Satellite radar altimetry: principles

Presented by

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With invaluable help (and material) from
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and my colleagues and friends
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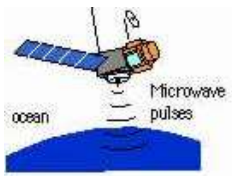
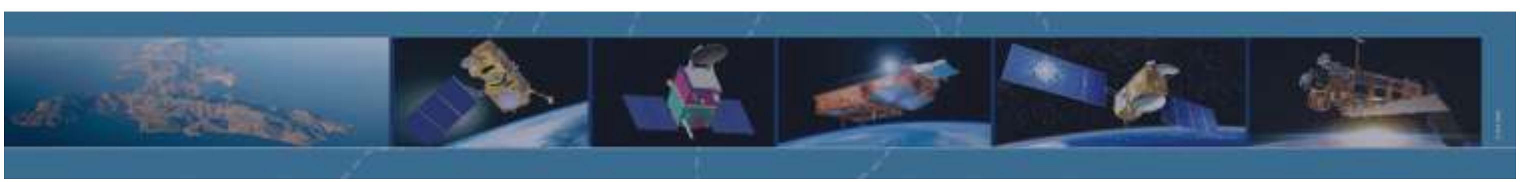
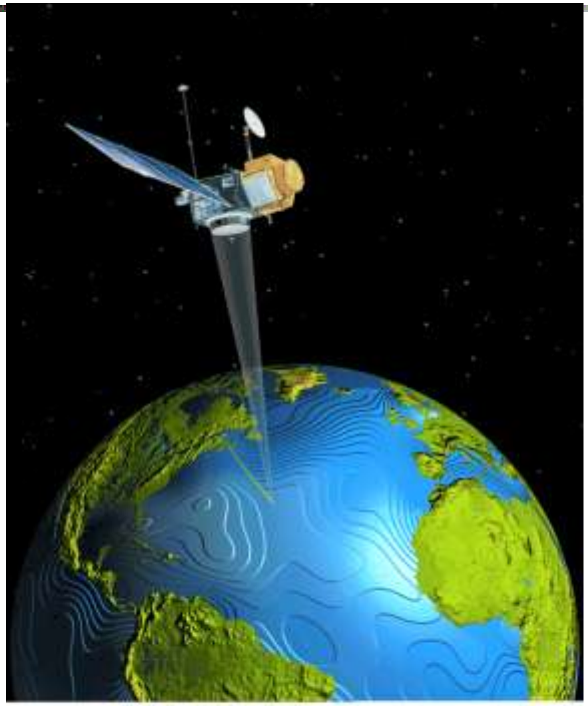
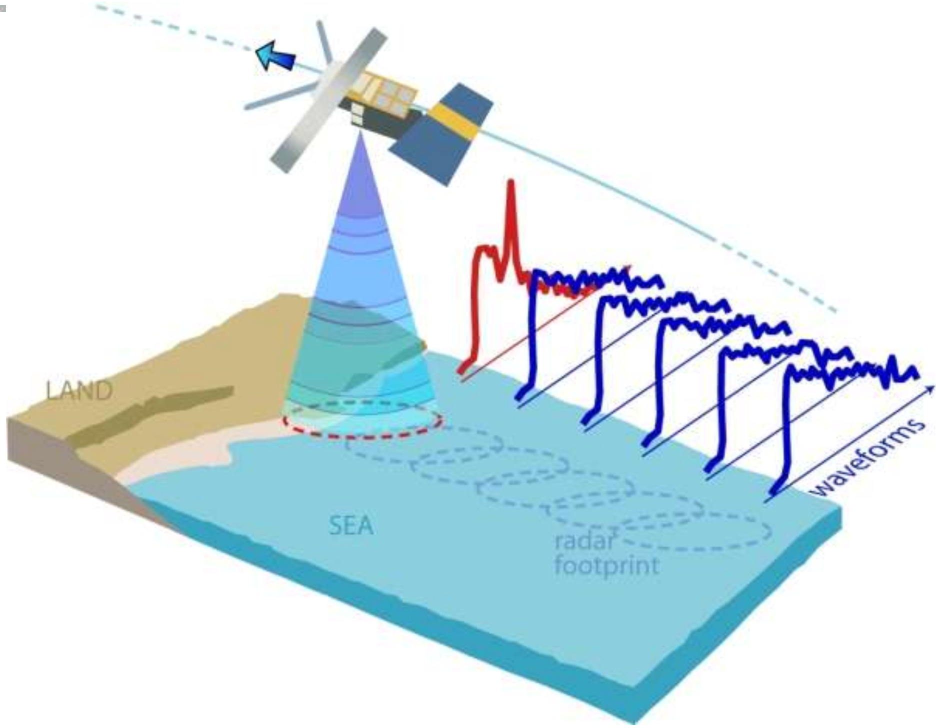


particular thanks also go to the
Coastal Altimetry and Inland water Communities



Satellite altimetry designed with the open ocean in mind

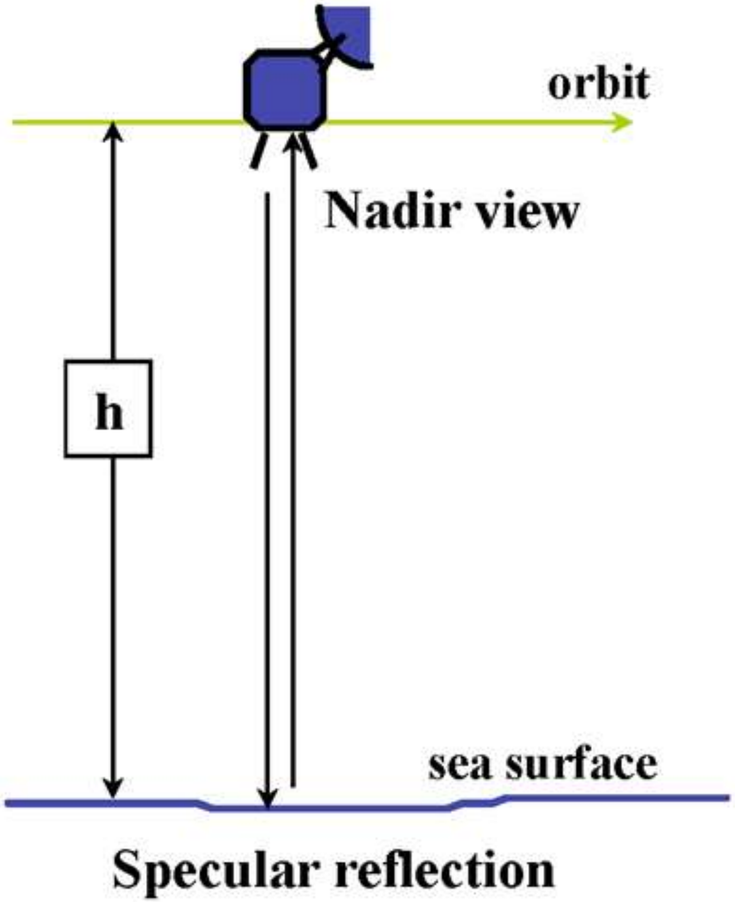




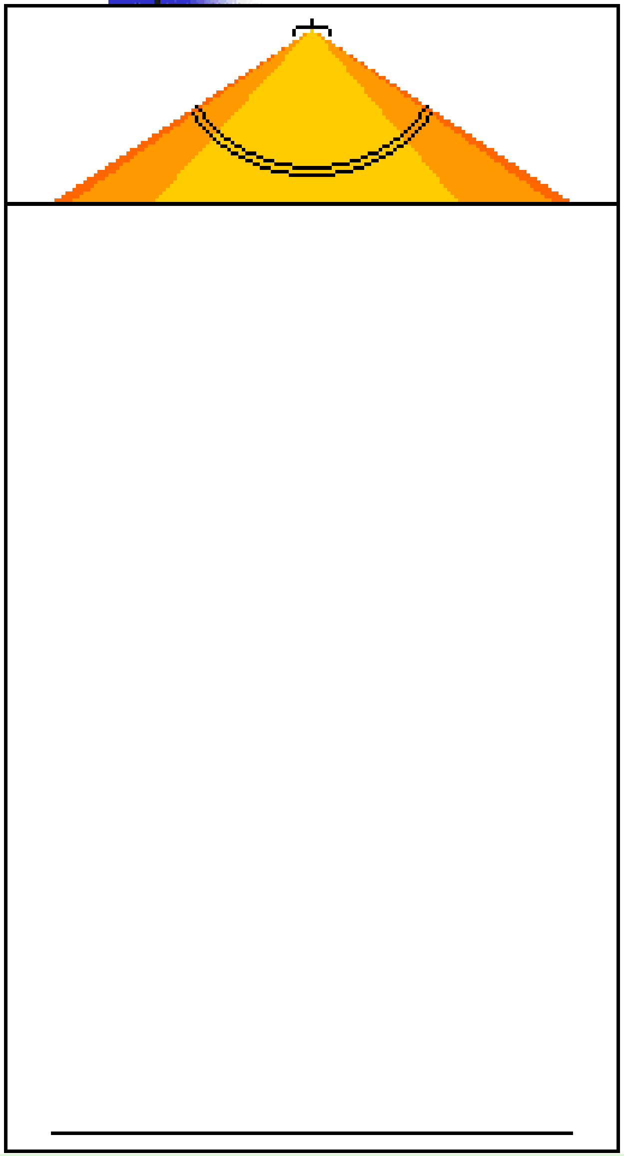
- Potential exploitation in challenging domains (coastal zone and inland waters) demonstrated in the last years
- **The main problem is that measurements are taken near land/water interface**
- **No dedicated mission to inland waters until now**; **SWOT will be the first one but launch time is on 2020**
- Satellite radar altimetry community is still limited in developing and exploiting satellite altimetry over the land

Basics of pulse-limited Altimeter theory (I)

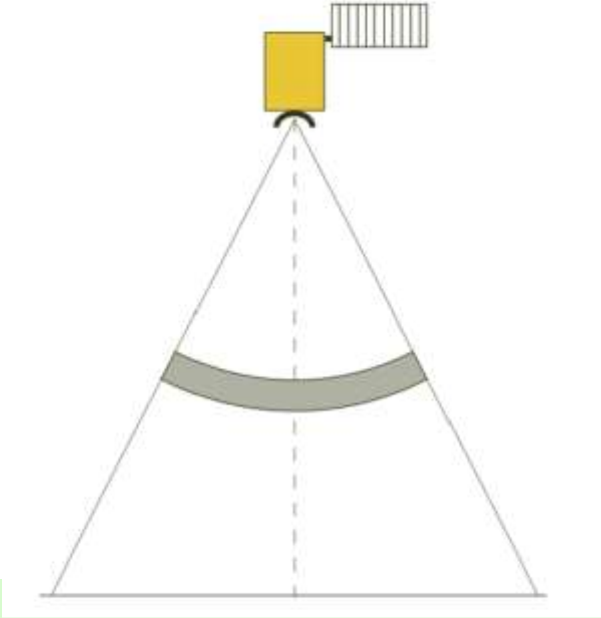
- Measuring travel time, **2T**, from emit to return
- **h=Txc** (c= 3x 10^8 m/s)
- **Resolution to ~1cm** would need a pulse of 3x10^{-10}s (0.3 nanoseconds)
- 0.3 ns would mean a bandwidth > 3 GHz that is very high radio frequency bandwidth
- The workaround is to use Frequency Modulation pulse compression



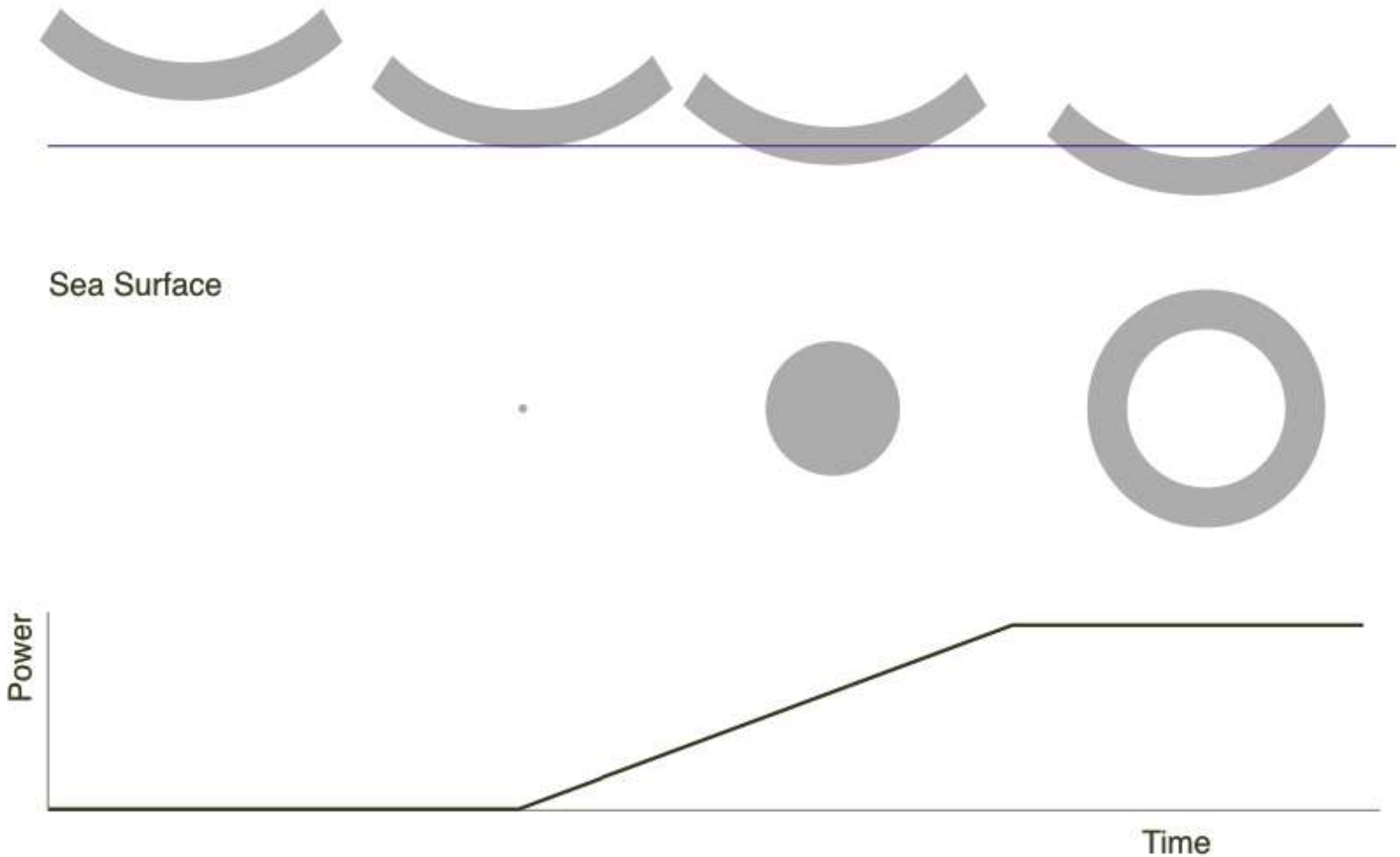
Basics of pulse-limited Altimeter theory (II)



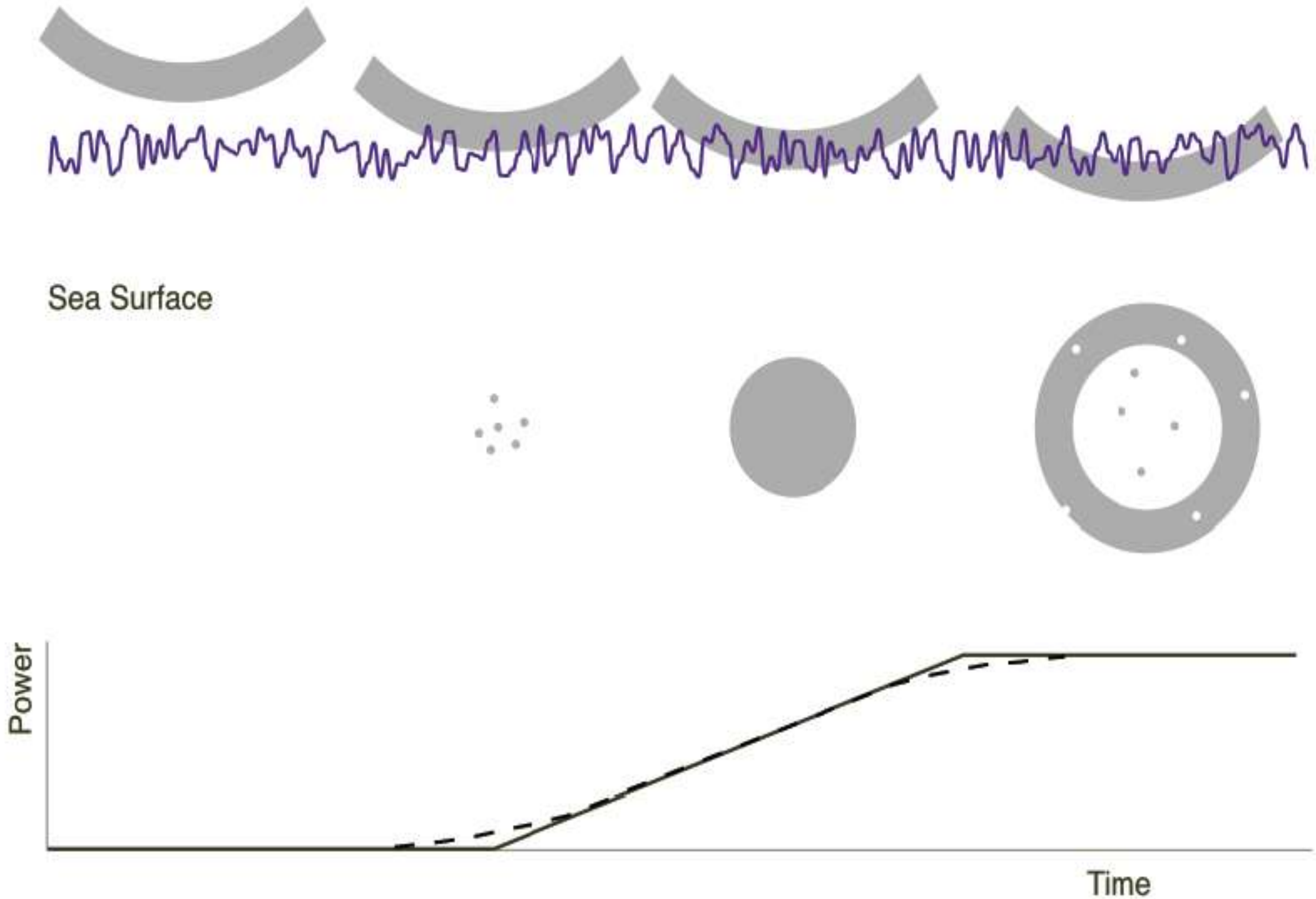
- We send out **a thin shell of radar energy which is reflected back from the sea surface**
- The power of the returned signal is detected by a number of gates (bins) each at slightly different energy
- In a pulse-limited altimeter **the shape of the return is dictated by the width of the pulse**



