with monthly data discharge data, including data derived from daily data (Status: 20 December 2013)
Koblenz: Global Runoff Data Centre, 2014.

GRDC

River Discharge from remote sensing

- Increasing of satellite observations during last three decades.

- The estimation of river discharge by satellite data is carried out through the use of:
    - ❑ radar altimetry
    - ❑ passive microwave and optical sensors

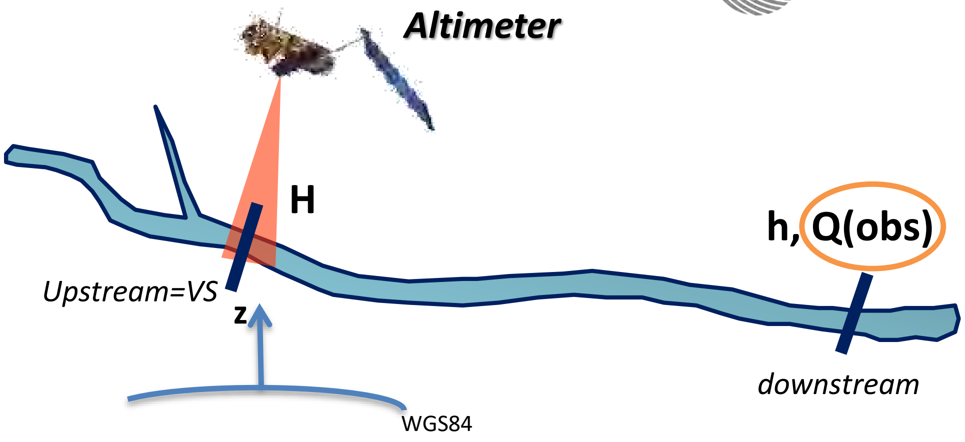
- The availability of new sources of data motivates the development of new procedures for river discharge estimation adapting the traditional approaches to the use of remote sensing technologies.

River Discharge from radar altimetry

- **RATING CURVES** *(Leon et al., 2006 JoH; Papa et al. JGR; Tourian et al., 2013 WRR; Getirana et al., 2013 HESS)*
- **EMPIRICAL FORMULAS** *(Negrel et al., 2011 HESS; Michailovsky et al. HESS; Tarpanelli et al. 2015 JSTARS)*
- **HYDROLOGICAL MODEL** *(Milzow et al. 2009 JEM; Getirana et al., 2010 JoH; Paiva et al. 2013 WRR)*
- **HYDRAULIC MODEL** *(Birkinshaw et al., 2012 HyP; Domeneghetti et al., 2014; Tarpanelli et al., 2013 RS; Schneider et al., 2017 AWR)*
- **ASSIMILATION TECHNIQUES** *(Biancamaria et al., 2011 RSE; Michailovsly et al., 2013 WRR)*
- **FUSION TECHNIQUES** *(Frappart et al., 2005 RSE; Creteaux et al., 2011 IWTC; Tarpanelli et al., 2018 TGRS)*

River Discharge from radar altimetry

The **rating curve** is a functional law linking the water stage to the discharge. In the majority of the studies, a rating curve is developed considering the water level retrieved by satellite altimetry and the discharge observed to the nearest ground sections.

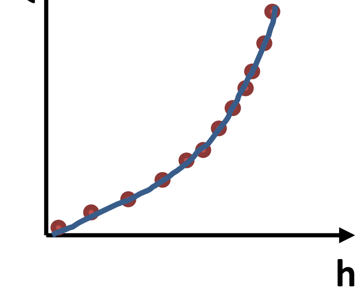


LARGE RIVERS	SAT	STUDY
Ob'	T/P	Kouraev et al. 2004, RSE
Amazon	T/P	Zakharova et al. 2006, CRG
Brahmaputra	T/P	Papa et al. 2010, JGR
Ganga	ERS-2	
Brahmaputra	JASON-2	Papa et al. 2012, JGR
Ganga		
Chad	T/P	Coe et Birkett, 2004, WRR
Zambesi	ENVISAT	Michailovsky et al. 2012, HESS

H is river surface height above WGS84

z is height of the river bottom above WGS84

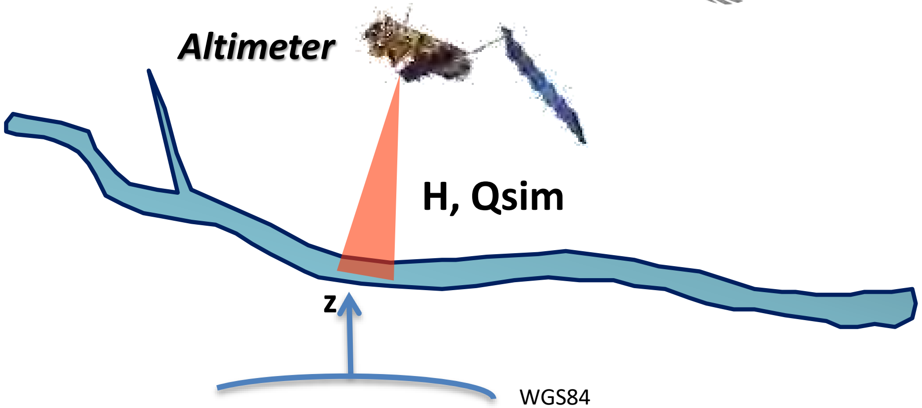
$$Q=a*h^b=a(H-z)^b$$



SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from radar altimetry

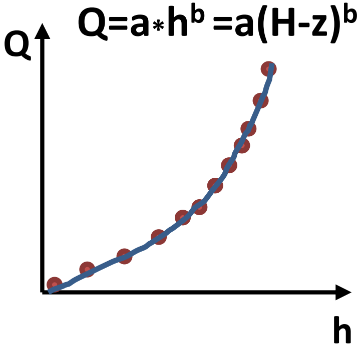
If in-situ discharges are not available, the water level is linked to the discharge simulated through rainfall-runoff models (taking in account other variables as rainfall, soil moisture, etc.).



RIVERS	SAT	STUDY
Negro	T/P ENVISAT	Leon et al. 2006, JoH
Branco	ENVISAT	Getirana et al. 2009, JoH
Branco	ENVISAT	Getirana et al. 2013, JoH
Amazon	ENVISAT JASON-2	Paris et al. 2016, WRR

H is river surface height above WGS84

z is height of the river bottom above WGS84

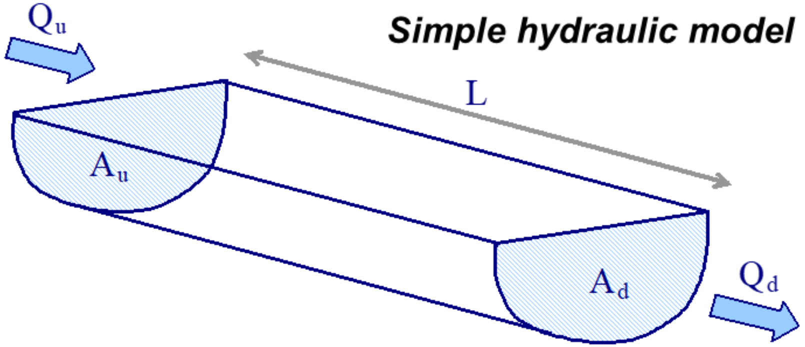


SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

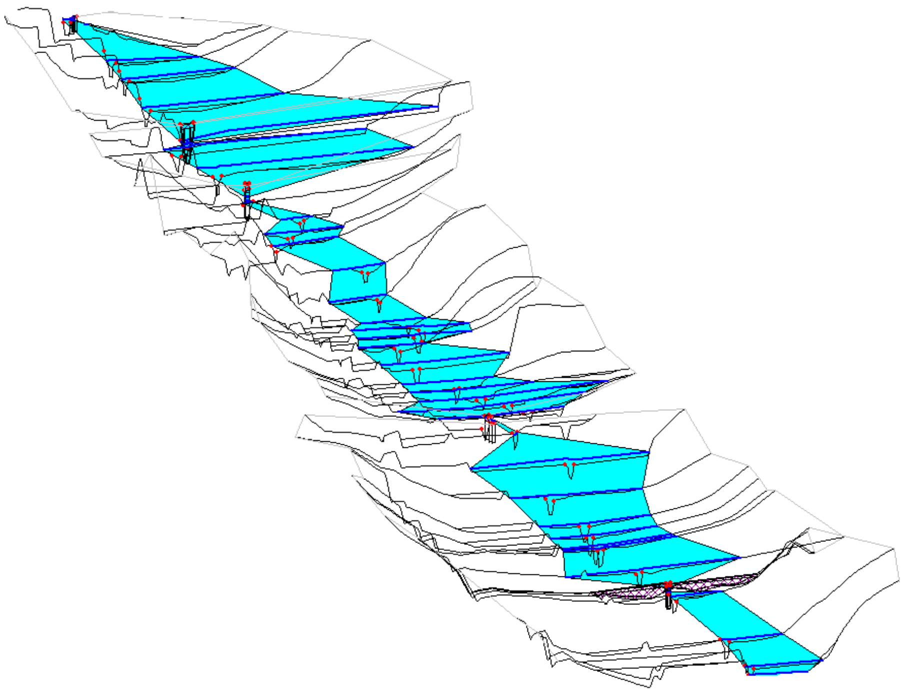
River Discharge from radar altimetry

The water level measurements provided by radar altimetry in the continental environment represent a valid support for **hydraulic modeling**. Approaches can vary from employing of simple to complex hydraulic models, going from steady uniform flow to unsteady flow.