This is what happens

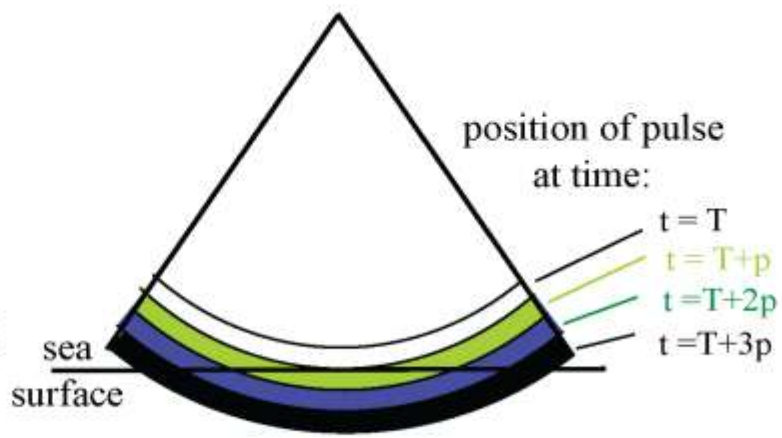


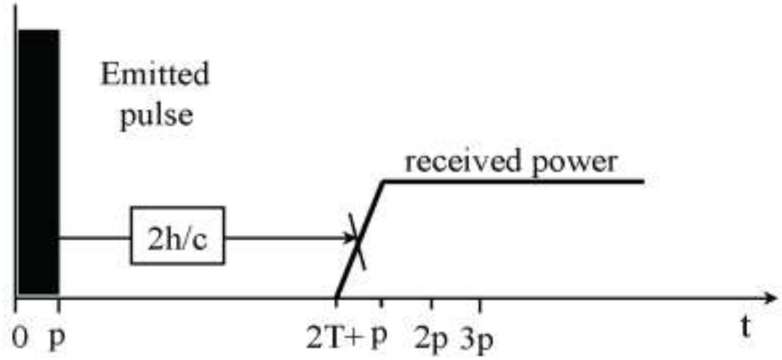
and if we add waves

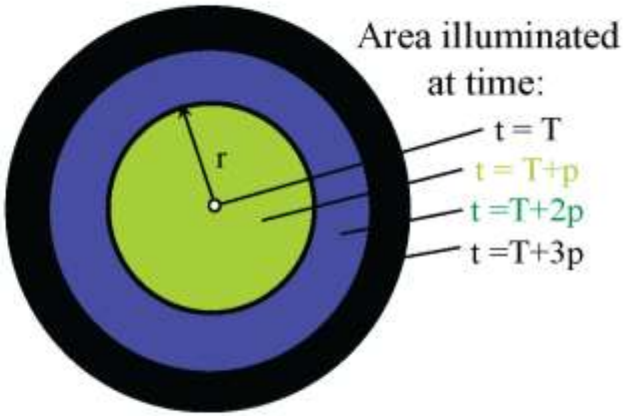


The Pulse Limited "footprint"

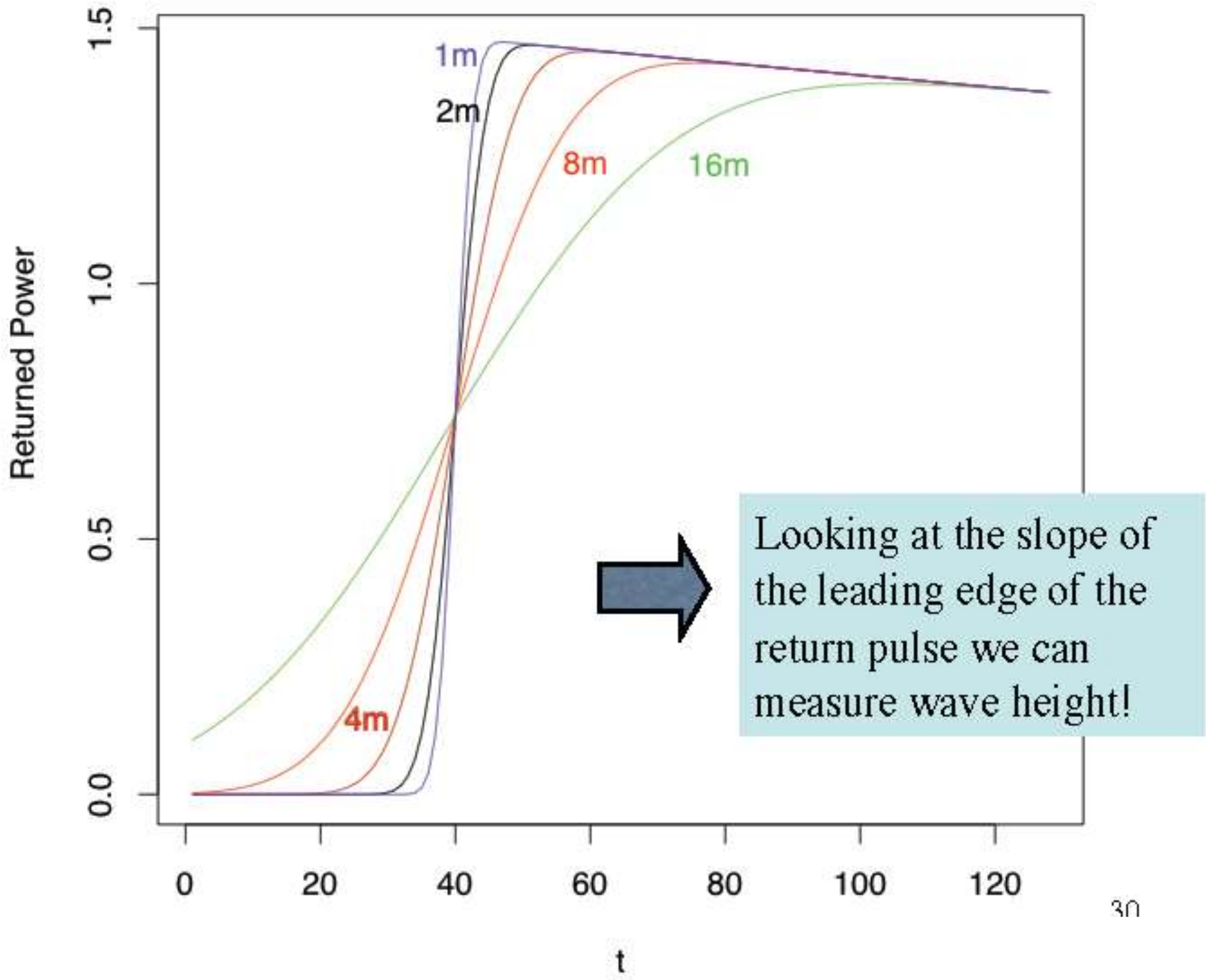
- Full illumination when rear of pulse reaches the sea – then area illuminated stays constant
- Area illuminated has radius
  $r = \sqrt{(2hcp)}$
- Measure interval between mid-pulse emission and time to reach half full height





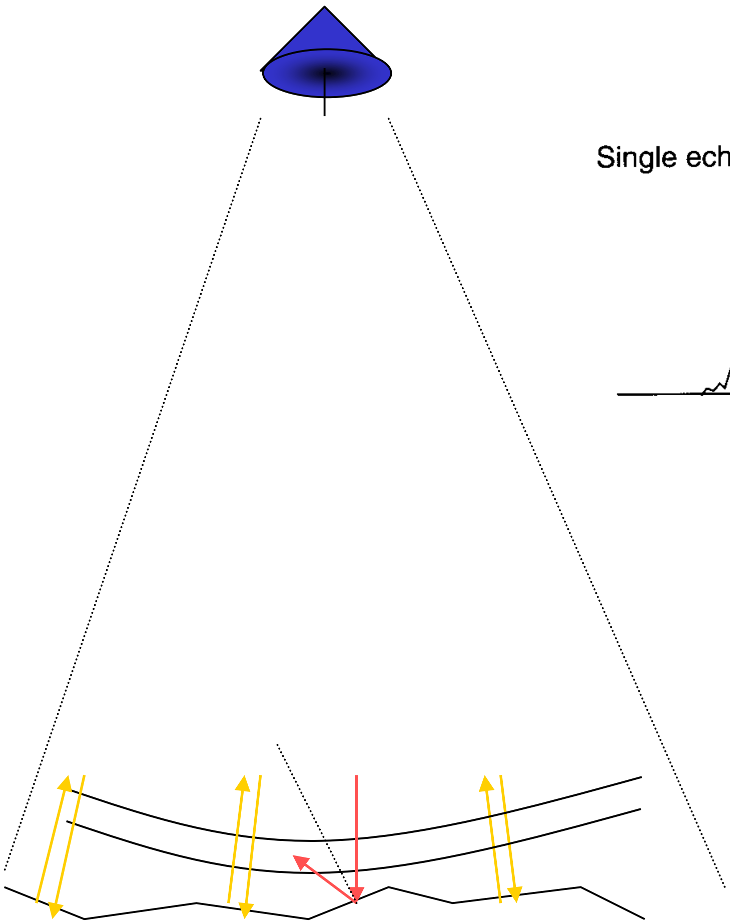


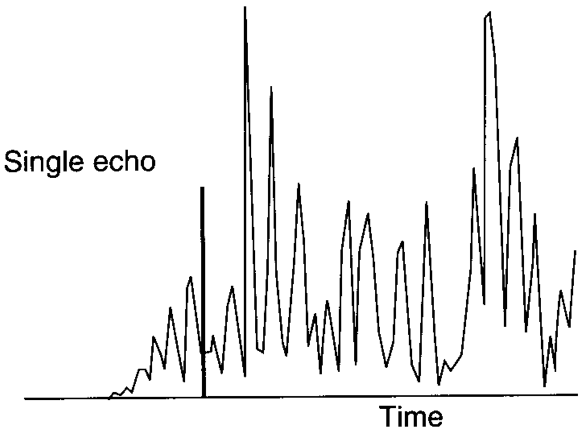
This is what we get at end



In big lakes we can have waves as they behave as oceans in miniature

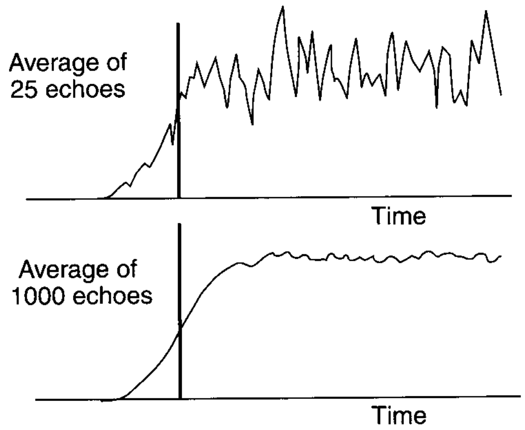
One single pulse collected over ocean is noisy





This is a result of **random distribution of the ocean wave facets** at any instant

Averaging many successive pulses can reduce noise

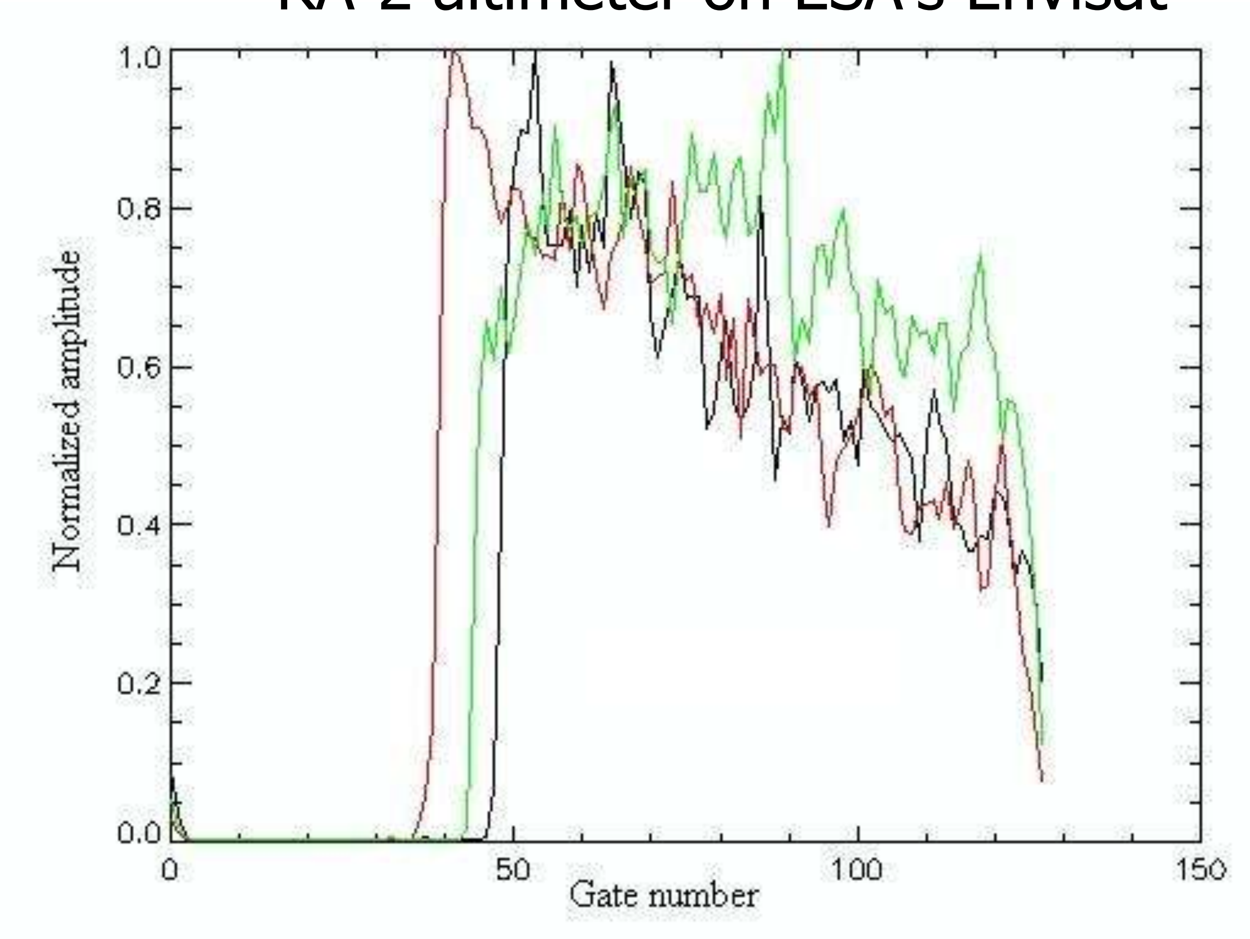


- We average (**incoherently**) consecutive pulses to achieve good Signal to Noise Ratio
- The pulse repetition frequency is **thousands per second** (e.g., 1020 for ERS-1/2, 1800 for Jason & Envisat, 4500 for TOPEX)
- Usually data are transmitted to the ground over 1/18 second of flight. This means **measurements every 350 m along track**
- However, data are furtherly averaged on ground over 1 second of flight, i.e. 7 km

7 km is the nominal resolution in standard open ocean products

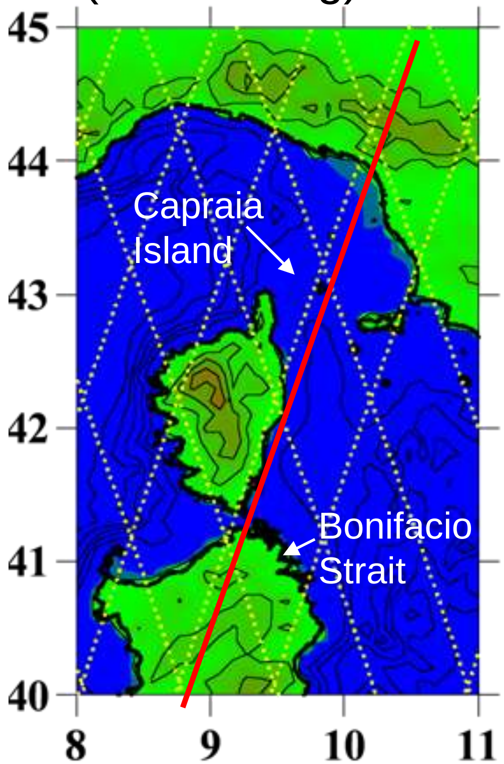
Real radar return signals (waveforms) in open ocean and big lakes

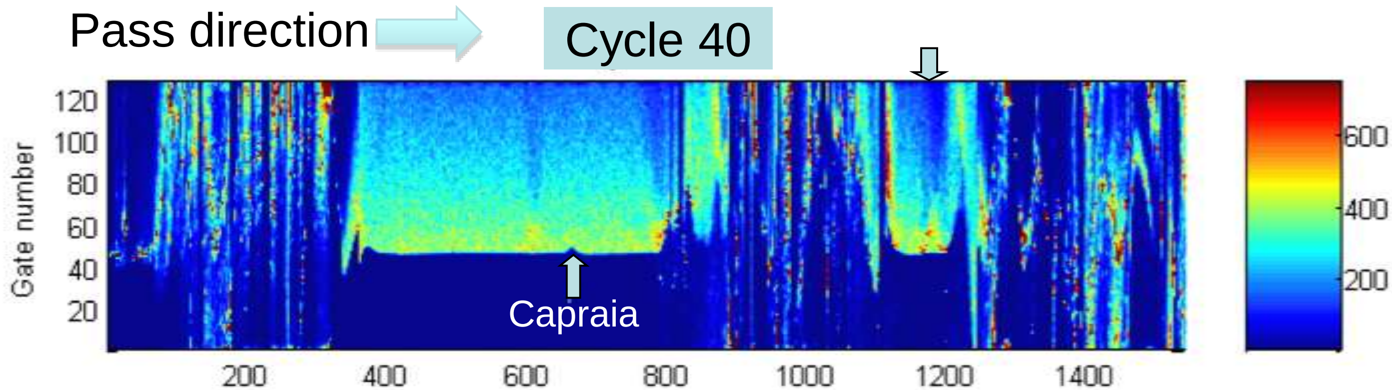
RA-2 altimeter on ESA’s Envisat

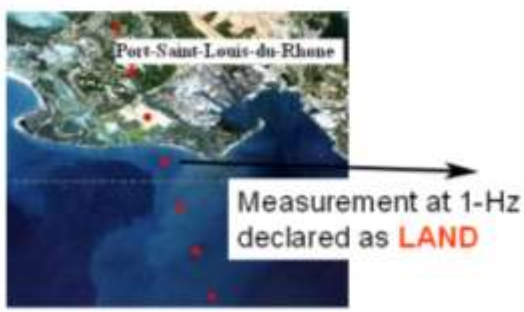


This is to illustrate how complicated the radar signals get close land

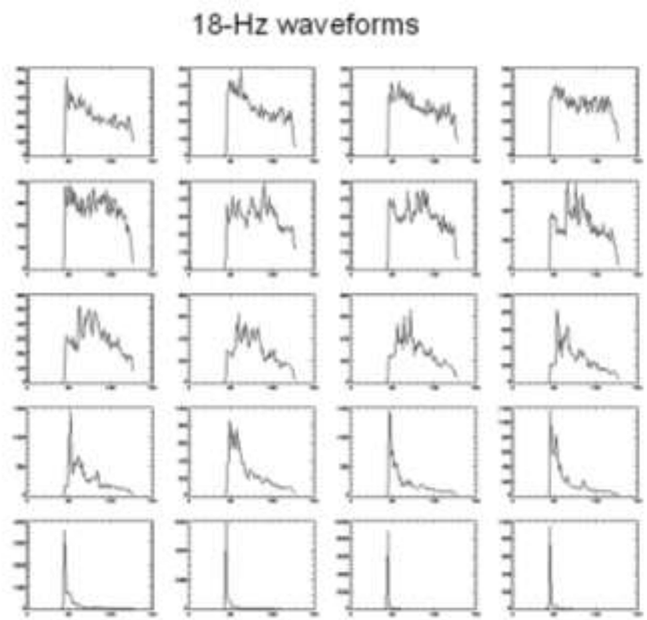
ENVISAT **pass** (descending)



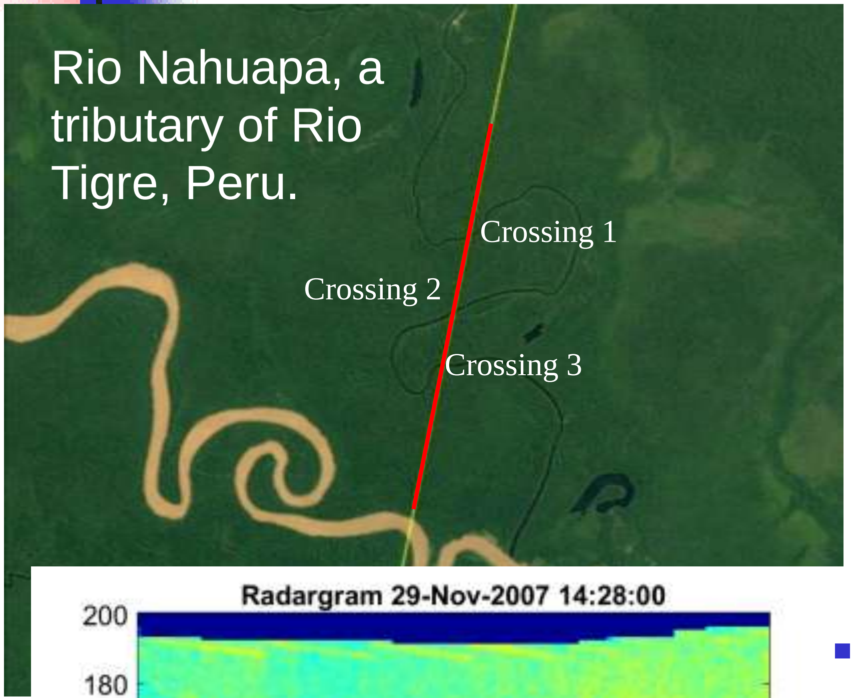


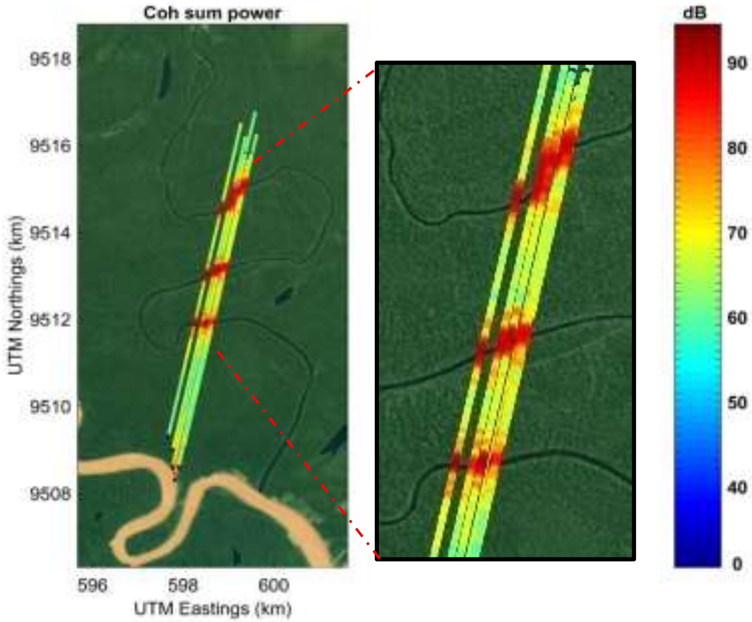


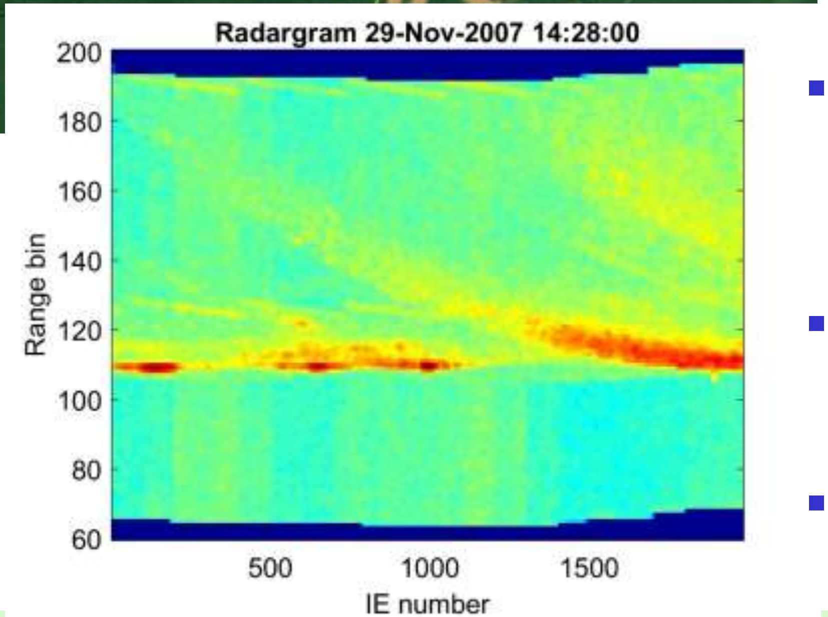
ENVISAT **pass** (ascending)



Here what happens when the satellite overflies small water targets

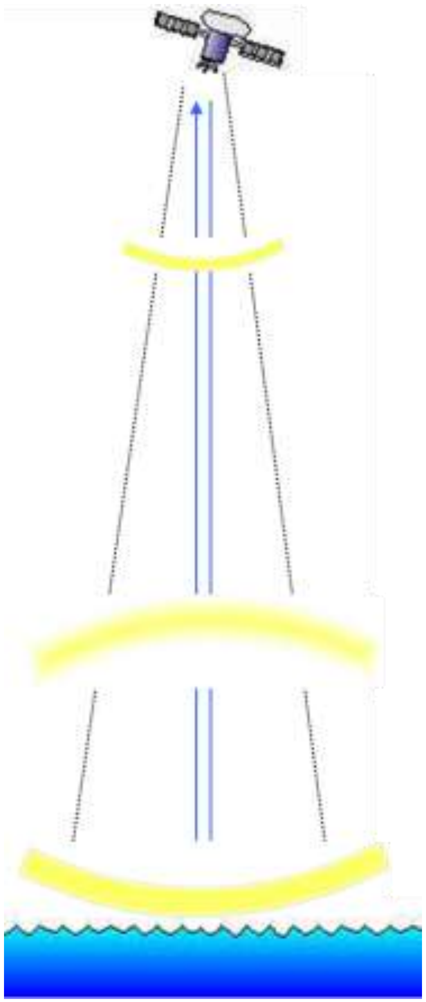




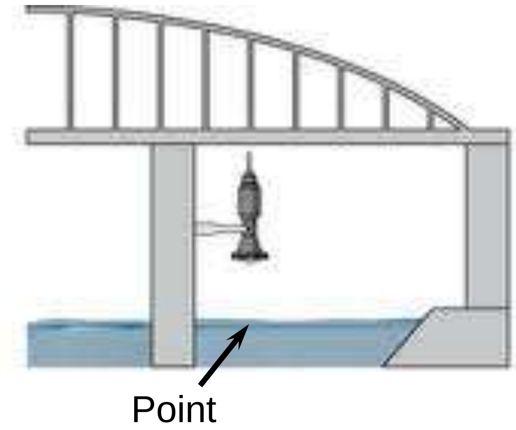


- **Successive radar altimeter passes drift in longitude**; interestingly, the effect of many passes over the area is **to paint a map of the water surface**
- **The radargram has three striking flashes of specular returns corresponding to the three river crossings**
- The altimeter track never quite reaches Rio Tigre but some off-nadir returns from Rio Tigre are presumably seen at the far right

The altimeter system is just a more complicated radar water gauge mounted on satellite



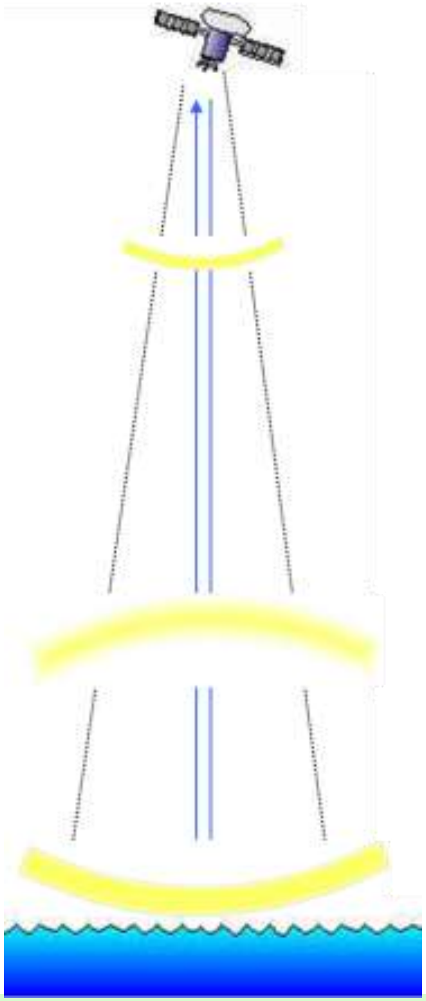
In situ

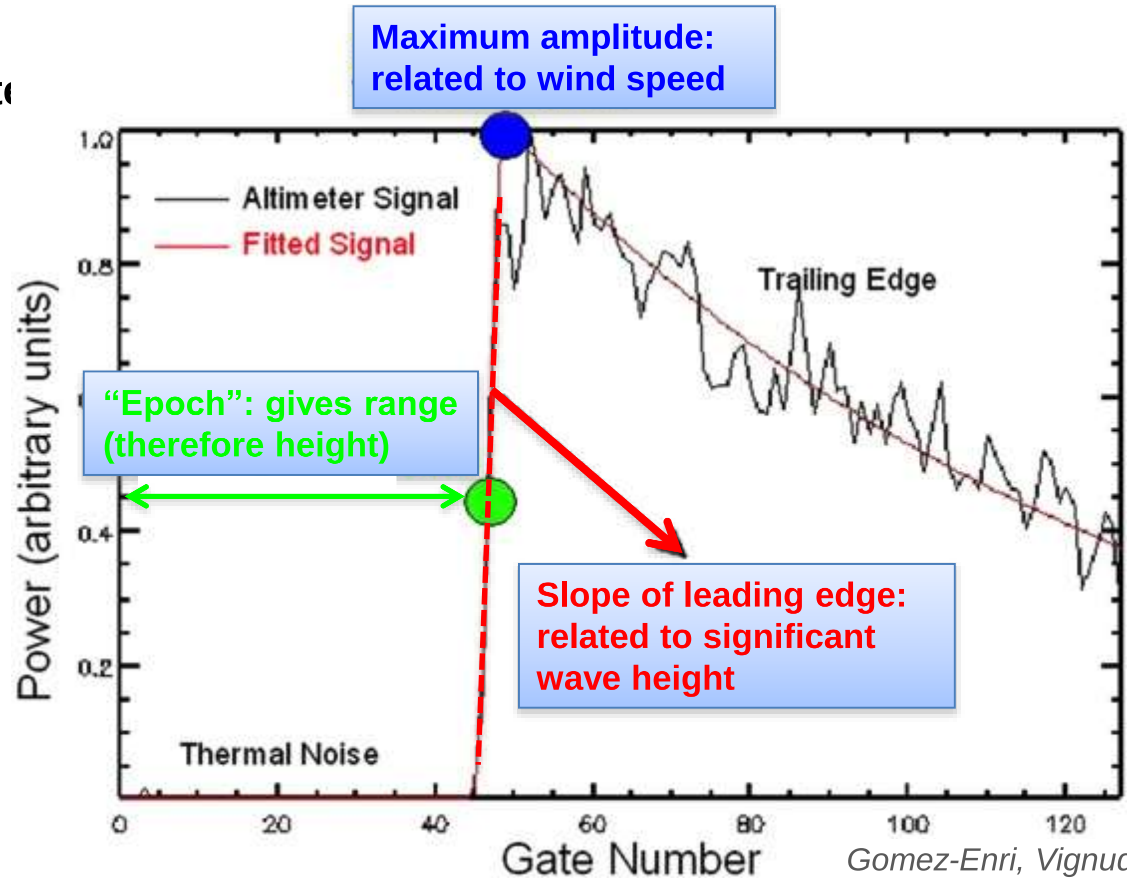


- Need of **additional data** (e.g. orbits and corrections)
- But **more uses** (waves, winds, currents, bathymetry in addition to water level)
- **Averages** over **footprints** vs point-wise
- Sampling of **order of days** vs **min/hour**