Simple hydraulic model



Complex hydraulic model

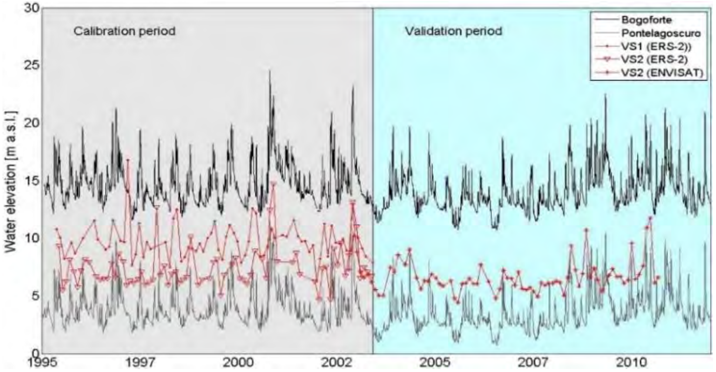


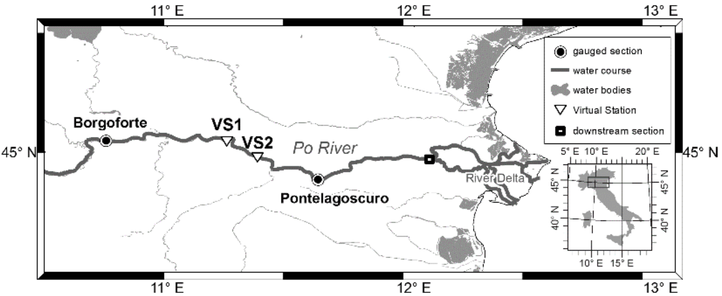
SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

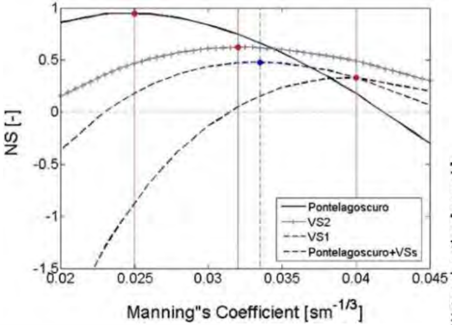
River Discharge from radar altimetry

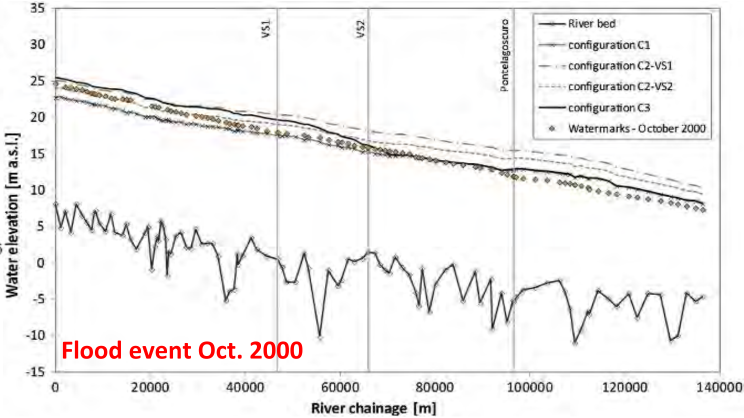
Domeneghetti A., Tarpanelli A., Brocca L., Barbetta S., Moramarco T., Castellarin A., Brath A. (2014) The use of remote sensing-derived water surface data for hydraulic model calibration. *Remote Sensing of Environment*, 149, 130-141.

Altimetry data could be efficiently used to calibrate the friction coefficient that describes the roughness conditions along the main channel of a quasi-2D dimensional hydraulic model (HEC-RAS). The integration of the satellite datasets with traditional in-situ observations fosters the trustworthiness and reliability of the hydraulic model.









SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

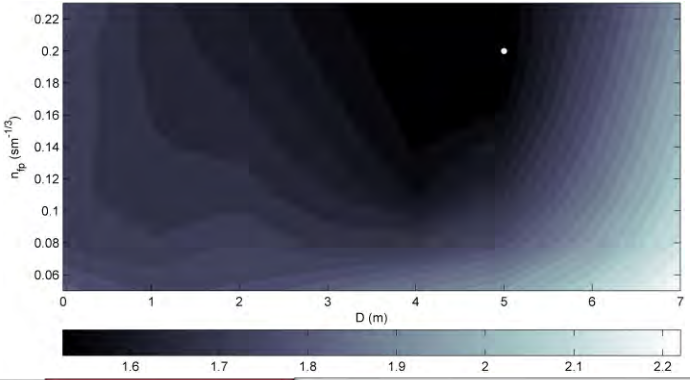
River Discharge from radar altimetry

Yan K., Tarpanelli A., Balint G., Moramarco T., Di Baldassarre G. (2014) Exploring the potential of radar altimetry and SRTM Topography to Support Flood Propagation Modeling: the Danube Case Study. *Journal of Hydrologic Engineering* 20(2).

Radar altimetry along with SRTM topography is used in supporting **flood level predictions** in data-poor areas. 2-D hydraulic model (LISFLOOD-FP) is calibrated (in terms of roughness coefficient and depth of the section), by using the water level of the 2006 flood event and validated with the 2007 flood event.

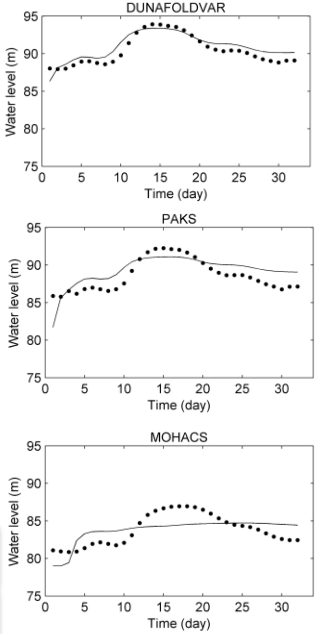
Calibration:

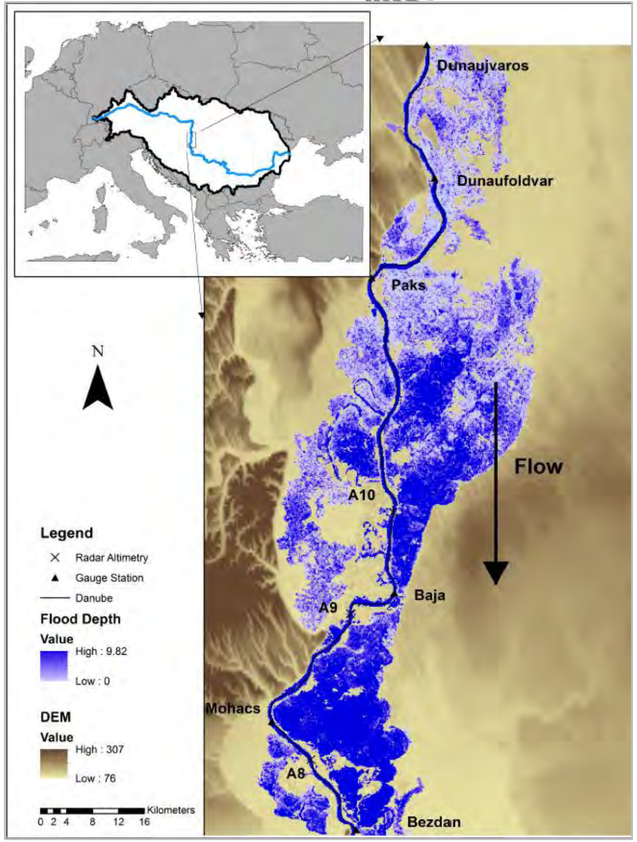
2006 FLOOD EVENT



Validation:

2007 FLOOD EVENT

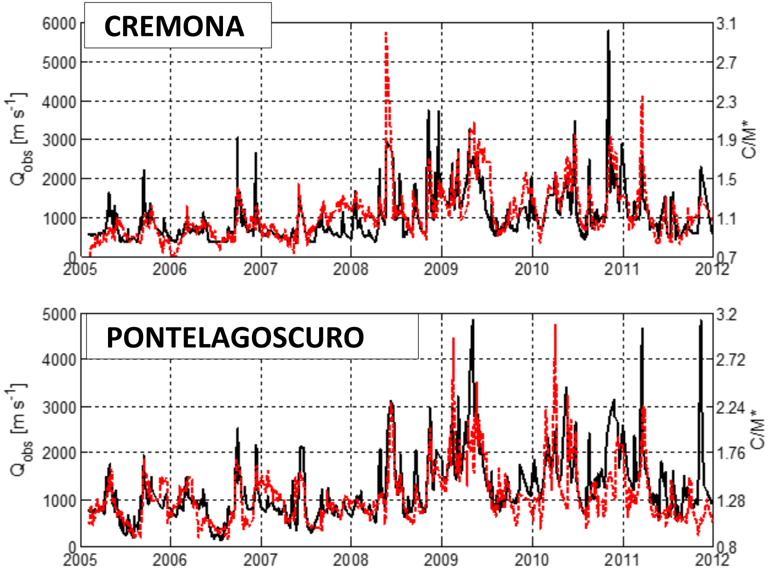


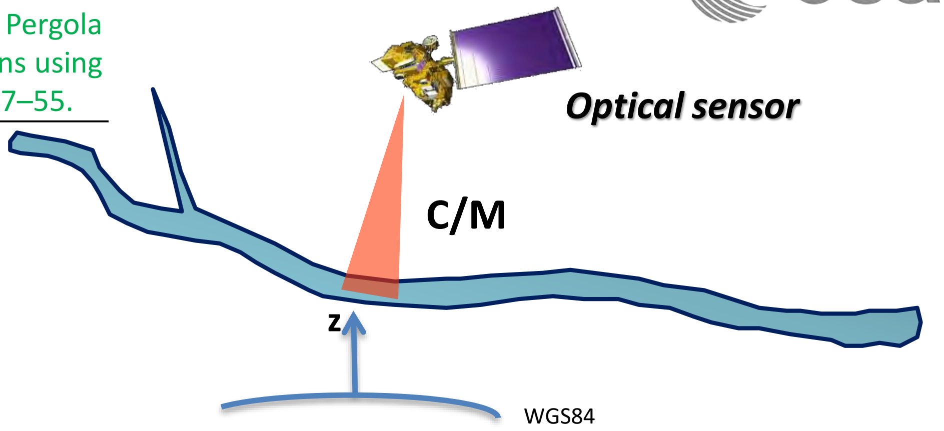


SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

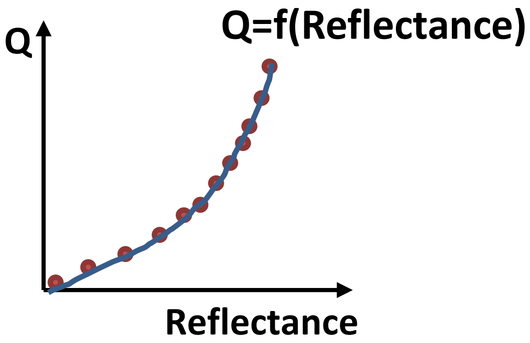
River Discharge from imaging sensors

Tarpanelli A., Brocca L., Melone F., Moramarco T., Lacava T., Faruolo M., Pergola N., Tramutoli V. (2013) Toward the estimation of river discharge variations using MODIS data in ungauged basins. *Remote Sensing of Environment*, 136, 47–55.





Extending the concept of **rating curve**, a functional law can be expressed between the discharge and the signal derived by passive microwave or optical sensors.



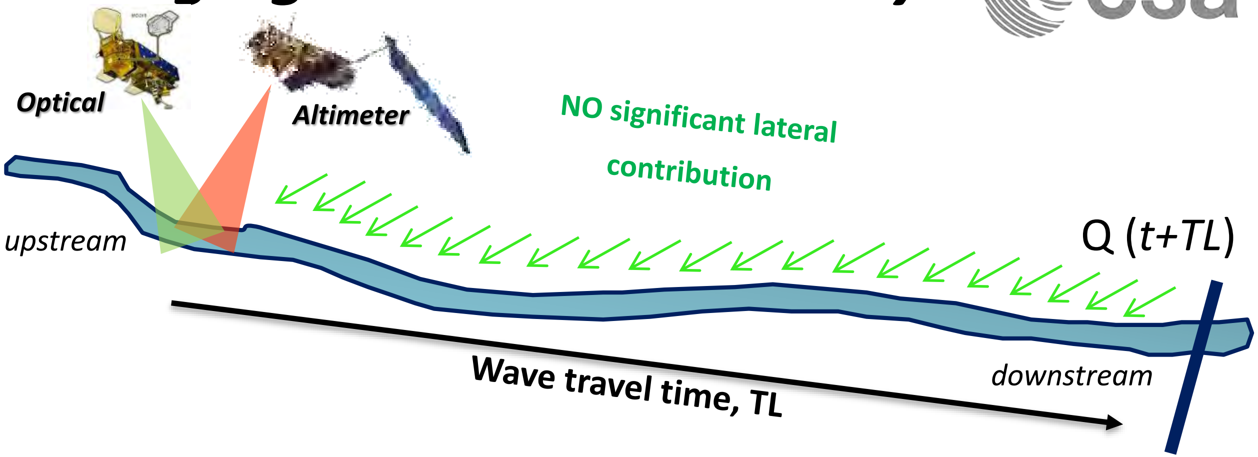
SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

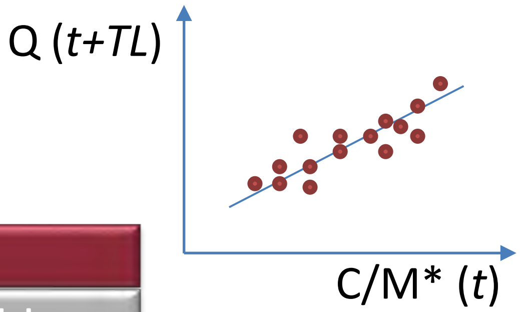
River Discharge from imaging sensors & altimetry

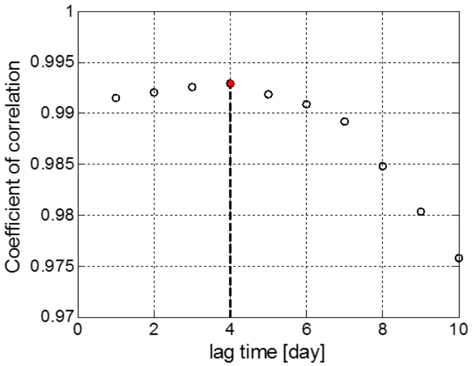
FORECASTED DISCHARGE

The observation acquired some days before at an upstream section is informative of the downstream discharge.

It is plausible to suppose that the discharge at the upstream section is proportional to the one that flows at the gauged station (assuming that the discharge contribution of the intermediate basin is proportional to the contribution at the upstream section). Therefore, by using the information acquired by satellite at an upstream section, the river discharge at downstream section with a forecast of some days (equal to the wave travel time) can be assessed.

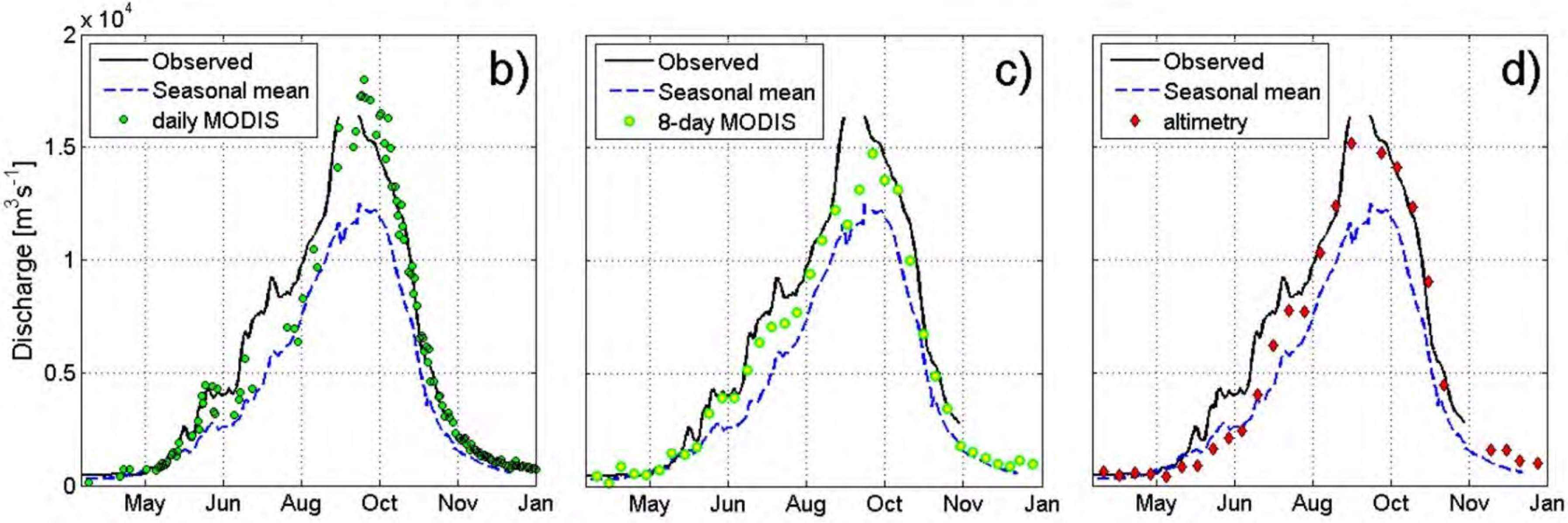






SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from imaging sensors & altimetry



SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

Tarpanelli A., Amarnath G., Brocca L., Massari C., Moramarco T. (2017). Discharge estimation and forecasting by MODIS and altimetry data in Niger-Benue River, *Remote Sensing of Environment*, 195, 96-106.