How we turn 'return radar signal' into useful data

Radar onboard satellite

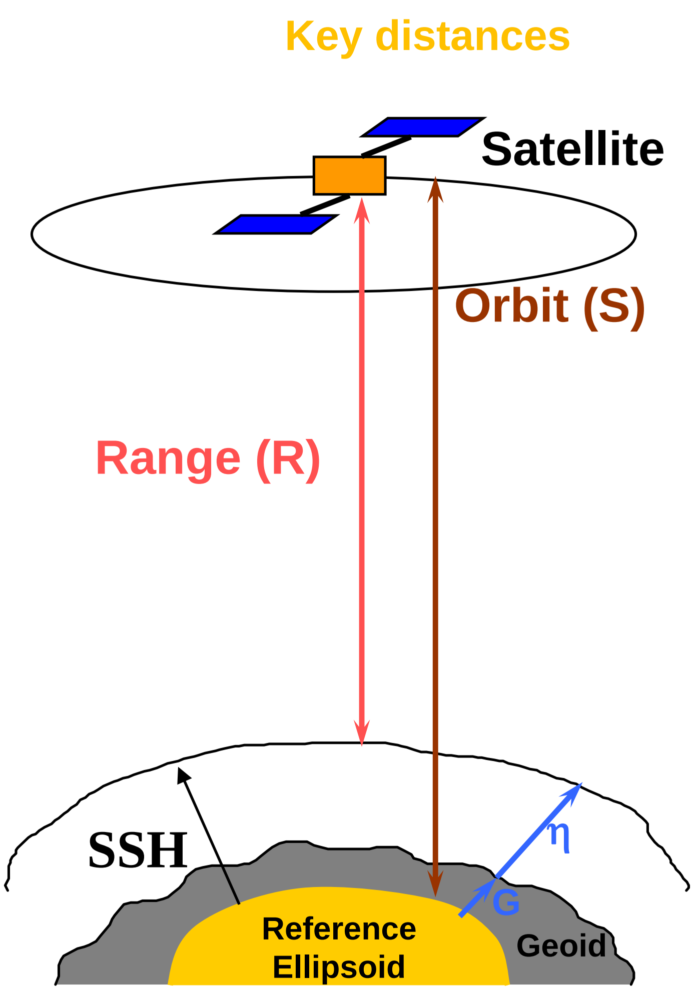




Gomez-Enri, Vignudelli et al., SPIE, 2009

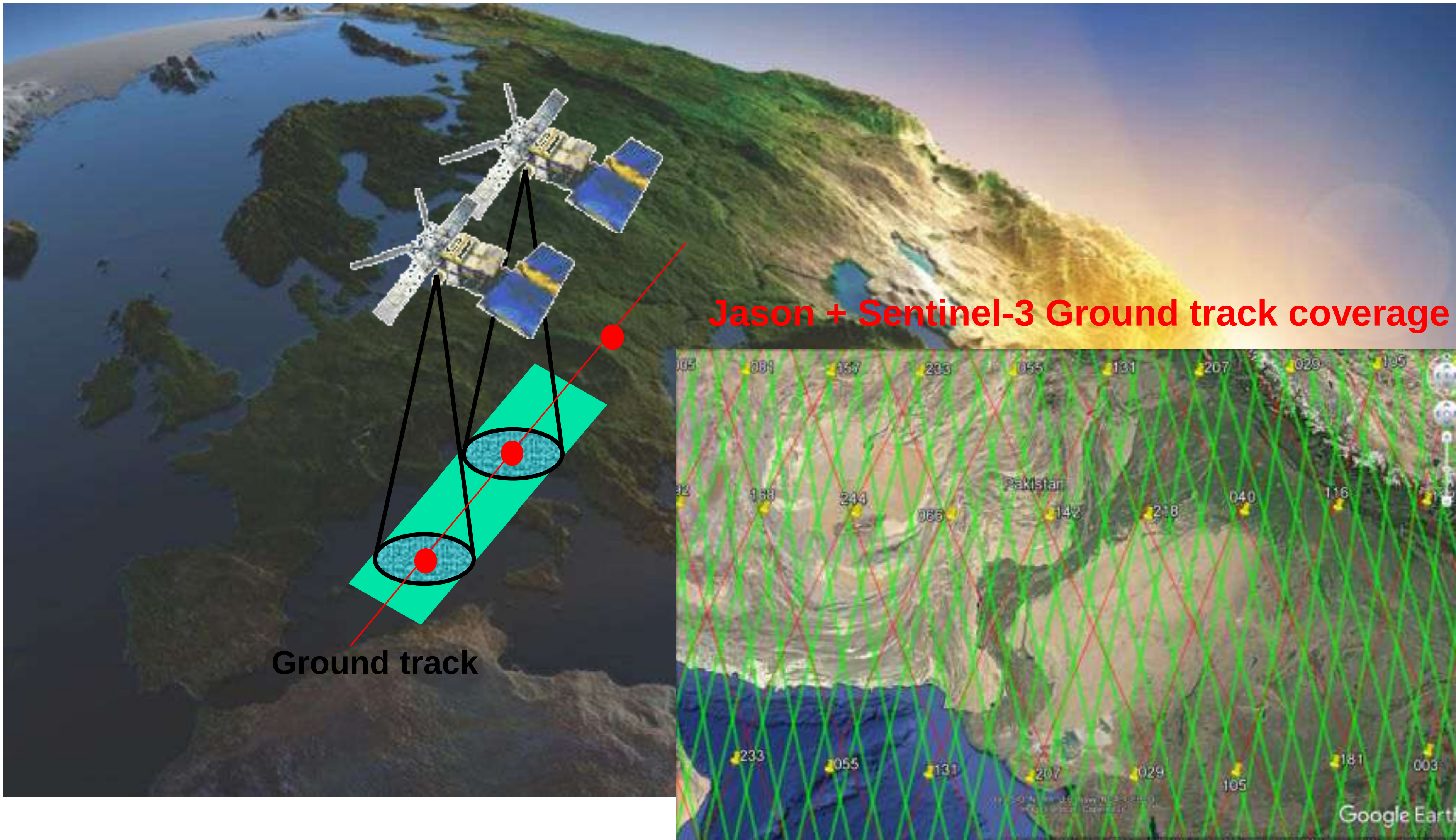
- Fitting the **waveforms** with a model (**waveform retracking**)
- That is how we estimate the so called **range**, wave height and wind from the waveforms

How to transform range in usable quantities

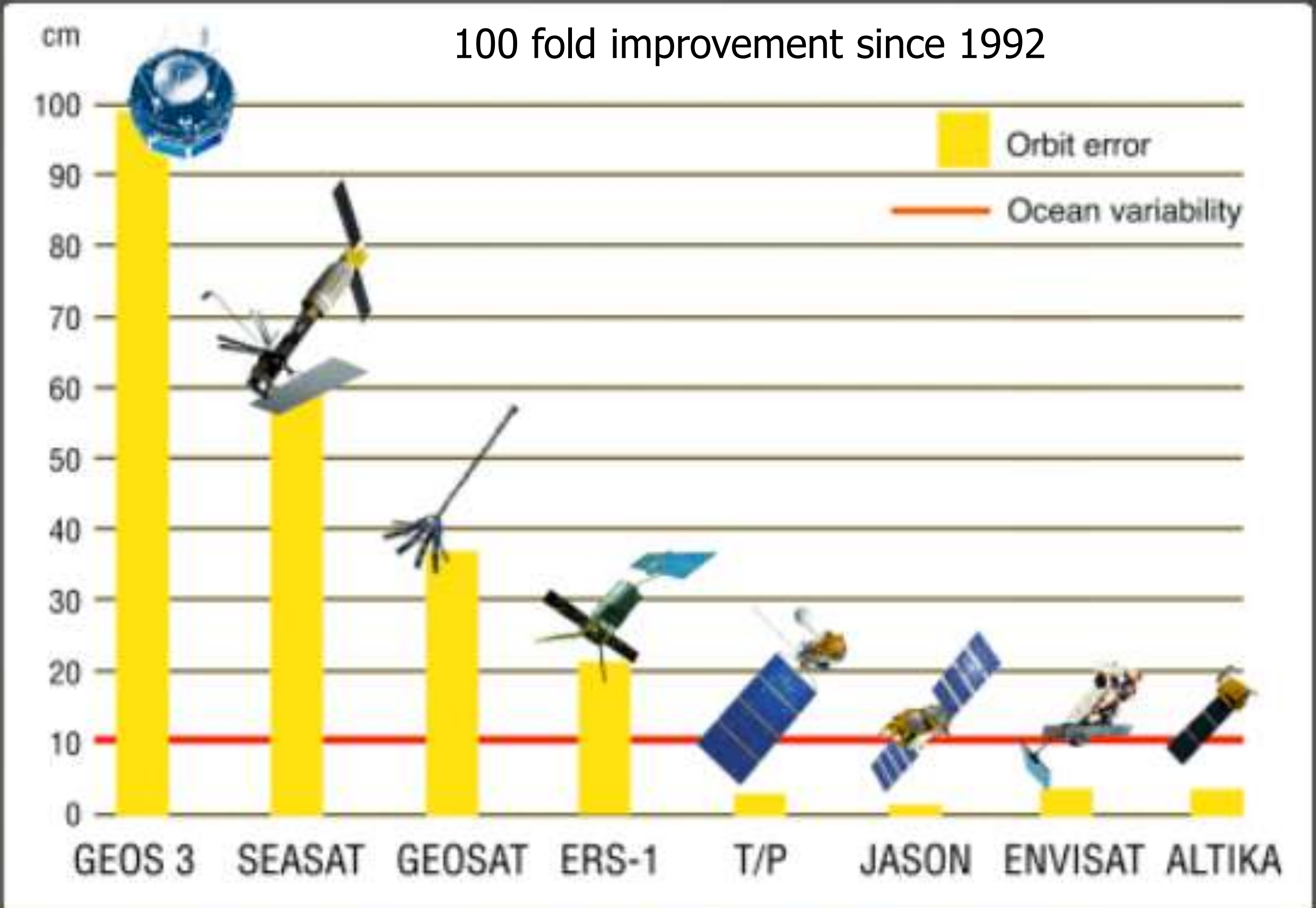


- Range (R) must be corrected for various effects (tropo, iono, SSB)
- We determine the position of satellite (S)
- Hence we compute the height of water surface (S-R)
- That height is usually referred to ellipsoid (called **SSH**)
- Ocean applications require to remove tides and wind/air pressure effects
- Auxiliary information (MSS, MDT) is then used to compute quantities used in oceanography (SLA and ADT)
- In hydrology, **the height of water surface (SSH) is usually referred to the geoid**

Remember: The current altimeters are not collecting pixels



History of satellite altimetry accuracy in open ocean



Improvements in measurement accuracy since the first satellite altimetry missions has enabled us to observe ocean variations at close quarters since 1992. (Credits Cnes).

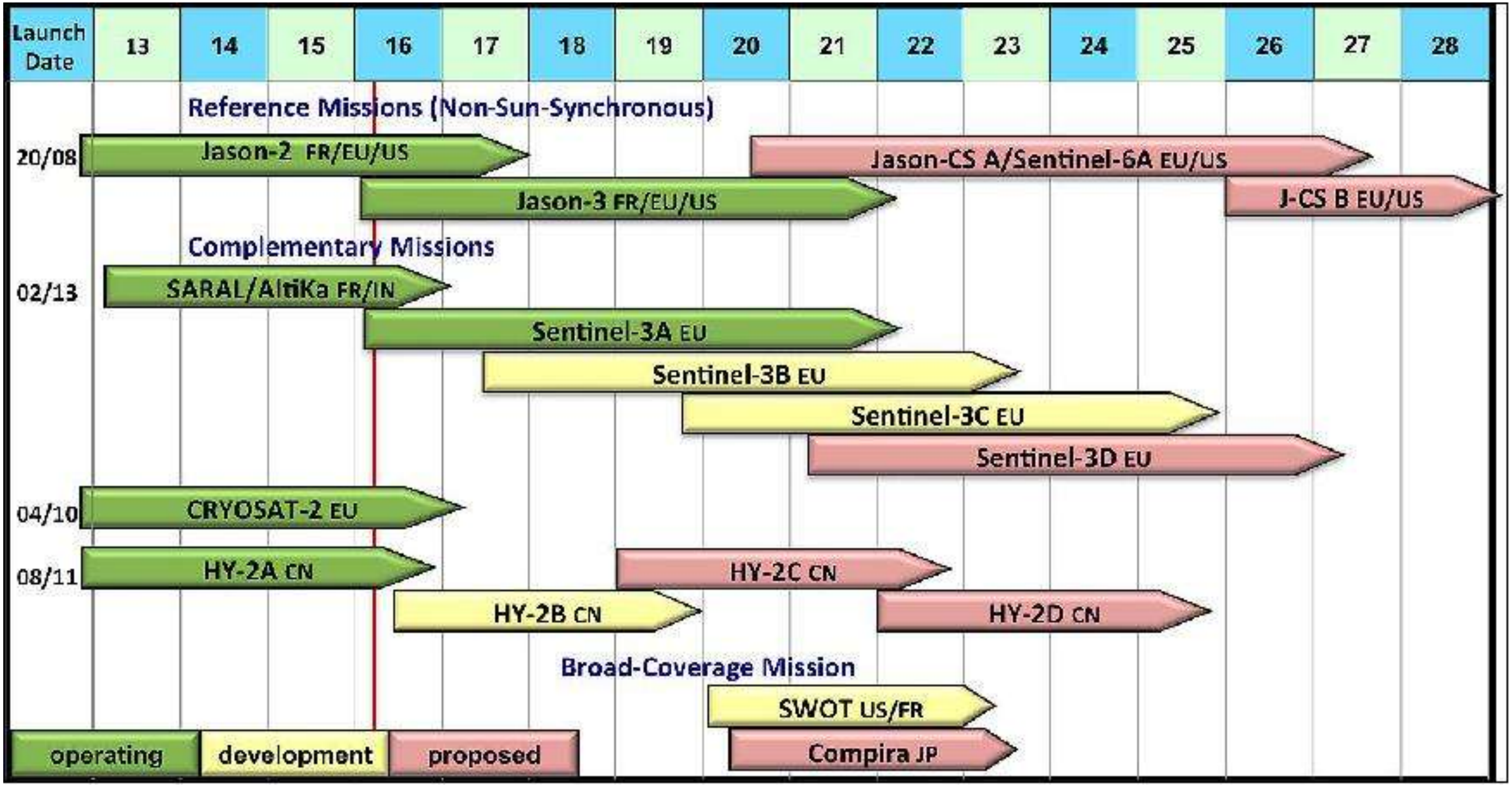
Error budget for water level rivisited (in open ocean)

- **Values in centimeters (1-sigma)**
  - For average conditions (2 m wave height)
  - SAR reduces noise and overall SSH anomaly error

	Envisat	Sentinel-3	Jason-2	Jason-CS
Altimeter noise (LRM)	1.8	1.7	1.8	1.7
Altimeter noise (SAR)		1.3		0.8
Ionosphere	0.5	0.5	0.5	0.5
Sea state bias	2.0	2.0	2.0	2.0
Dry troposphere	0.7	0.7	0.7	0.7
Wet troposphere	1.4	1.4	1.0	1.0
Orbit error	1.9	1.9	1.0	1.0
SSHA error (LRM)	**3.6**	**3.6**	**3.2**	**3.2**
SSHA error (SAR)		**3.5**		**2.8**

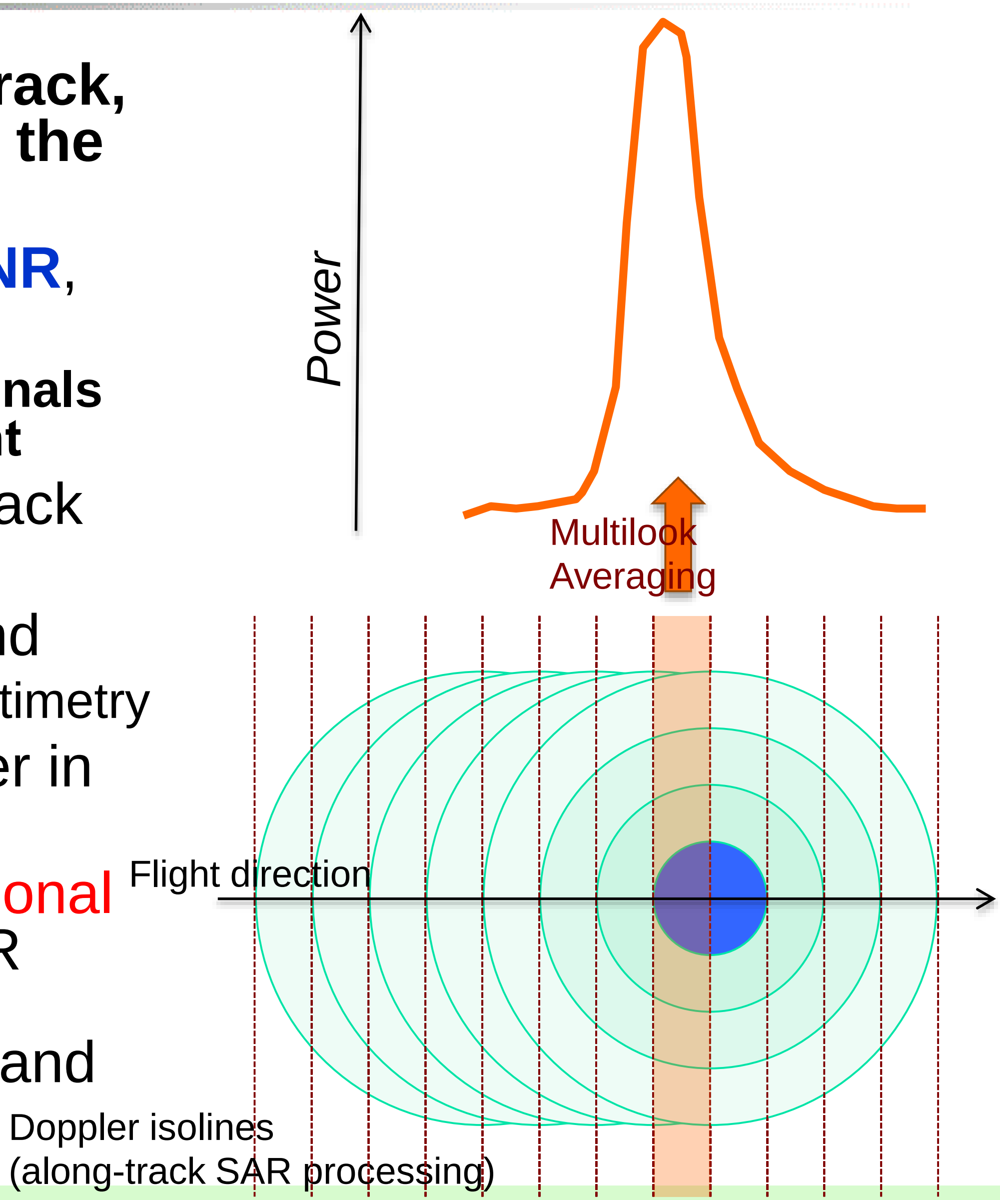
Courtesy: Scharroo et al.

Global Altimeter Missions: now and then



Technical advances in challenging targets (coastal zone and inland waters): the SAR revolution

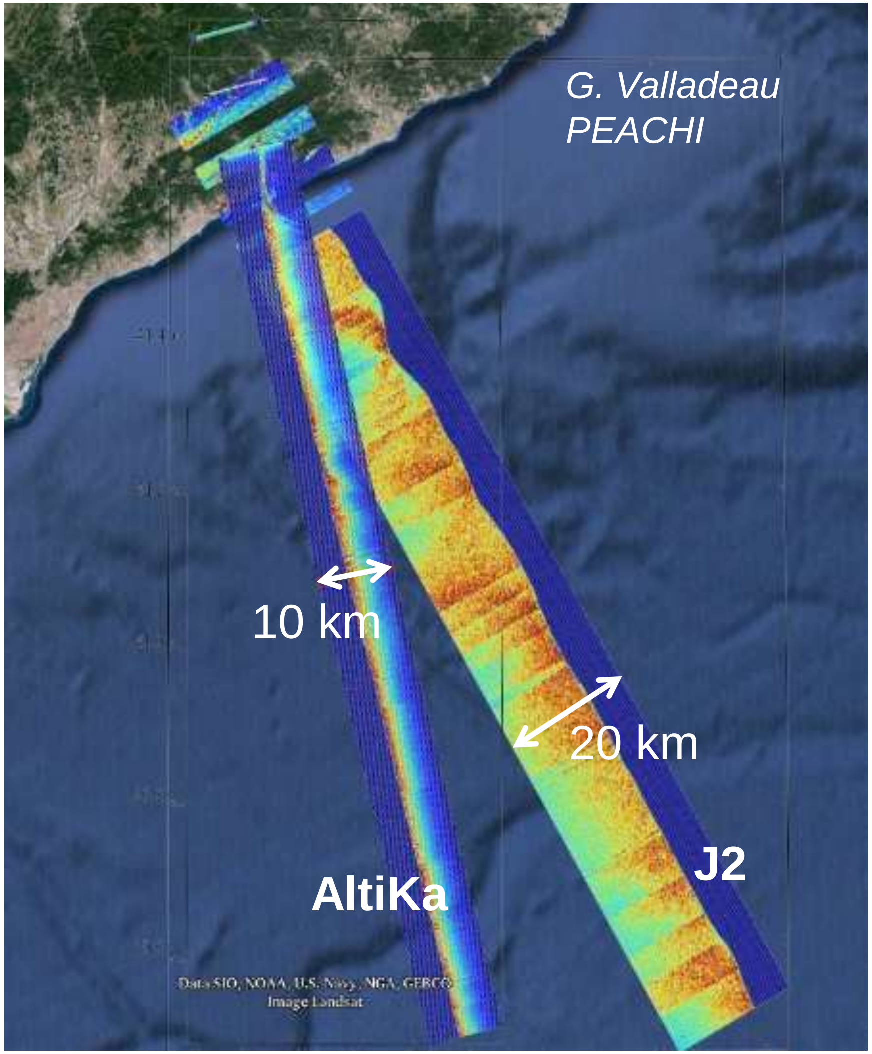
- **We split the footprint along-track, and align multiple <u>looks</u> over the same resolution cell**
- More "**looks**" means **higher SNR**, i.e. improved SSH accuracy
  - **We can better detect small signals in "noisy" coastal environment**
- Finer spatial resolution along track
  - ~ 300 meters along-track
- Less contamination close to land
  - So very well suited for coastal altimetry
- Cryosat-2 the first SAR altimeter in orbit
- Sentinel-3 now the first "operational coastal altimetry mission" - SAR mode over the whole ocean, including the world's coastline and inland waters"
-



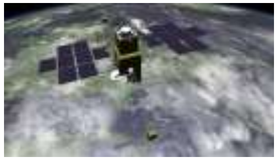
Technical advances at land/water interface: the AltiKa mission

- **Smaller footprint** than other missions
- **Reduced range noise and SWH noise and finer spatial resolution** (3db beam narrower than range gate limit) all promised a significant refinement of coastal altimetry (when matched by improved corrections)
- PEACHI project has introduced many improvements in processing
- **AltiKa extremely good near land**

AltiKa / Jason-2 West Mediterranean Sea



SWOT – A revolution

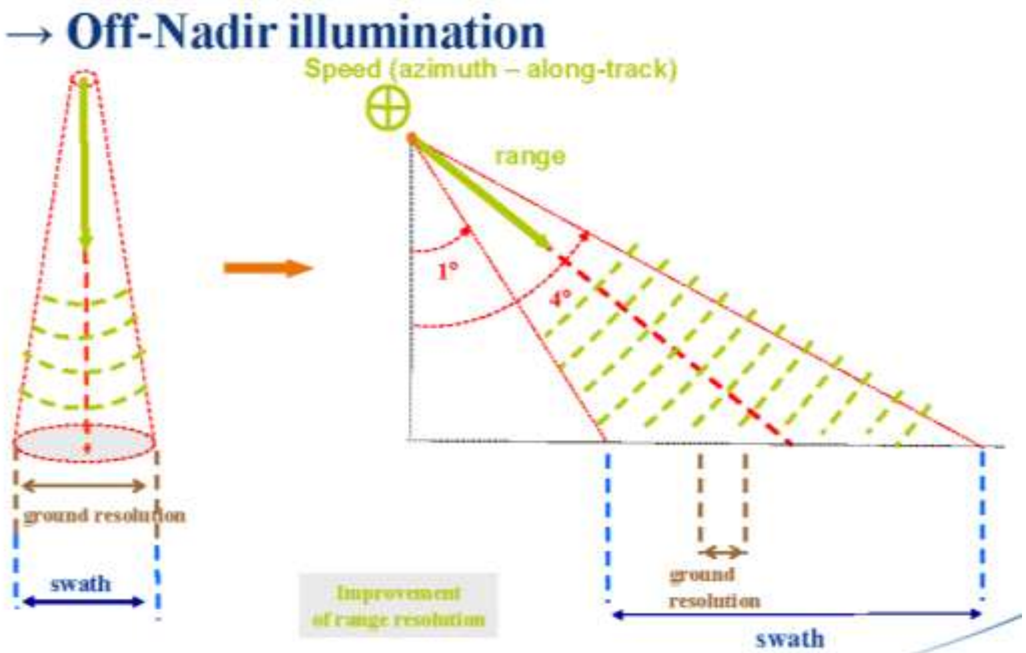


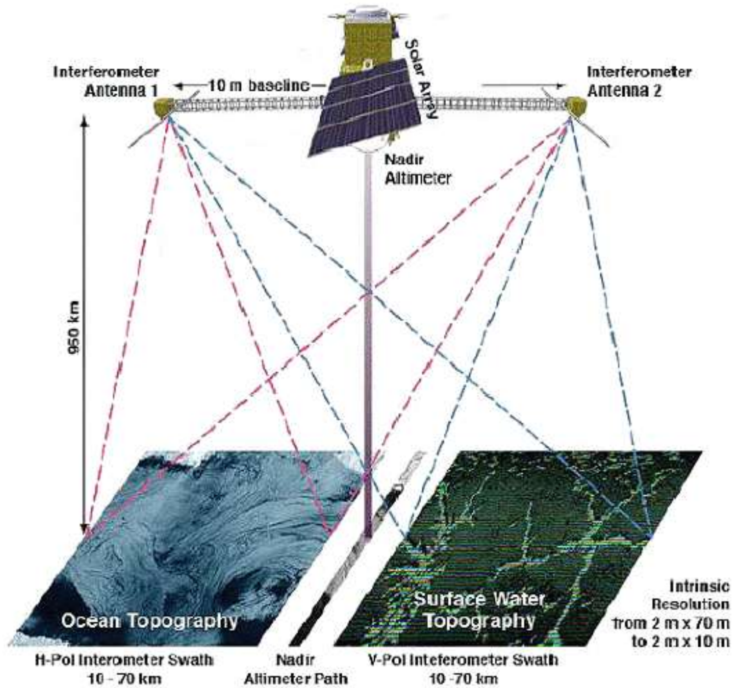
- SWOT means **Surface Water & Ocean Topography**
- Combining research needs associated to hydrology and oceanography
- **From a fixed pattern (1D along track) to images (pixels)**
- Mapping of water level for rivers, lakes, and oceans (including coasts)
- Principle : **Wide-Swath Interferometric, Ka-band altimeter**
- Expected launch date around 2020

http://swot.jpl.nasa.gov/

From nadir altimetry to SWOT

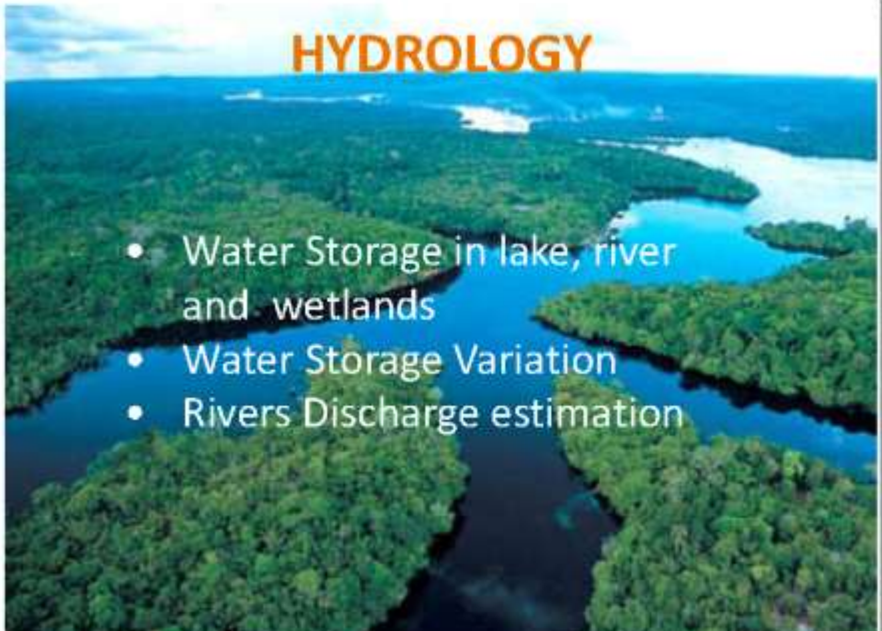
https://swot.cnes.fr/en/SWOT/index.htm





- It overcomes the **main limitation of current altimetry** (data collected along track only) using the interferometric technique
- It will provide a **bi-dimentional image** with an horizontal resolution of about 50-100 m.
- With its large swath, **SWOT satellite will overfly water bodies at least twice every 21 days.**
- **Potential of SWOT for transboundary surface water monitoring in International River Basins**

SWOT – the first altimeter mission for hydrology

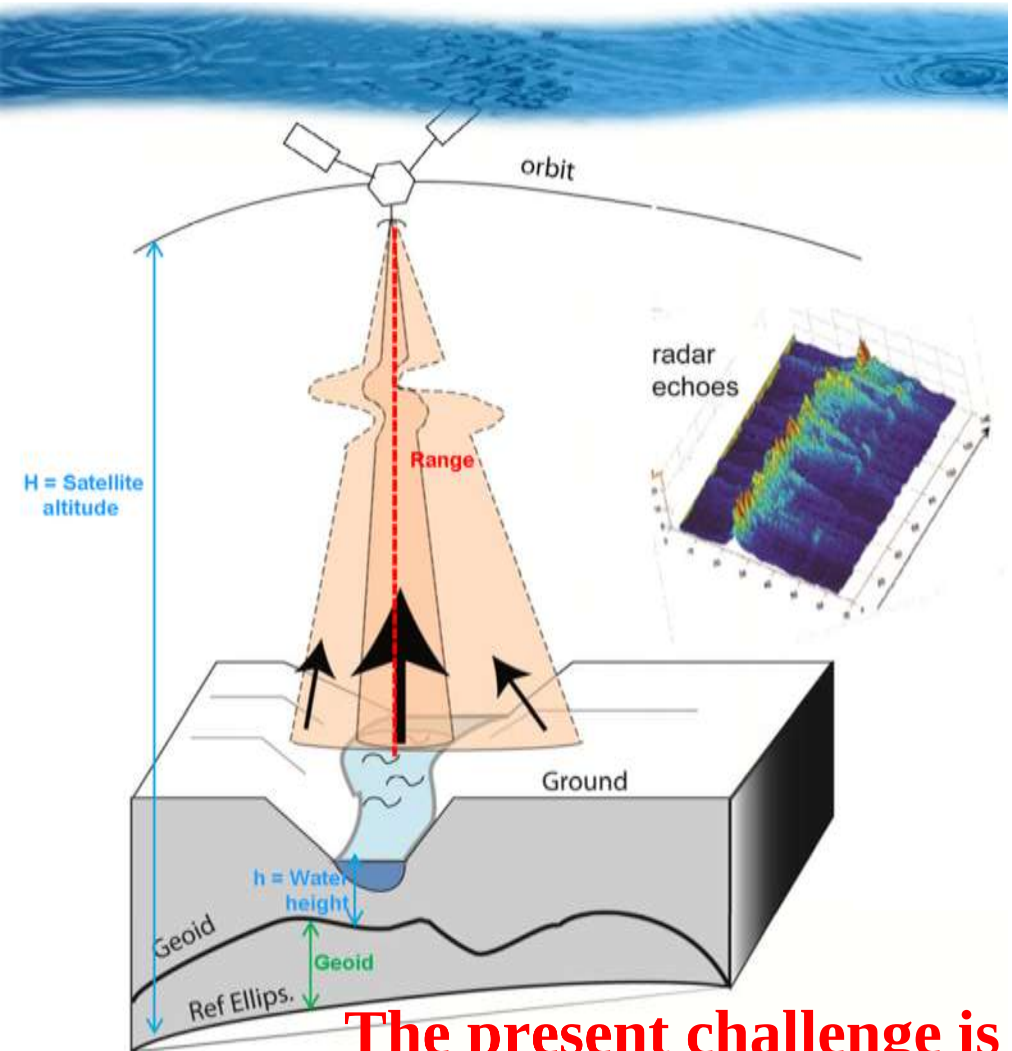


SWOT products

1. Transboundary rivers management (international & interregional)
2. A better modelling of flood
3. Clear water management for urban, industrial and agricultural
4. Hydroelectricity production management
5. Prevention of the propagation of epidemics
6. Fluvial navigation support
7. Integrated management for estuaries

Possible Applications

The inland water scenario



h= H- Range- Geoid

- **The actual radar altimeters collect data along fixed ground tracks**. A critical limitation, even in a multi-mission configuration, is **the coarse spacing** (hundreds kilometers) between satellite orbital tracks, which means **many water targets are missing from the observation**
- Roughly **700 of the world's lakes** are crossed by the 35-day ERS/Envisat series, about **300** are crossed by the 10-day TOPEX/Poseidon Jason series
- Small water bodies have also proved tough targets for radar altimeters, because **echoes deviate from the Brown shape**

The present challenge is how to make the best use of the altimeter-derived water heights

This is where satellite radar altimetry can contribute

- **Water volume monitoring** in lakes and reservoirs exploiting synergy with satellite imagery
- **Bathymetry** of water bodies
- **Water discharge** in rivers
- **Water level** in modelling, mapping and forecasting of flood events

Measurement of the water volume

- **Radar altimetry used to measure the water level (L)**
- **Satellite imagery is used to measure the surface area (A)**
- Abileah and Vignudelli further improved the technique with a **water area algorithm** and **L-A fitting method**
- The test case was **Lake Nasser** and artificial lakes it creates in the nearby Toshka basin
- Earlier results were also then validated with in situ water gauge data provided by Egyptian authorities
- The above research established a **remote sensing based and consistent globally applied methodology to water area/volume measurement.**
- This method can be applied everywhere

Imaging satellites

- **Water area extent can be measured with a variety of space-based optical and SAR imaging sensors**
- The different sensor systems and sensor modalities vary in **revisit frequency**, **spatial resolution**, and very significantly in **cost**
- **Cost of imagery is a key consideration for L-A analysis** due to the need for a time series of hundreds of images
- In this context the **Landsat constellation** is the best option as it provides images free
- **Sentinel-2 constellation** is now complementing Landsat and provides images free too

Synthetic Aperture Radar (SAR) imagery (I)

- At low to moderate nadir angles **the radar backscatter is very good at discriminating land and water**
- **Radar can 'see' day/night and through clouds** which can be an important consideration the cloudiest regions
- According to NASA (http://isccp.giss.nasa.gov/) and Washington University cloud data bases (http://www.atmos.washington.edu/CloudMap/) worldwide daytime average cloudiness is 50-60%, but is geographically variable, from cloud 10% in Egypt to 70-80% at very high Northern latitudes
- **SAR satellites can potentially revisit in, two days** (much higher frequency than Landsat - especially in the cloudiest regions)
- **Radar and optical systems can be considered complimentary**
- Radar is suitable during the rainy season but is affected by wind and lack of vegetation context during the dry season.

Synthetic Aperture Radar (SAR) imagery (I)

- **The one big drawback is cost**. One of the most accessible space-based SAR is the **C-band RADARSAT-2**, operational launched December, 2007. It must be specifically tasked to collect data in an area of interest. If one begins a data collection effort, the data required for an L-A fitting would be available in several years. A ballpark cost estimate: 100 images at **10-m pixel resolution**, $500,000.
- **TerraSAR-X** features **1, 3, and 18 m pixels and repeats up to two days** and has been operational since 2007. There is an archive of historical images but that is not likely to provide enough images for L-A fitting. A new acquisition costs $5000 per image (about the same as RADARSAT-2) providing 30 km x 50 km strips with 3 m resolution.
- The **COSMO-SkyMed constellation**, which began with the first launch in 2007, and several more later, is an X-band SAR. **Their 30 km x 30 km stripmap products, 3 or 15 m pixel resolution would be the most useful for an L-A analysis.** The 3-m resolution cost is about the same as above. The lower resolution cost is about half.
- **Sentinel-1 (ESA) constellation is now providing SAR imagery free of charge**

Visible and IR imagery

- The SAR advantage with regards to clouds is not that helpful. **For the L-A method clouds are not detrimental**, just a minor annoyance
- **The approach can wait for suitable cloud free images to populate the L-A curve of a particular water body**
- Usually **there are several years, in some cases decades, of imagery data for this calibration**
- **Once the calibration is made, the water volume can be monitored with radar altimetry alone and radar altimetry is of course immune to clouds**
- There are two related issues to using imaging satellites: **which of the several commercial imaging systems are most suitable**, and in the case of multi-spectral imaging, **which spectral band(s) are best for water area discrimination**.