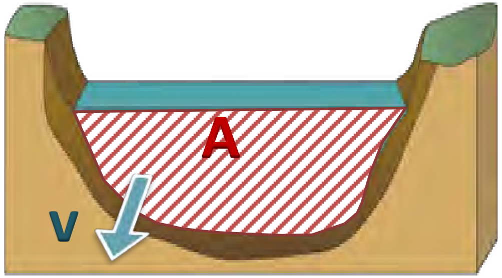
River Discharge merging imaging sensors & altimetry

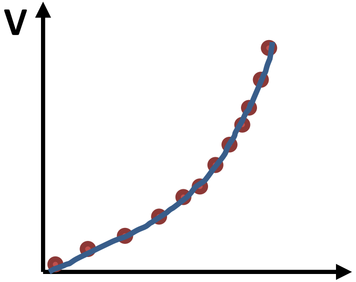
The discharge is inferred as the product of the mean flow velocity by the flow area. The flow velocity is derived by imaging sensors (MODIS, MERIS, etc.) images, whereas the flow area is estimated considering the water levels derived by radar altimetry data and the cross section geometry that can be known from bathymetry surveys. If we don't know the geometry of the cross section different approaches can be used for its estimation.

$$Q = v \cdot A$$

Flow velocity derived by multispectral/ optical sensors

Flow Area





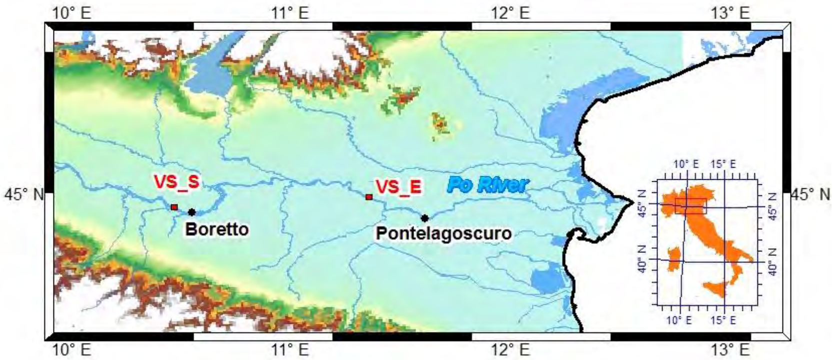
A=f(water level, geometry)

- water level: **derived by radar altimetry observation**
- geometry: **Known (Topographic survey)**
- geometry: **unknown** (Moramarco et al., 2013 – Journal of Hydrology)

SENSORS	**Altimeter**	**Optical**
APPROACHES	**Rating curve**	**Hydraulic models**

River Discharge merging imaging sensors & altimetry

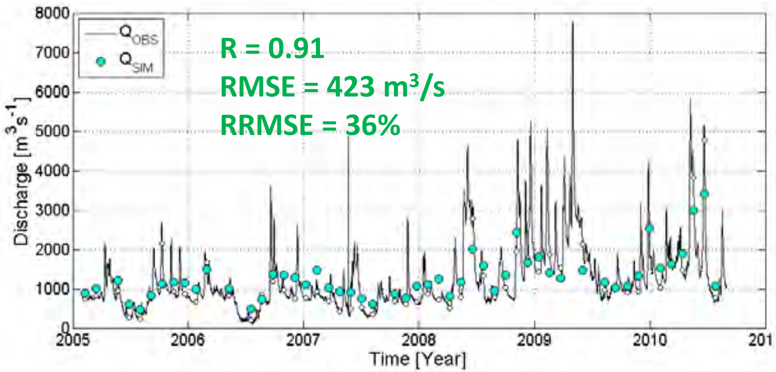
Tarpanelli A., Brocca L., Barbetta S., Faruolo M., Lacava T., Moramarco T. (2015) Coupling MODIS and radar altimetry data for discharge estimation in poorly gauged river basin. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 8(1), 141-148.



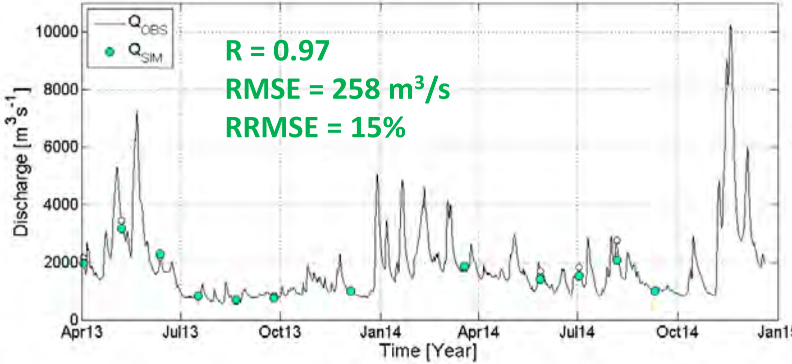
In correspondence of the altimetry track, we selected the MODIS images to derive the mean flow velocity (by using the regional law). The estimated velocity are compared with the ones observed at the gauging stations of Boretto and Pontelagoscuro.