Satellites useful for water area mapping

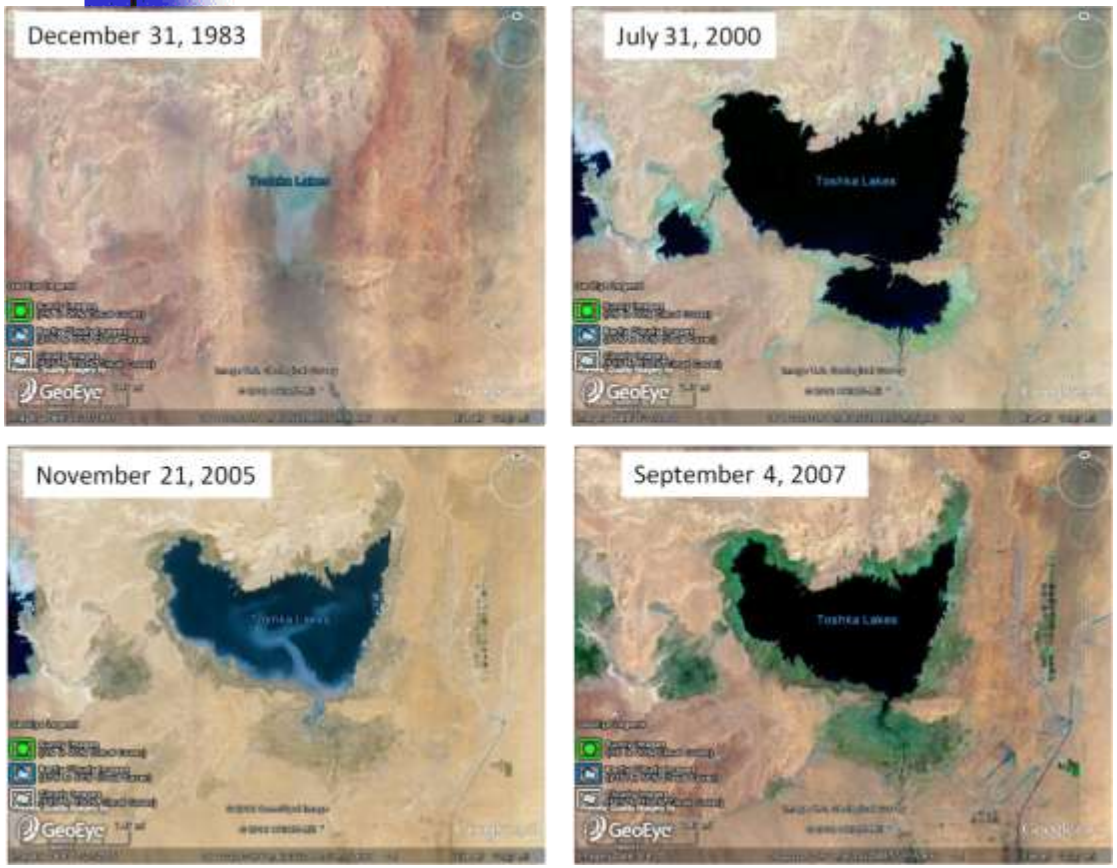
Sensor	Resolution (m)	Revisit (days)	Cost	Bands[1]
MODIS	500	1-2	Imagery is free	36 spectral bands
LANDSAT	30	16		B G R NIR SWIR Thermal, Pan
SPOT	10/20	3	Archival data available for sale	B R G NIR SWIR Pan
IKONOS	4	3		B G R NIR
WorldView 2		3	Tasking satellites for user's area of interest is expensive	Coastal-blue B G Y R RE NIR SWIR & Pan

- The spatial resolution of IKONOS and WorldView-2 is ~1-4 m depending on which satellite and water algorithms are used
- It would be desirable for accurate water cover mapping, especially smaller water bodies
- **WorldView-2 has eight spectral bands including SWIR** which is especially useful for mapping water
- **WorldView-2 also provide 11 bit dynamic range, vs. 8 bits from most other satellites.**
- The three additional bits of radiance resolution can be very useful in the marine environment

High resolution imagery is expensive

- **The cost of the high resolution imagery is so prohibitive that they are unlikely to be used in the L-A analyses**
- To illustrate this point, suppose a time series analysis is desired for a small catchments of 10 km x 10 km with 100 images. The image cost is about $300,000. Also, as with SAR, there is unlikely to be archival data so a study of a particular water body would require the initiation of priority tasking (with extra cost) and results will not be available for several years

Example of Toshka basin, Egypy



Unfortunately these images are based on RGB colors, nice for visualizing the planet but the worst choices for land-water discrimination.

It is worth mentioning that the images from these satellites, or equivalent high resolution images, are easily and **freely accessed with Google Earth**. **The images are limited to a few dates, typically ~5**. **The images are color composites, not the individual spectral bands.** But some hydrological studies should be possible with such data, possibly in combination with radar altimetry time series.

Here you can see **Toshka basin lakes, Egypt, in four stages as seen in Google Earth snapshots.** December 31, 1983 (before water fill), July 31, 2000 (near maximum), November 21, 2005, and September 4, 2007

Example of Shasta reservoir California, USA

Shasta reservoir, California, USA, in **four fill levels as seen in Google Earth very high resolution snapshots**, Clockwise from top left: June 11, 2005; November 7, 2006; July 27, 2009; April 24, 2010

Landsat and MODIS (I)

- **Landsat and MODIS are the most practical choices for most applications**
- Not only because the imagery is **freely distributed**, but also because of their **long historical record** (there is no equal)
- **Landsat satellites have provided worldwide coverage since 1972** with a series of satellites
- In certain periods there were up to three Landsat satellites operating simultaneously (Landsat 4, 5, and 7)
- **MODIS images are available from 1999 to present**
- All the radar altimetry data is also free. So in **the combination of altimetry satellites with MODIS or Landsat there is no data cost**
- **MODIS with 500 m resolution (in bands relevant to water area analysis) is most suitable for monitoring flood plains where the water cover can change in a matter of days.** The relatively poor resolution of MODIS may be acceptable price to pay for daily revisits
- **Landsat is better in cases where the water level change is slower, and resolution is more important in the tradeoff**
- **The pixel resolution of MODIS and Landsat can, for our purposes, be improved by a factor of 3-6, as will be discussed later**

Landsat

- **Landsat revisits at 16-day intervals**, but this is only part of the revisit story
- In certain time periods there were **multiple satellites in orbit** and thus potential for more frequent revisits
- On the other hand **there are areas of the world with months and even multiple years gap in imaging**
- **The revisits over the USA are at typically 16 days, but much less in other parts of the world**
- On average **there is a 50% loss of data due to clouds, with much geographical variability**
- Another consideration is the hardware anomaly that occurred on Landsat 7 in May 2003 The imagery after that date has missing data stripes affecting 22% of the image area. Some Landsat users have managed workarounds to this problem.
- **Given all the variables it is difficult to summarize the effective revisit rate in a simple way but one image every two month is typical.**
- It is easy to navigate the Landsat portal (http://earthexplorer.usgs.gov/) to find images of interest Images may be available for instant download. More often images must be restored from archive. This may take a few days.

Spectral bands (I)

- Landsat, like most other imaging satellites, is **multispectral**.
- **The bands are Blue, Green, Red, near IR, and short wave IR, all with 30 m resolution**
- **There are one or two (depending on the satellite) thermal IR bands with 60 m resolution**
- **There is a panchromatic image with 15 m resolution.**
- In principle all spectral bands can contribute towards land-water discrimination, but **in practice only a few bands provide robust and substantial leverage on classification land-water**.
- **Blue and green have the least contrast** due to a combination of low and variable land albedo and possible strong and variable reflection from below water substrate.

Spectral bands (II)

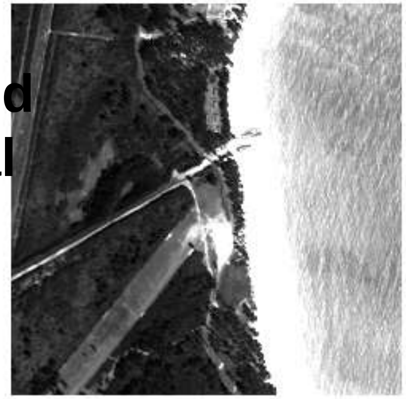
- **In turbid waters, the water spectrum shifts to red-near IR** (Moore 1980)
- The degree of turbidity may be spatially variable, leading to variability in the near IR radiance
- This pushes our preferred discrimination band to the longer wavelength, i.e., the short wave IR, Landsat band 5 with response in 1.55 - 1.75
- **If one desires one simple and robust approach to water detection, requiring a minimum of training and supervision, this is the band of choice**
- The availability of 1.55 - 1.75 in Landsat is another of the several advantages of Landsat over other satellite systems for L-A analysis
- **As an alternative to one band discrimination one may consider the water index (NIR-SWIR)/(NIR+SWIR), which combines the near IR and shortwave IR, as a pseudo one band input**
- The higher resolution of panchromatic (15 m) would be also attractive for water mapping
- However the panchromatic spectral response spans blue to near IR, and does not extend to short wave IR so is not as robust land-water discriminator.
- The Landsat thermal IR bands (designated bands 61 and 62 in Landsat 7) are not considered due to the large pixels (60m), since our goal is accurate observations of smaller lakes and reservoirs.

Spectral bands (III)

RGB

Comparison of shoreline and inland waterway in several spectral bands.

Green

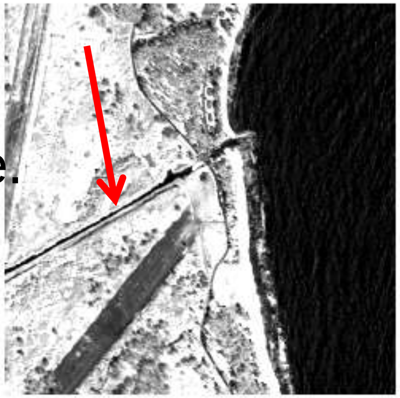


Strong bottom reflection is evident just offshore.

Yellow

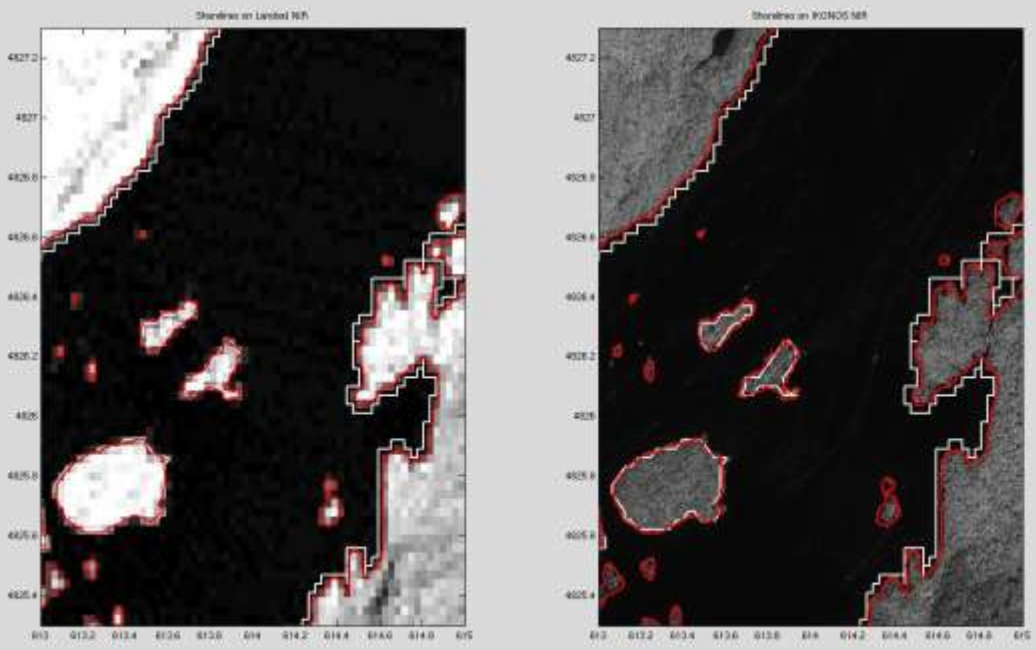
Figures show a stretch of the Oahu shoreline in Hawaii, imaged with the WorldView-2 satellite.

Short Wave IR



Note that **an inland water channel is indistinguishable from the nearby airfield runway in blue and green. IR bands are generally better for water discrimination because there is a sharp increase in land albedo and increased absorption in water, leading to greater land-water contrast.**

Water Area Algorithm



- **The simplest and most often used land-water discrimination algorithm compares the IR to a preset threshold**
- **The darker pixels are classified water**
- The water area is then defined by the outer boundaries of the water pixels
- The Landsat short wave IR band (or equivalent band in another satellite) is usually sufficient data for the method
- Figure shows an example with a section of Lake George, New York, USA
- The left panel is shoreline based on simple threshold (white) and spectral unmixing method (red) superimposed on Landsat IR image.
- The right panel is the same area in high resolution from Google Earth
- **Lake George water level varies only <u>+</u>0.5 m in an annual cycle, so the comparison is useful even if Landsat and Google Earth images are from different dates.**

Methods (I)

- It is evident that the white contour captures most of the water surface.
- It misses only water area that is within less than a pixel width from the shoreline because that 'last pixel' is contaminated with some land radiance
- **A little land radiance in the mix makes the pixel indistinguishable from pure land pixels**, at least when the discrimination is based only on pixel radiance level
- **The omission of the 'last pixel' leads to an underestimate of the total water area**. If the lake is large, this error is acceptable and nothing further is needed
- But for **smaller water surfaces it is desirable to improve the resolution to capture more of the total water area**
- There are two methods for improving the resolution: **panchromatic sharpening** and **spectral unmixing**

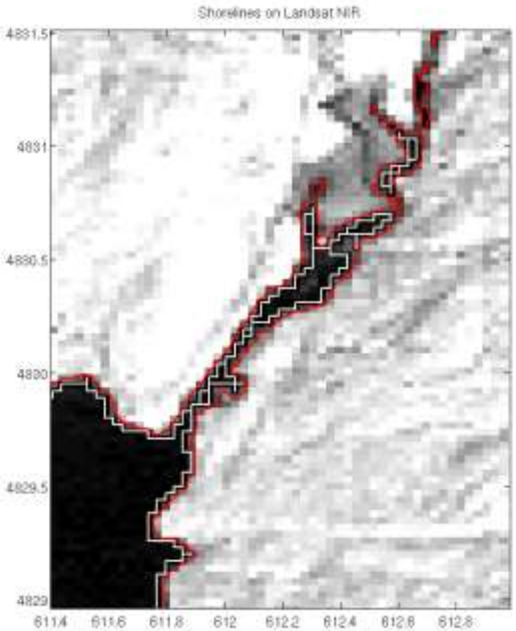
Methods (II)

- l**Panchromatic-sharpening** combines 30-m MSI information with the 15-m panchromatic. Fox et al. (2002) tested four pan-sharpening methods on Landsat images in the vicinity of a small lake. The MTM, which was one of the four methods tried, appears to be as good as any method for water-land discrimination. It is also the simplest. The multi-spectral bands are up-sampled to 15-m and multiplied by the Panchromatic values. Then the multi-spectral images can be processed into water flags. But as noted earlier the panchromatic image is not always a robust water discriminator and it has no response in the short wave IR. For these reasons, we prefer the spectral unmixing, which also improves resolutions but does not use the Panchromatic image, and can be adapted to an optimum mix of spectral bands.

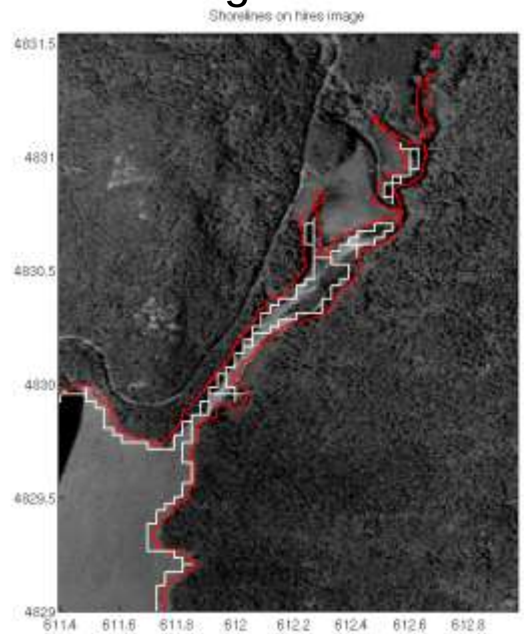
- The **spectral unmixing** method estimates the fraction of M pure material types present in each pixel. For example, we may estimate the relative amounts of water, vegetation, and sand (M=3), or water, trees, bare ground, and grass (M=4), etc. The simplest would be water and non-water (M=2). It is assumed that the total spectral radiance in a given pixel is a sum of the M types in different amounts. Since we are only interested in determining the water area, the desired shoreline are the pixels where the mixture is close to 0.5 water and 0.5 everything else.

Spectral Unmixing (I)

Landsat



Google Earth

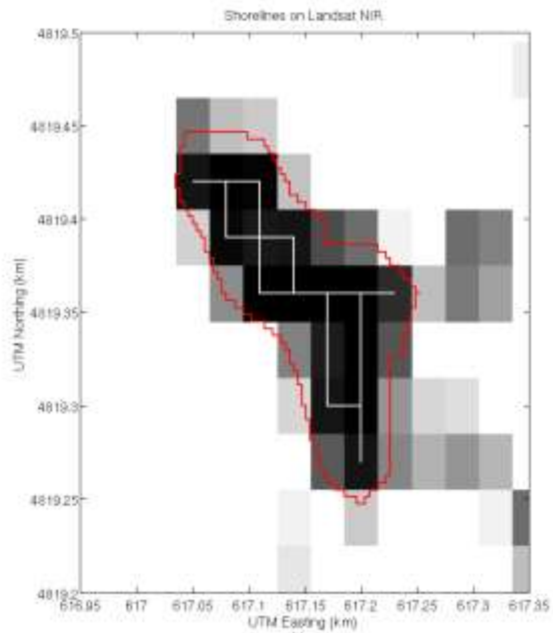


- This is a narrow water inlet attached to Lake George
- Simple threshold (white line) and spectral unmixing method (red line)

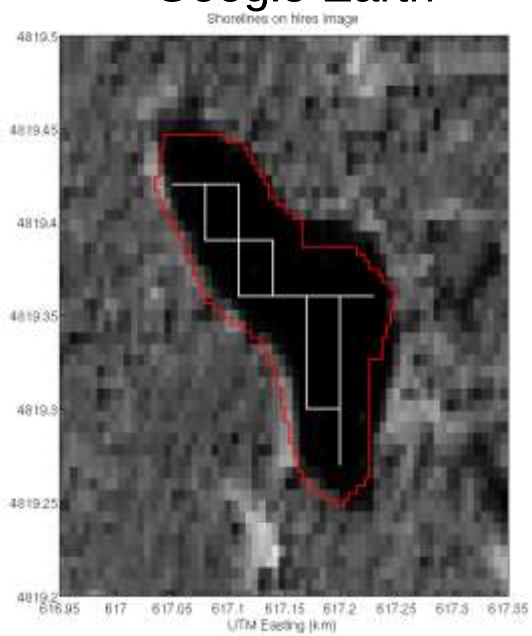
- In both images **the ability to discriminate land from water is stressed with 30-m Landsat resolution and the simple threshold method misses a significant fraction of the water surface**.

Spectral Unmixing (II)

Landsat



Google Earth



- This is a tiny unnamed lake at 43.518°N, 73.550°W
- Simple threshold (white line) and spectral unmixing method (red line)

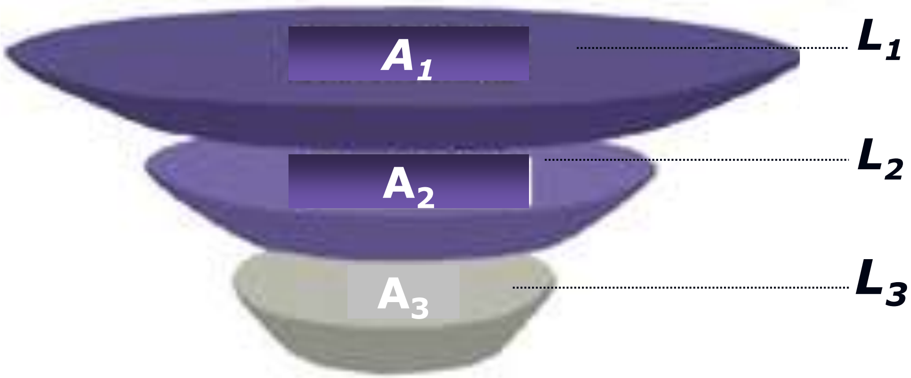
- This very small lake is less than 100 m across the smaller axis
- **The simple threshold identifies water in only a few pixels in the middle of the lake**
- **The unmixing process captures most of the water.**

Our synergistic approach vs other studies

Other papers	Our approach
Radar altimeters	***Radar altimeters***
TOPEX + Envisat	***TOPEX + Envisat***
Modis	***Landsat***
Daily revisits	***16-day revisits***
500 m resolution	***30 m resolution***
Floodplains monitoring	***Reservoir volume***
	Bathymetry
(daily revisits desirable)	***(monthly revisits suffice)***

- Some papers already introduced **the idea of fusing radar altimetry and optical imaging satellites**. In the same way, we combined TOPEX and Envisat radar altimeters into one time series of water surface elevations.
- **The main distinction between the other papers and us is in the imaging satellite used.** The others used the Modis satellite images with daily revisits and 500 m ground resolution.
- **We used Landsat which has much better ground pixel resolution, but at expense of less frequent revisits.** Landsat can revisit once every 16 days, but often less due to other operational constraints.
- Our choice of satellites matches the application. **For the other authors daily revisits are more important than resolution**. For our application resolution is more useful than frequent revisits.

Heron's Volume Method 10-70 A.D., Alexandria



$$\Delta V_{12} = \frac{|L_1 - L_2|}{3}\left(A_1 + A_2 + \sqrt{A_1 A_2}\right)$$

$$\Delta V_{23} = \frac{|L_2 - L_3|}{3}\left(A_2 + A_3 + \sqrt{A_2 A_3}\right)$$

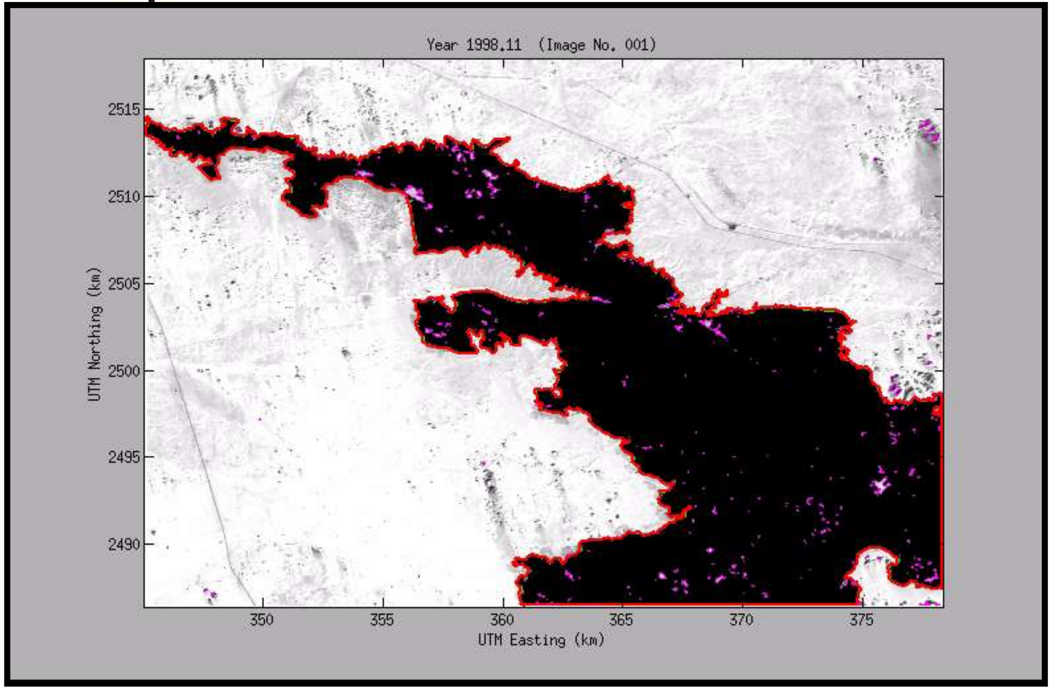
The basic idea in deriving the volume of a body of water is the same as first developed by Heron, a mathematician and citizen of ancient Alexandria.

As the water level rises and falls we measure the volume of slices of the water column.

Each slice is described by observations of area and level. Heron's formula gives the volume of each slice. Then we add all the slices.

We'll now show the modern, satellite based version of this idea.

Landsat Temporal Image Series



In this example, **the water area used in Heron's equation is total area encompassed by [the red shoreline] minus [total area of all the islands enclosed by the red shoreline]**. This area is used in the following….

Shown here is the Landsat image of a section of Lake. We click to view movie of the temporal series.

The red line delineates the main shoreline. **Pink outlines the shorelines of islands**.

Many techniques exist, including commercial GIS software, to map water surfaces. We have our own customized Matlab algorithm that we think is an improvement of previous algorithms.

How to fuse water level and area observations (I)

- The **L-A function** is found through **fitting the temporal time series of area and water level**
- However, since **the two measurements are not co-aligned in time**, one of the two time series needs to be interpolated to the times of the other.
- Radar altimetry data is more frequent than Landsat, typically **10 days vs. 2 months**.
- Given this fact **it is preferable to interpolate the radar altimetry data to the dates of Landsat imagery**.
- Typical altimetry data is **adequate for sampling of seasonal water level changes**, as is common in lakes and reservoirs and can thus be safely interpolated. Interpolation is not appropriate in cases where there are diurnal tides, sudden floods, and similar short term variability.

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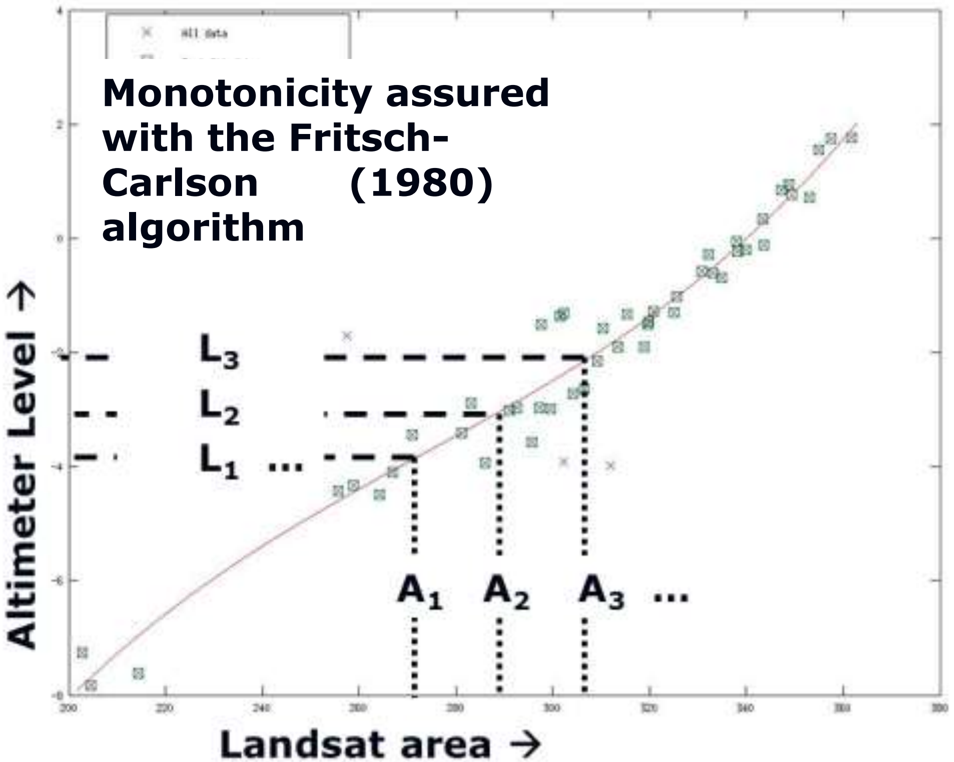
How to fuse water level and area observations (II)

- Some form of **a least square fitting** is used for a function relating the interpolated altimeter levels and Landsat water areas.
- Experience has shown that the **conventional polynomial least squares fitting does not work well**, either failing to capture all the inflection points in the data or oscillating wildly outside the data range.
- A much better fitting process is the **SLMfit routine** developed by John D'Errico (2009). SLMfit finds a set of connected cubic splines with various user specified physical constraints.
- **In the L-A fitting the most useful is the monotonicity constraint** of Fritsch and Carlson (1980).
- The slope range can be specified (MinSlope, MaxSlope in SLM language). Knot points (breakpoints) can be provided by the user or determined automatically to specify where there is a slope discontinuity and a need for fitting another spline.
- SLMfit also incorporates data weighting to desensitize the fit to data outliers. The process can be fully automated.

Polynomial Volume Method

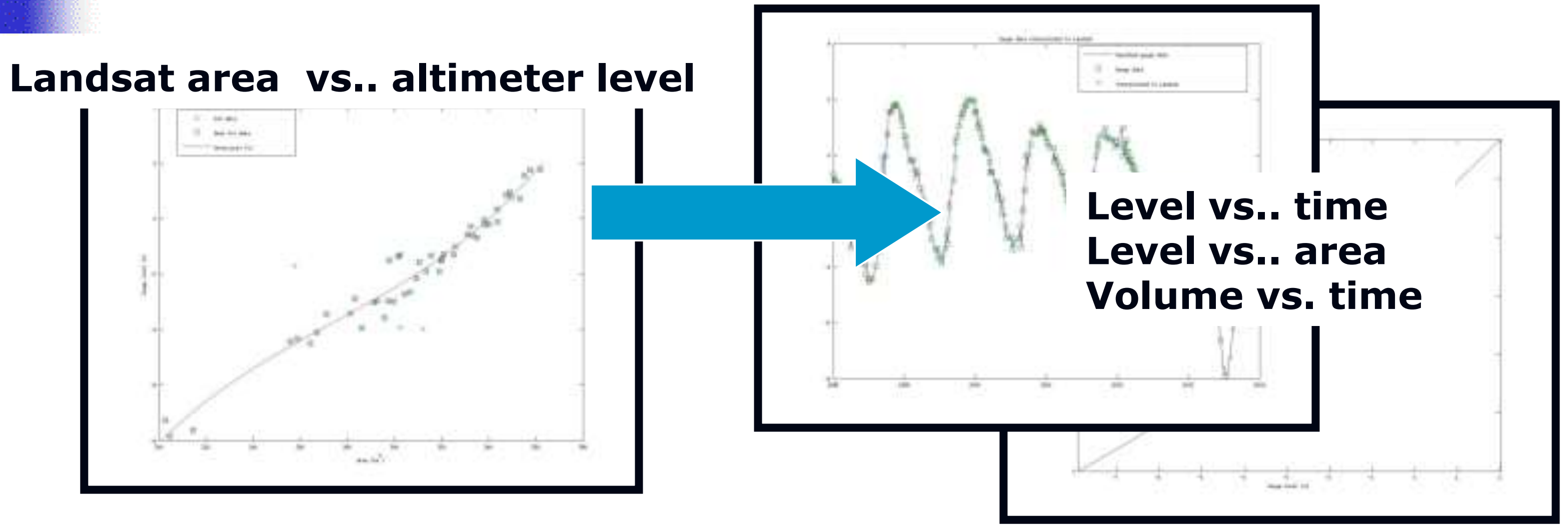


- Here **individual observations of water area are plotted against the corresponding water level** measured with a radar altimeter.
- **X axis is area** measured in Landsat images.
- **Y is corresponding altimeter level**.
- While there is a clear trend – **water area increases as the water level rises** (obviously!)- there is some unphysical variability about the trend line.

Error sources

- The water levels deviate from a strict monotonically increasing relationship due to errors in the measurements and data reduction
- Further analysis (showed later) shows that most of the error comes from radar altimetry. So, the raw data can not be directly used in Heron's equation.
- The robust least-squares fit is used to parameterize the area-level relationship with a polynomial (with the fit constrained to be monotonically increasing) smoothes out the altimeter errors. This makes the data usable for volume estimation
- Error sources
  - Radar altimeter levels
  - Interpolation to Landsat dates
  - Water area
    - Image pixel resolution
    - Land-water classification
  - Level vs. area fitting

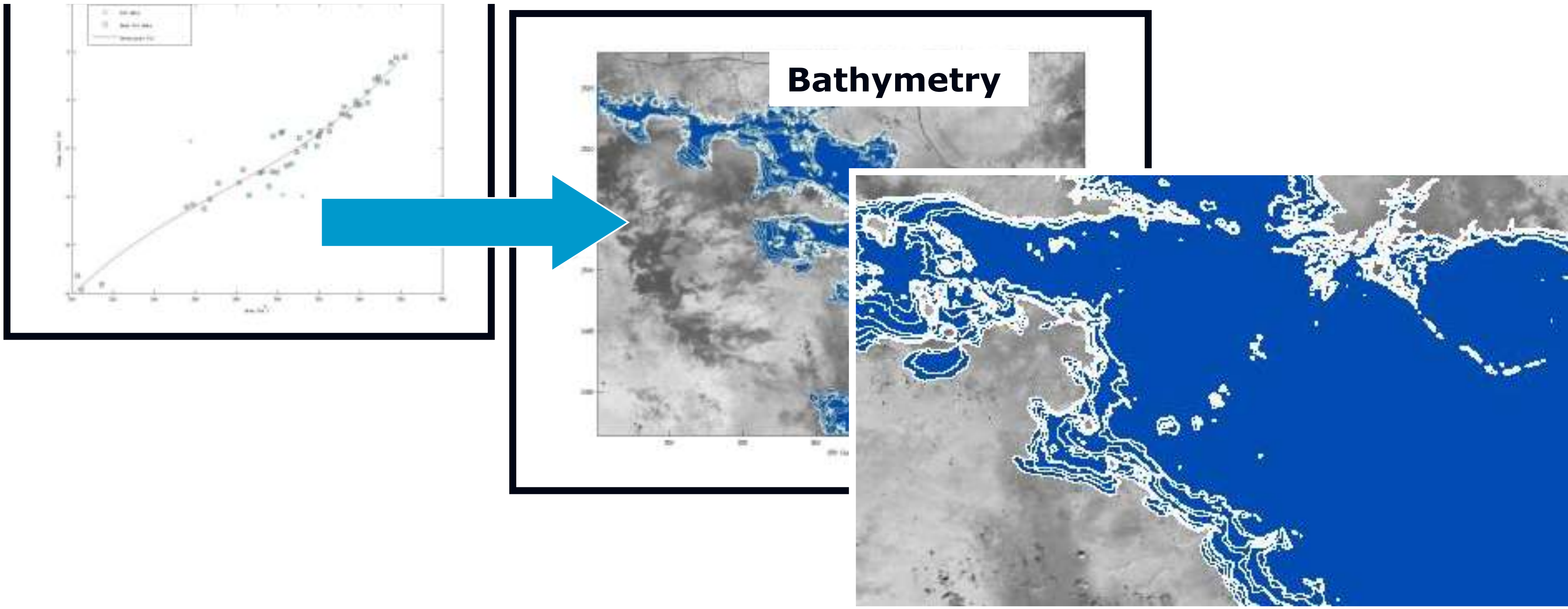
Analysis Products (I)



- **Volume can be derived as a function of time**, the water level, or the water area
  - Volume is relative to the minimum observed level
  - The volume below the minimum (down to dry lake) is not known
- **Smoothed water level time series**
  - Once the smooth Level-Area relationship is established future Landsat images can be used to derive the water level to very high accuracy
  - Landsat images become very precise water level gauges.