SENSORS	Altimeter	Optical
APPROACHES	Rating curve	Hydraulic models

Envisat + MODIS vs Pontelagoscuro



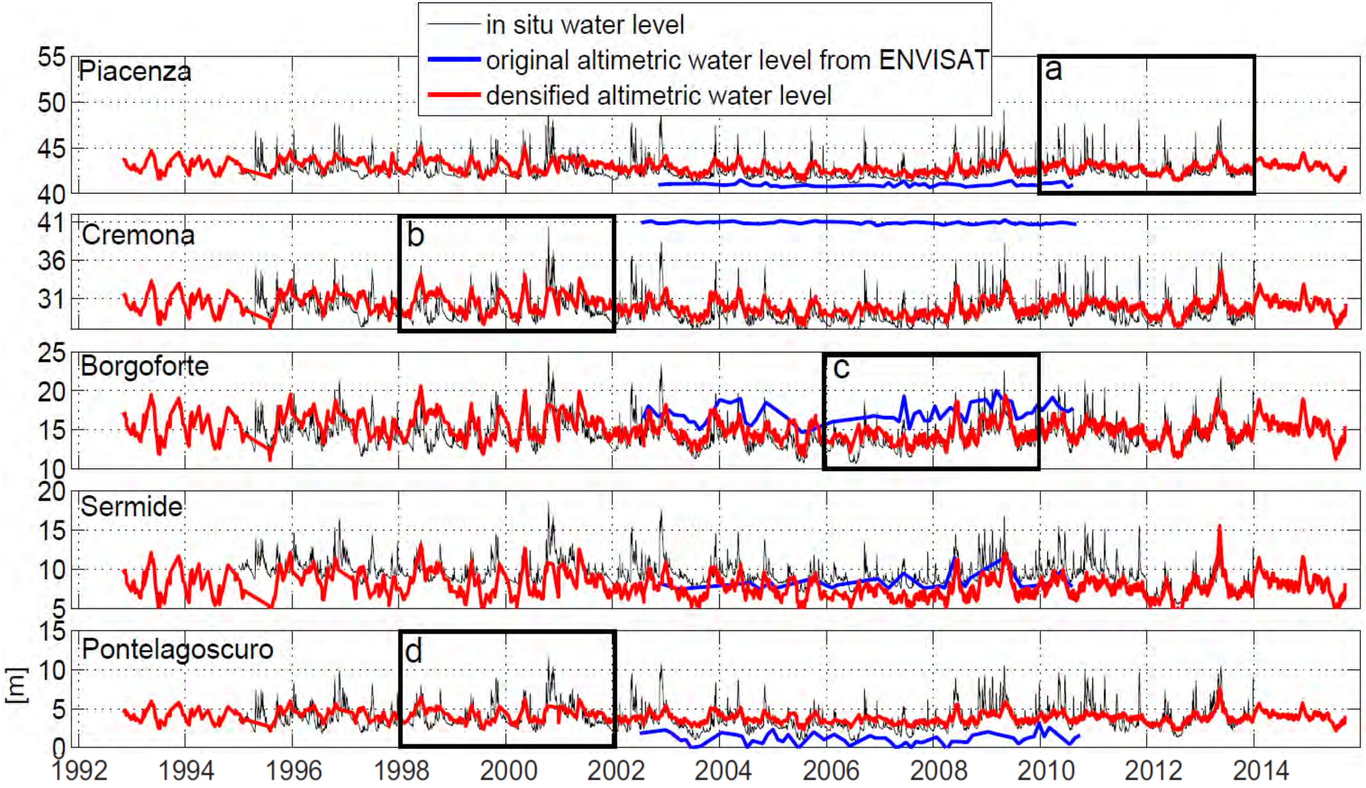
Saral + MODIS vs Boretto



River Discharge merging imaging sensors & altimetry

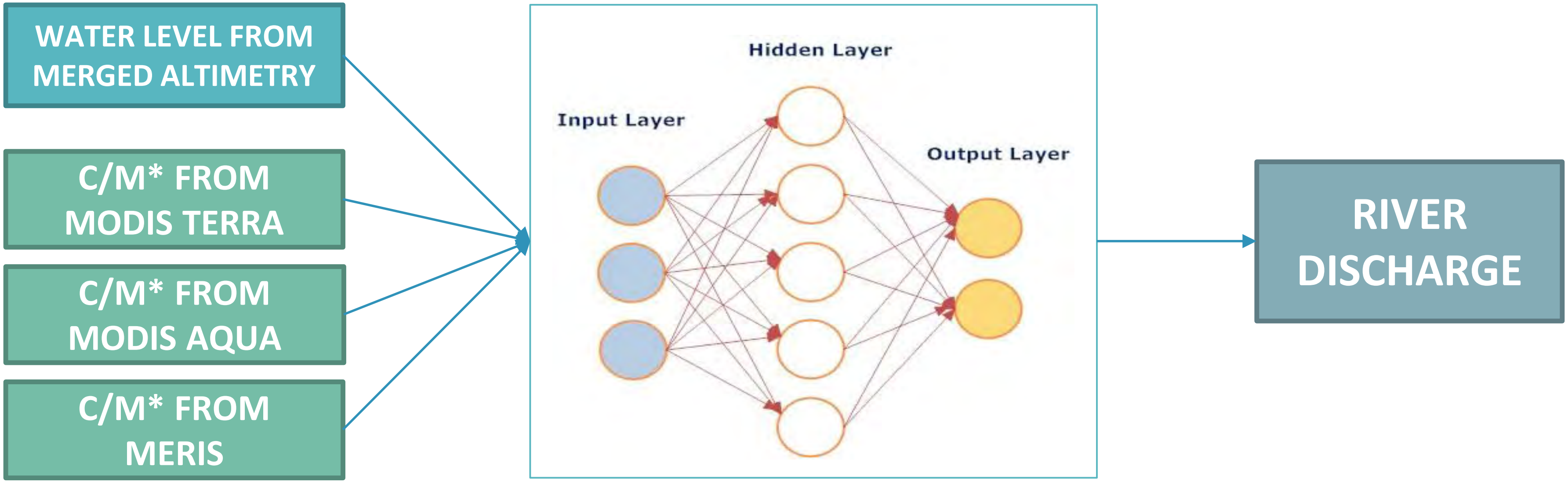
Tourian M.J., Tarpanelli A., Elmi O., Qin T., Brocca L., Moramarco T., Sneeuw N. (2016) Spatiotemporal densification of river water level time series by multimission satellite altimetry. *Water Resources Research*, 52.

A geodetic approach by which, after estimating and removing inter-satellite biases, all virtual stations of several satellite altimeters are connected hydraulically and statistically to produce water level time series at any location along the river.



River Discharge merging imaging sensors & altimetry

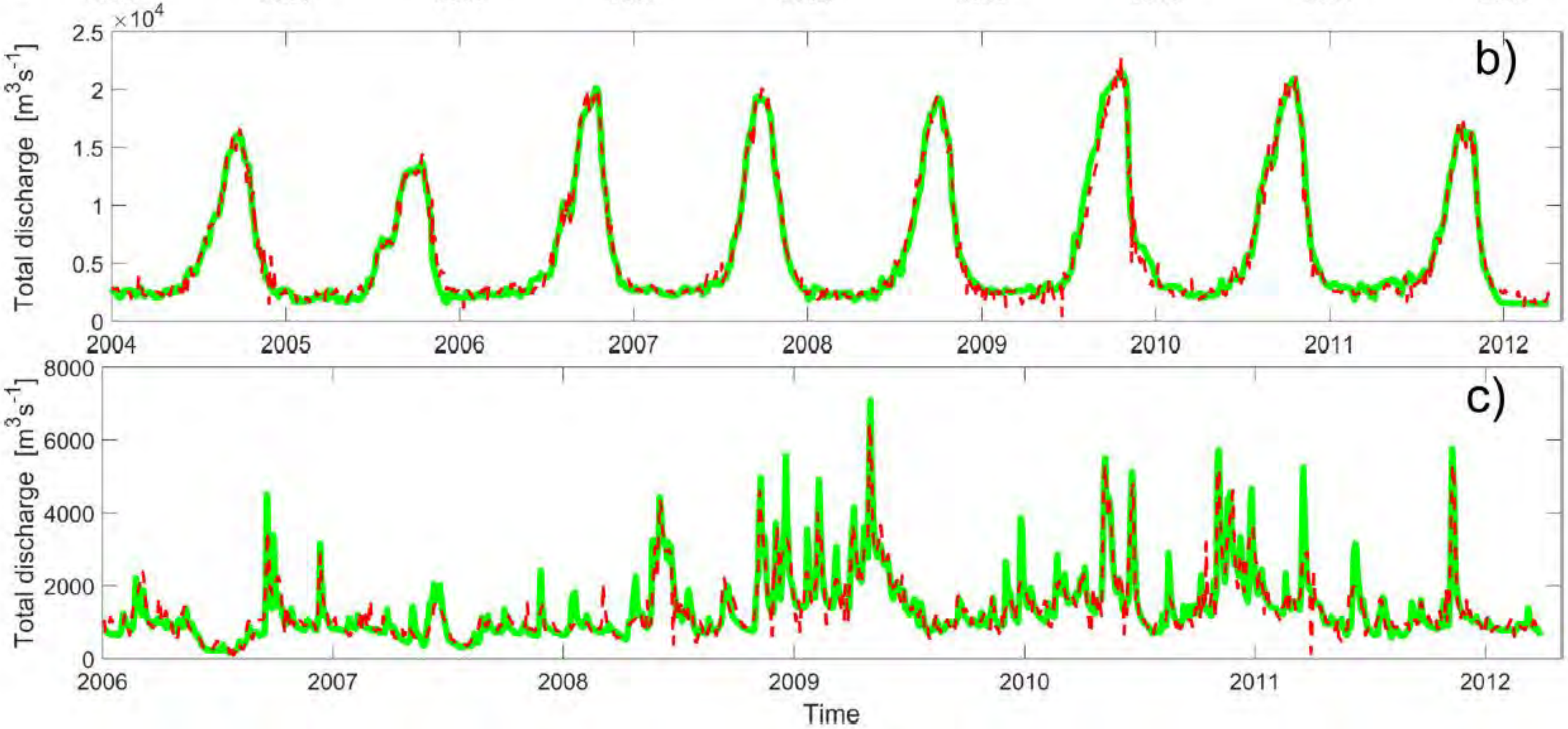
ARTIFICIAL NEURAL NETWORK



○ artificial neuron

→ Connection from the output of one neuron to the input of another

River Discharge merging imaging sensors & altimetry



R = 0.99
NS = 0.98

R = 0.91
NS = 0.83

Tarpanelli, A., Santi, E., Tourian, M.J., Filippucci, P., Amarnath, G., Brocca, L. (2018). Daily river discharge estimates by merging satellite optical sensors and radar altimetry through artificial neural network. *IEEE Transactions on Geoscience and Remote Sensing*, in press.

Summary

- *Satellite data: Radar altimetry*
  - *Principles*
  - *Missions and technologies*
  - *Data access and toolboxes*

- *Satellite data: Optical and multispectral sensors*
  - *Missions and technologies*
  - *Data access*

- *Hydrological Applications*
  - *River Discharge (from altimetry, from multispectral sensors, from multi-mission)*
  - *Lake Volume variation (from multi-mission)*

Lake volume variation (from multi mission)

20 Years of River and Lake Monitoring from Multi-Mission Satellite Radar Altimetry

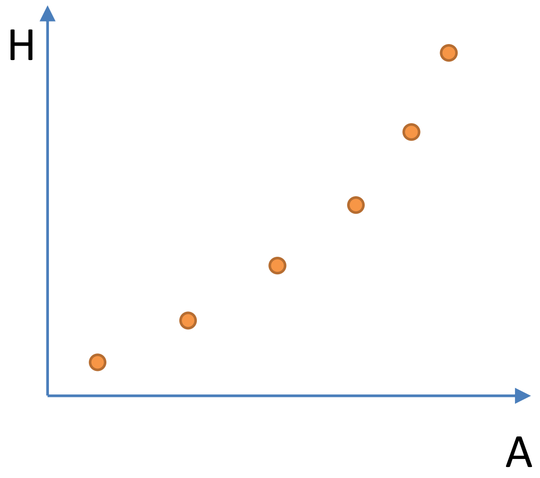
Philippa A.M. Berry [1], Richard G. Smith [1]
Mark K. Salloway[1], Monika Quessou[1],
Jérôme Benveniste [2]

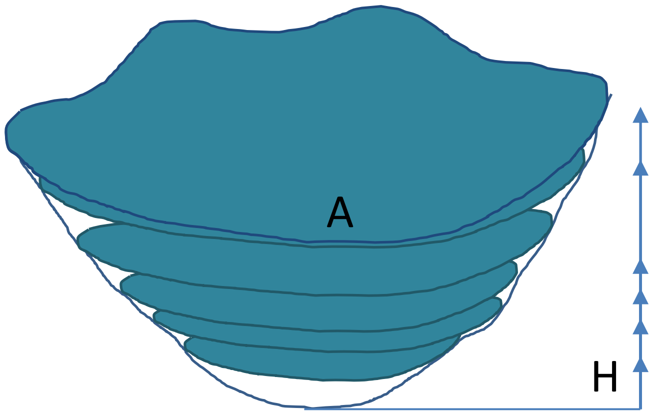
1. EAPRS Lab, De Montfort University
2. ESA ESRIN

Lake volume variation (from multi mission)

Lake volume estimation is only possible using bathymetry, but it is available only for a small number of lakes. Nevertheless, volume variation can be calculated for all lakes.
From satellite it is possible to estimate the water surface elevation, H, from altimetry and surface area, A, from imaging sensors or SAR.
The volume can be deduced from the observable function A(H) relating the surface area of a lake to a specific water level through this integration:

$$V(H) = \int_0^H A(H')dH'$$



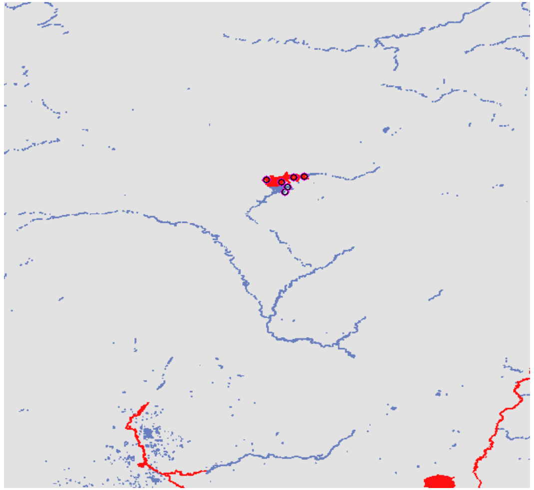


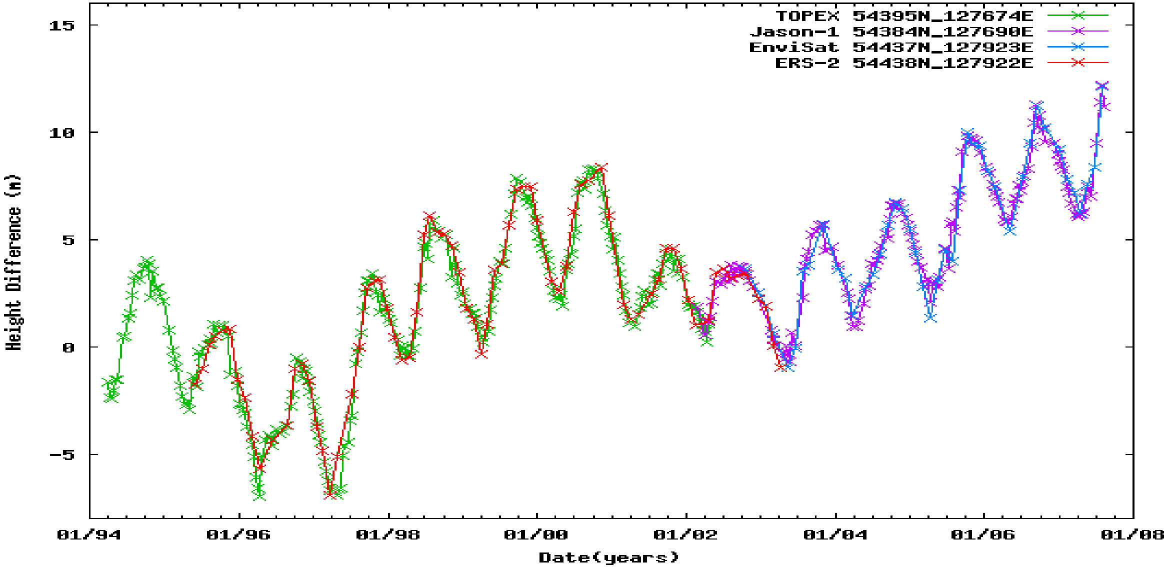
Monitoring H and A from satellite observations, the relationship can be continuously use to monitor water bodies.

Lake volume variation (from multi mission)

Zeyskoye Vodokhranilishche

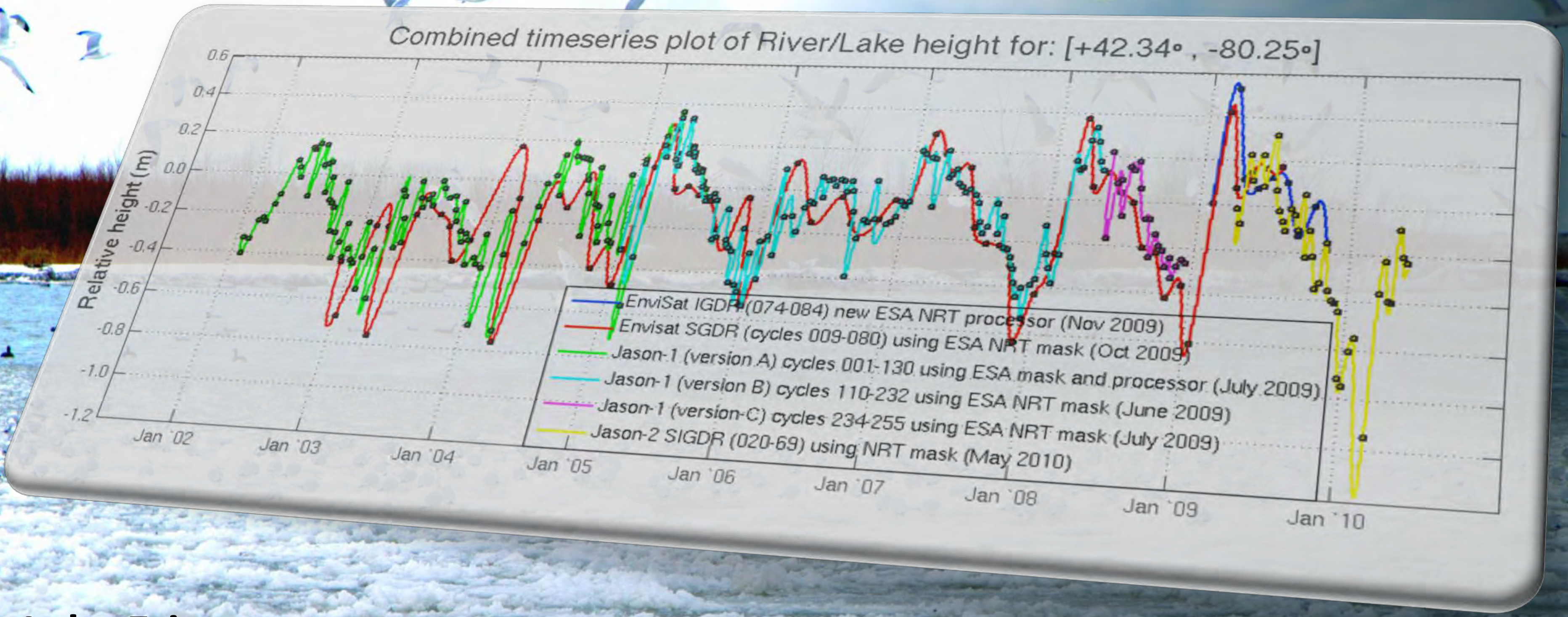
Reservoir Zeyskoye Vodokhranilishche, Russia, water level with 12 year combined time-series derived from retracked ERS-2, EnviSat, TOPEX and Jason-1 waveform data.





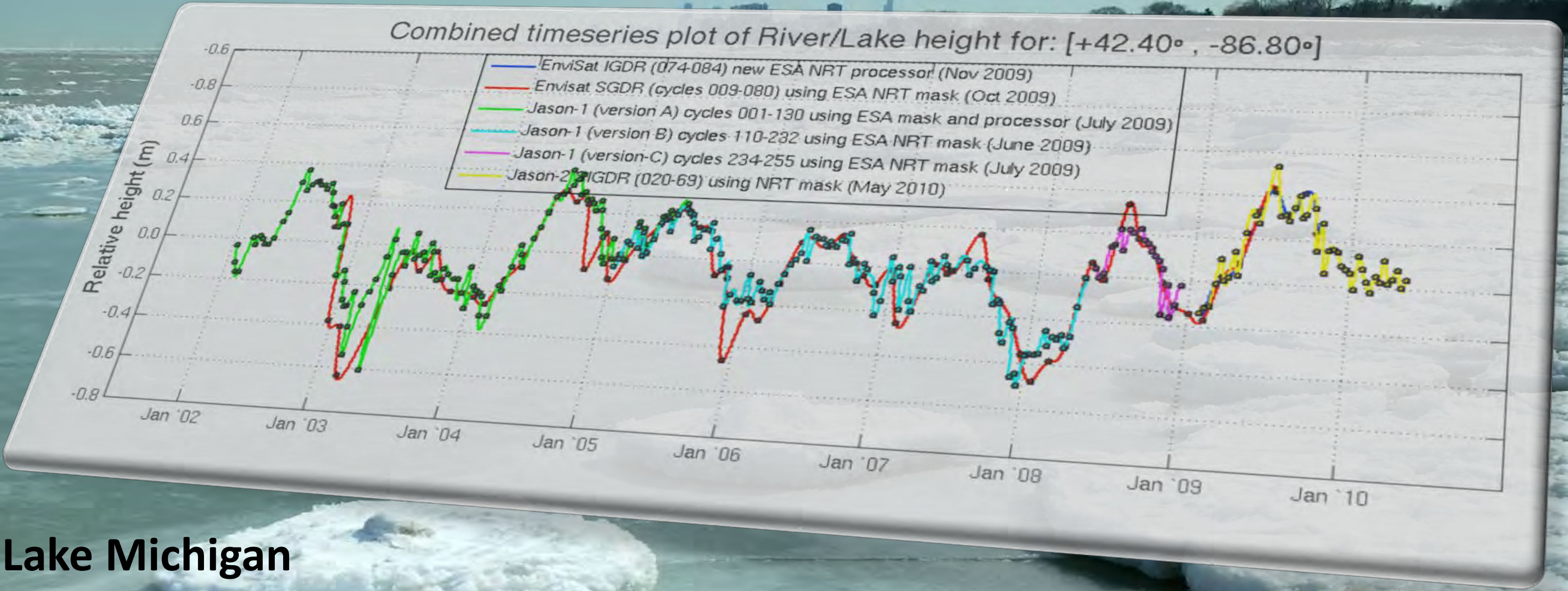
- Excellent agreement is achieved over this fairly complex target.
- Note the very good data from Jason-1 over this reservoir.

Lake volume variation (from multi mission)



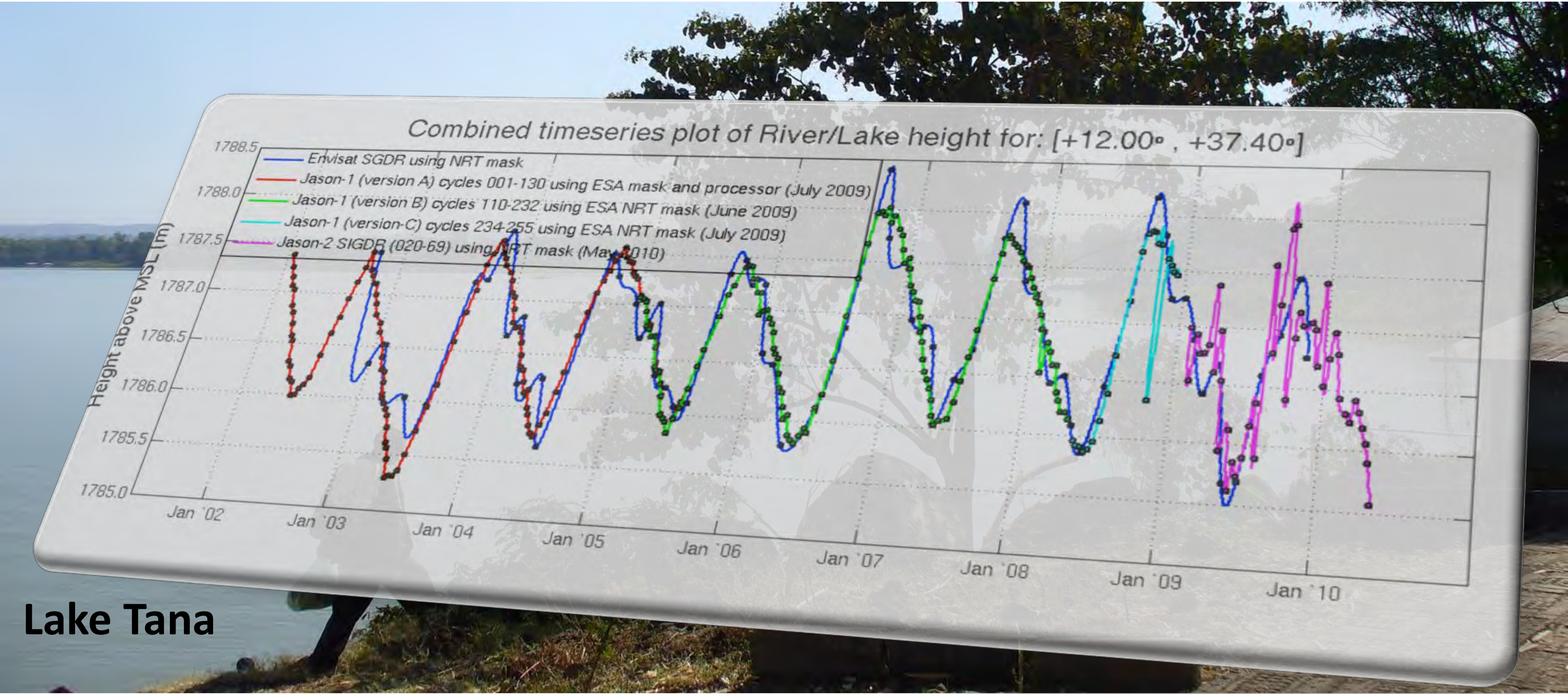
Lake Erie

Lake volume variation (from multi mission)



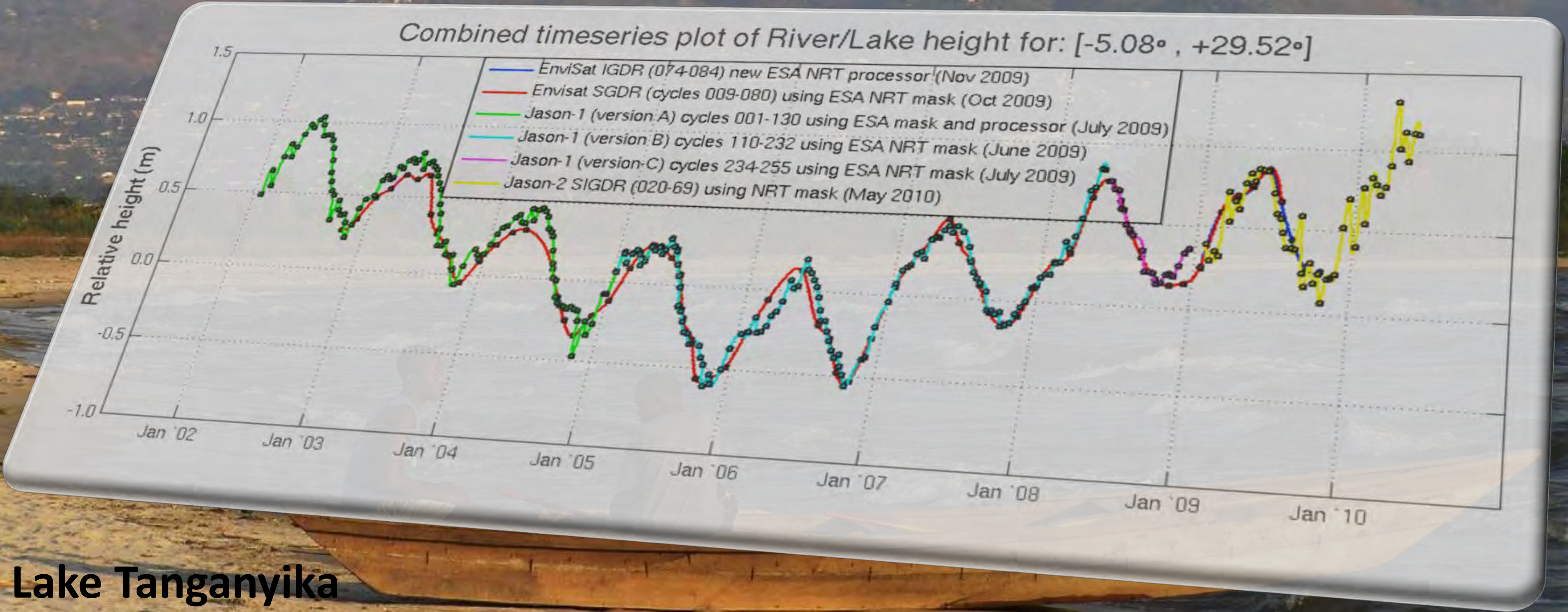
Lake Michigan

Lake volume variation (from multi mission)



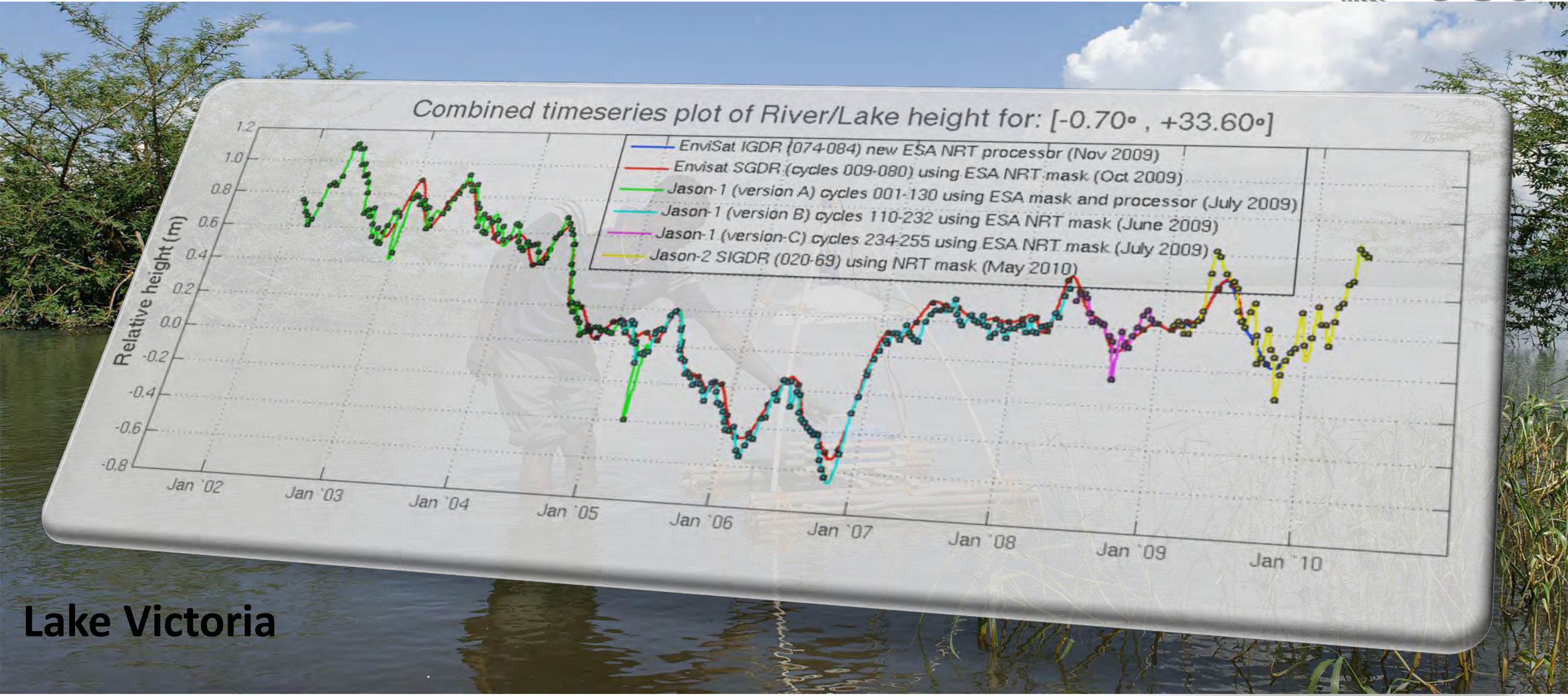
Lake Tana

Lake volume variation (from multi mission)



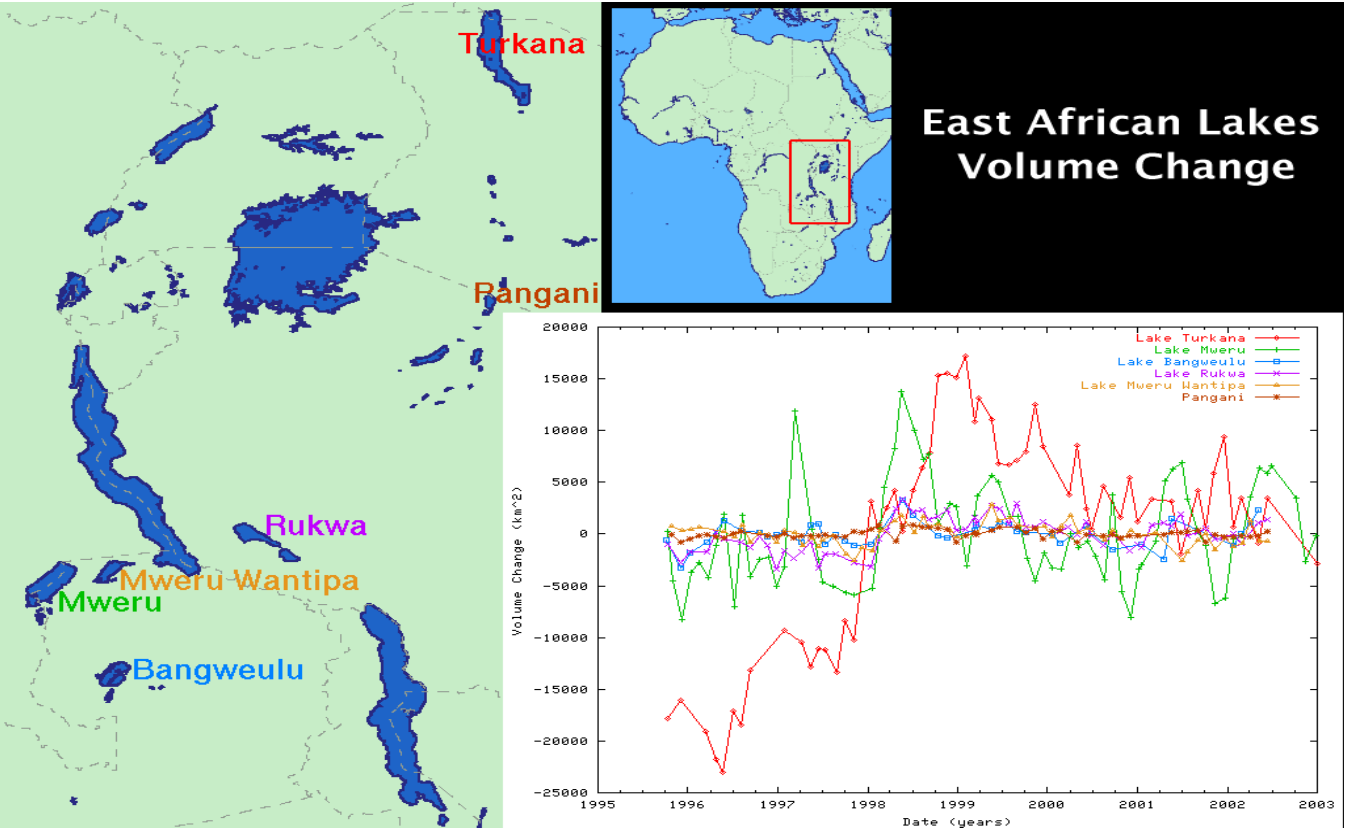
Lake Tanganyika

Lake volume variation (from multi mission)

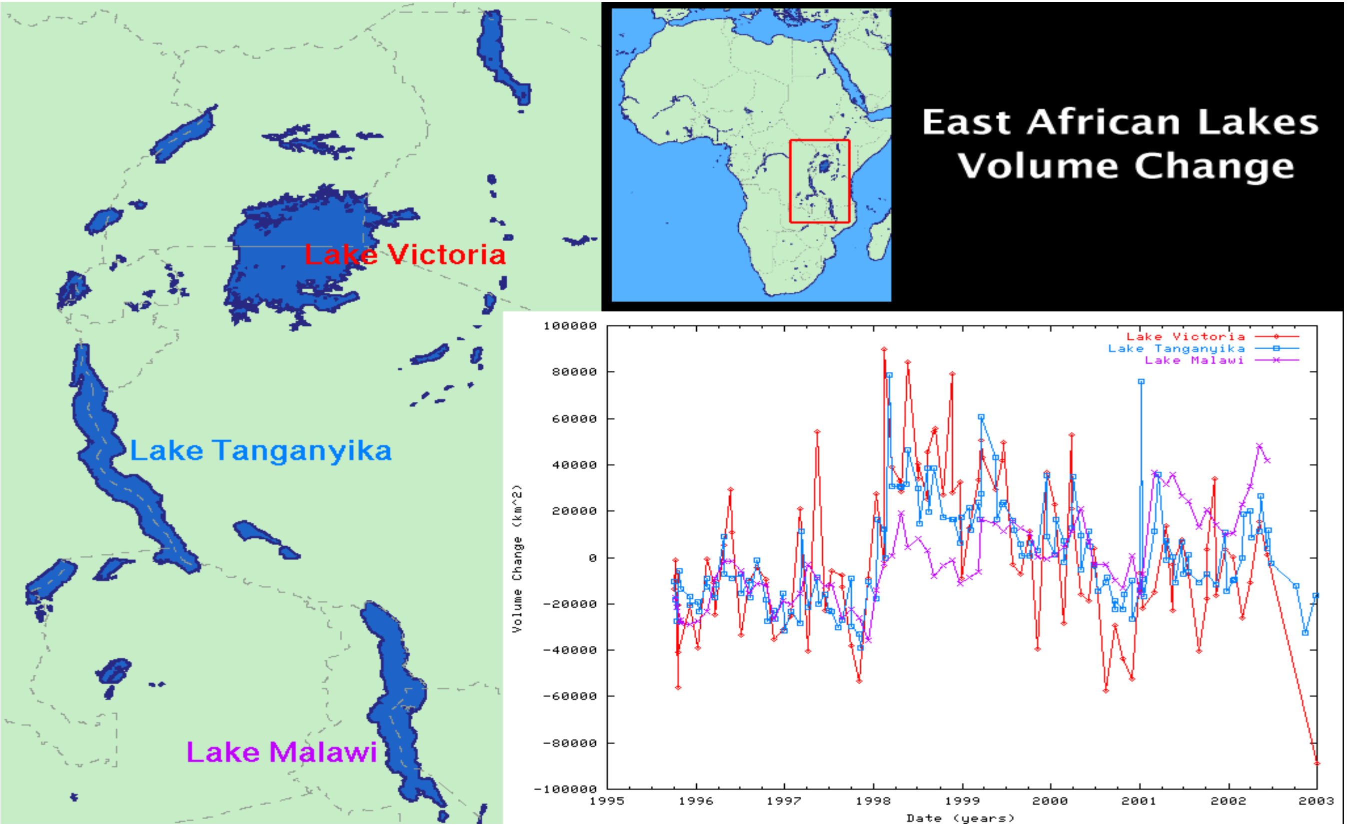


Lake Victoria

Lake volume variation (from multi mission)



Lake volume variation (from multi mission)



Thank you for your attention

CONTACT: angelica.tarpanelli@irpi.cnr.it
http://hydrology.irpi.cnr.it/people/angelica-tarpanelli/