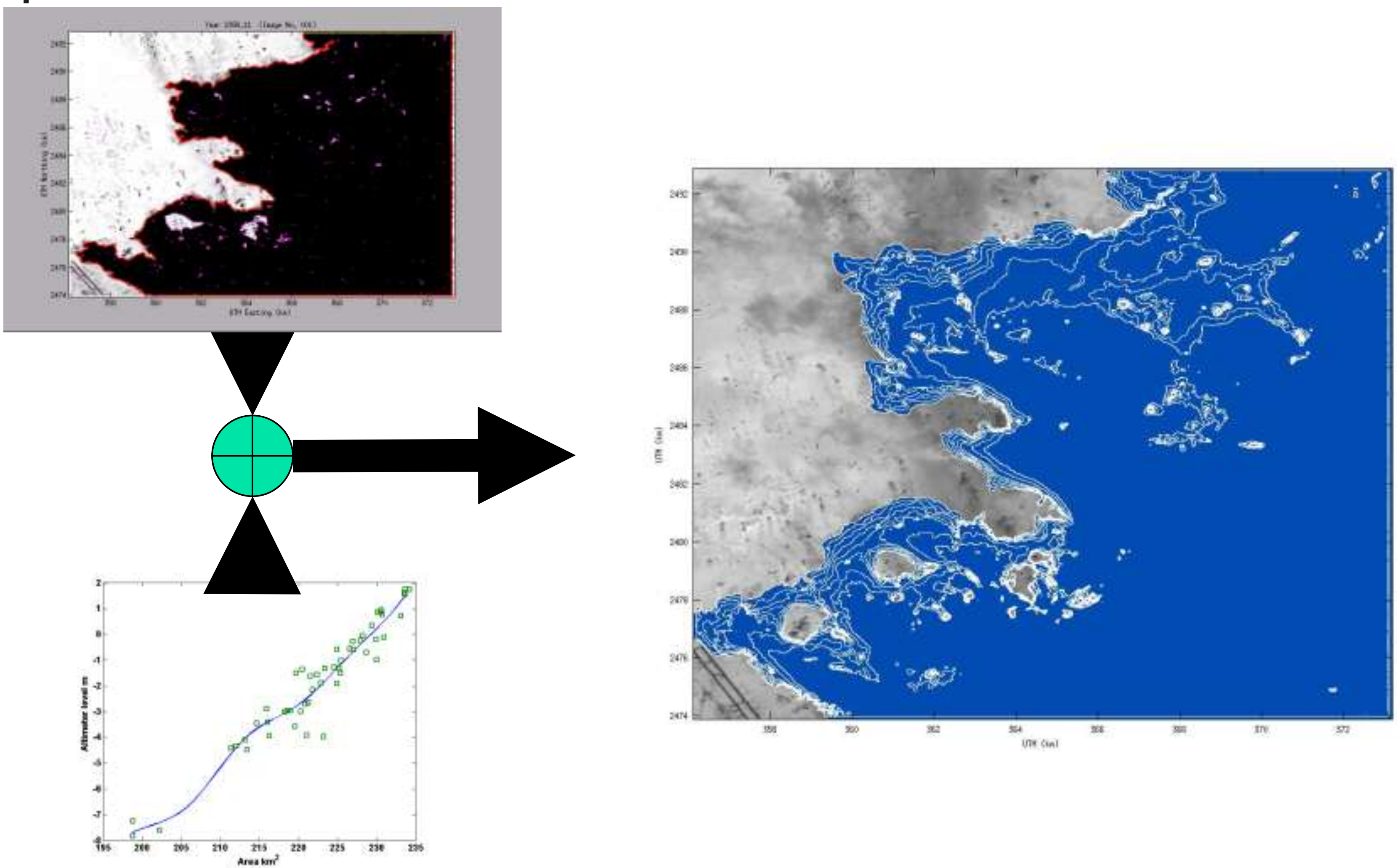
Analysis Products (II)

Landsat area vs.. altimeter level



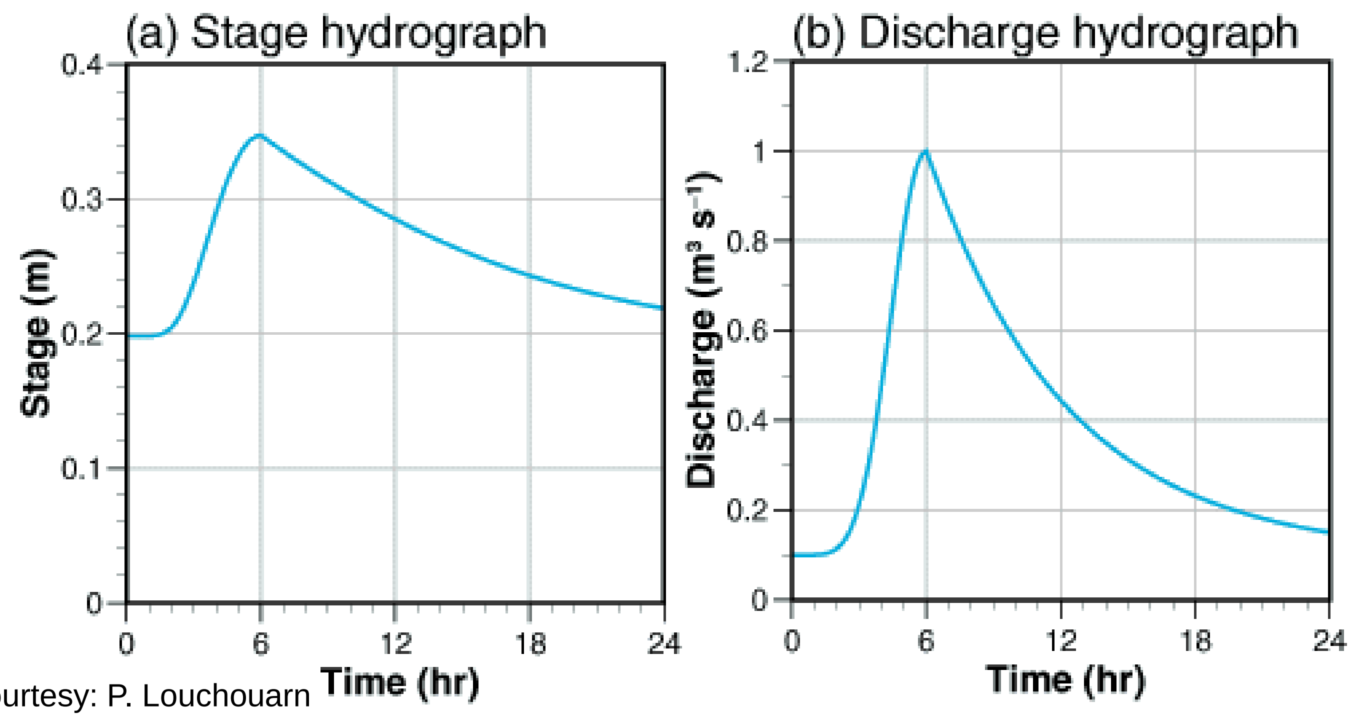
- **Bathymetry, based on the shorelines outlined at various water levels**
  - Here we show depth contours at 1 m intervals
  - In this method **bathymetry is mapped over the range from highest to lowest water level** experienced in the data
  - If observations extend from dry to full lake we can map the entire bathymetry

Bathymetry



River discharge and stage

- Fate of Precipitation -> runoff
- Rivers respond to precipitations
- Basic quantity to be dealt with is **river discharge** (as related to rain events) -> rate of volume transport of water (L3/t)
- **What is river discharge and how do you measure it?**
- Both river discharge and depth (so called stage) change with time.



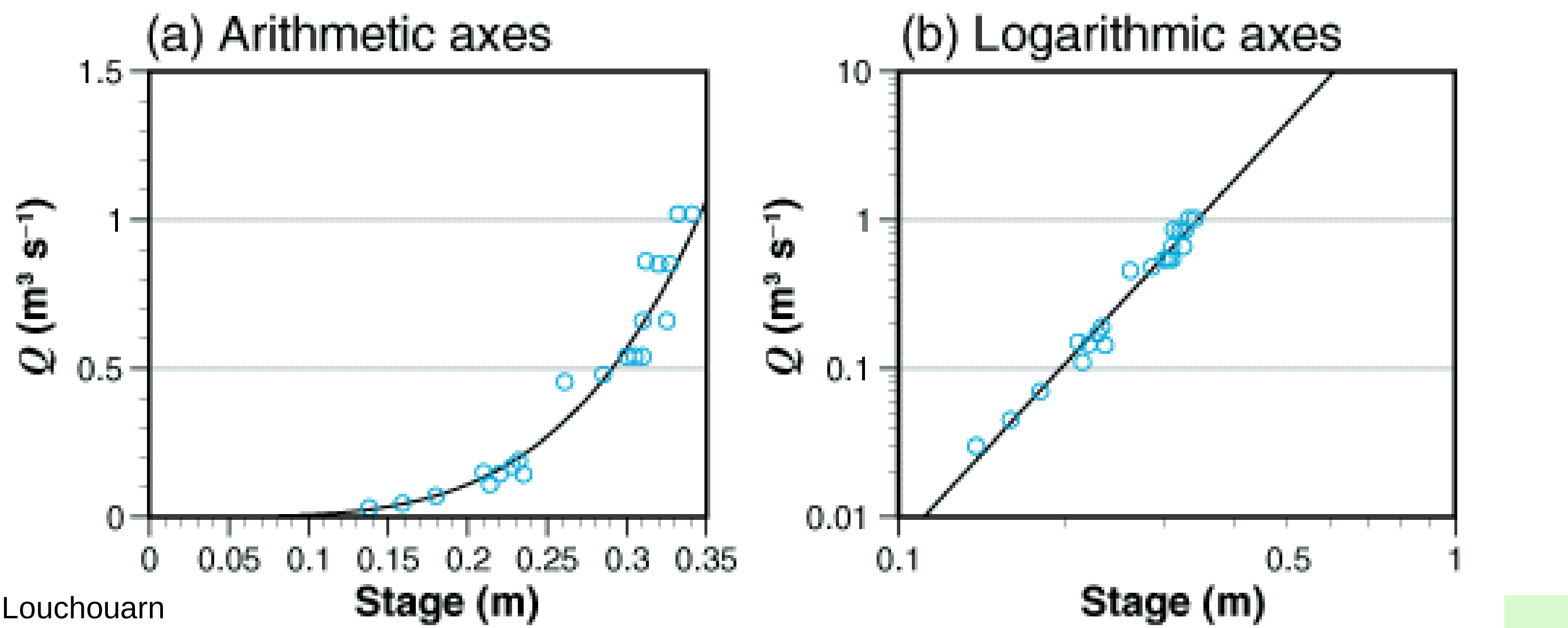
Courtesy: P. Louchouarn

The term "hydrograph" refers to a graph showing changes in the discharge of a river over a period of time. A hydrograph represents how a catchment responds to rainfall

Rating curves

- **Rating curve is a graph of discharge versus stage (height)** for a given point on a stream
- Rating curve can be derived at gauging stations (measuring heights), where the stream discharge is measured across the stream channel with a flow meter
- **The stage-discharge relationship will permit to derive river discharge using only stage measurements (assuming the relationship constant over time)**
- **Rating curves typically are nonlinear** and often can be approximated using power functions:

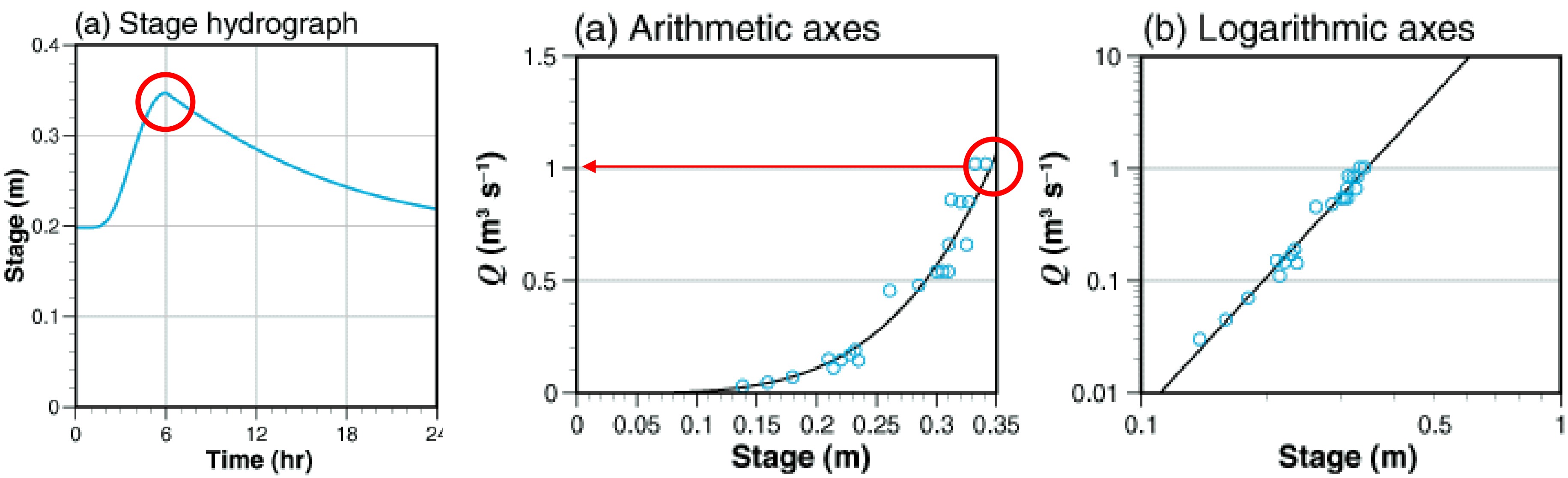
$$Q = 76.5(stage)^{4.1}$$



Courtesy: P. Louchouarn

Example

- e.g. If stage peaks at 0.35m (at t = 6 hours), then the corresponding peak discharge is Q = 76.5(0.35)4.1 = 1.0 m3.s-1
- This way, **a continuous measurement of river stage is used, in conjunction with established rating curve, to determine discharge as a function of time** (almost all discharge hydrographs are determined this way)



Courtesy: P. Louchouarn

Water Discharge

- **No remote sensing technique is currently capable of measuring directly river discharge**
- **Radar altimetry is the most promising technology to measure discharge from space**
- Radar altimetry alone not useful
  - **low spatial** (80 km inter orbit spacing at the equator for ENVISAT) and 18 Hz data unsuitable for the monitoring of narrow rivers.
  - **temporal resolution** (between 10 and 35 days return period) longer than what is needed in particular for real-time optimization problems such as flood mitigation or reservoir operation.
  - **do not coincide with in-situ gauges, so rating curves are not available** (typically established by fitting a power-law through a number of points corresponding to simultaneous measurements of discharge and level)
- **In order to overcome these limitations, many studies have focused on combining radar altimetry with other data or models**.

Bibliography (I)

- **Kouraev et al. [2004]; Zakharova et al. [2006] Papa et al. [2010]**
  - **The authors use in situ measurements of discharge and altimeter-derived river heights at the nearby satellite crossing of the river** (so called virtual station) to derive rating curves
  - **The limitation of this method is that flow at any time can be estimated only where rating curves are derived**, i.e., at virtual stations located near in situ gauges where the time coverage of the in situ and altimetric data sets overlap to derive rating curves
- **Bjerklie et al. [2003]**
  - The authors propose **a method to develop rating curves based on the measurement of hydraulic data (water-surface width and maximum channel width) from satellite platforms** in order to obtain discharge values at virtual stations not located near in situ gauges

Bibliography (II)

- **Getirana et al. [2009] and Getirana and Peters-Lidard [2013]**
  - The authors **develop rating curves based on altimeter-derived water heights and discharge estimated from a hydrological model** and a routing scheme
  - This methodology allows to obtain **discharge estimates at the time and location of the satellite altimetry passages**
- **Roux et al. [2008]**
  - The authors propose a method to obtain **daily time series of water heights from altimetry by exploiting neighboring in situ gauging stations**, thereby densifying an existing level gauging network in order to obtain measurements with a higher temporal resolution than the satellite revisit time
- **Biancamaria et al. [2011]**
  - The authors use **linear regressions between upstream radar altimetry data** over the Brahmaputra and Ganges and **downstream gauged levels** to improve water level predictions at locations not touched by the passages of the altimeters

Bibliography (III)

- The main point is that **many parameters in models are either not directly related to measurable quantities or need to be representative of large areas**
- Therefore, **hydrological models rely need a calibration/validation process where model parameters are tuned to fit simulated and observed states and fluxes**.
- **Calibration is generally made using in-situ discharge and levels**
- **The lack of such datasets for calibration can be a major obstacle in modeling of remote areas.**
- Milzow et al. [2011]
  - The authors use **altimetry in combination with other remote sensing data sources (surface soil moisture and gravity)** to successfully calibrate a model of the poorly gauged Okavango catchment.
- Even when models are well calibrated, **flow predictions are still subject to uncertainties due to errors in forcing data, model parameters and model formulation.**
- **For real-time applications, one solution is the use of data assimilation** (i.e., the integration of observations into the model framework to reduce these uncertainties)

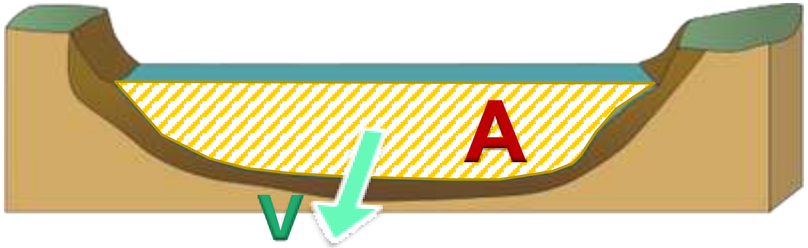
Bibliography (IV)

- **Getirana [2010]**
  - The authors shows that radar altimetry from the ENVISAT satellite (35 days repeat cycle) could be used for **automatic calibration of a hydrological model** of the Branco river basin
  - He find similar results to using in situ discharge data, provided knowledge of the rating curves at the virtual stations' locations
- **Refsgaard [1997]; Madsen and Skotner [2005]**
  - The authors show the **assimilation of daily in situ flows or water levels to routing models**
  - The assimilation has been successfully been implemented in terms of remotely sensed river water levels
- **Neal et al. [2009]**
  - The authors show that hydrodynamic **model predictions could be improved through the assimilation of water levels** derived from combining synthetic aperture radar imagery and high-resolution digital elevation models (DEMs).

Discharge estimated integrating optical and radar data

River Discharge

$$Q = v \cdot A$$



Flow velocity derived by MODIS

(Tarpanelli et al., 2013 - Remote Sensing of Environment)

Flow Area

A=f(water level, geometry)

derived by radar altimetry observation

Known (Topographic survey)

unknown

(Moramarco et al., 2013 – Journal of Hydrology)

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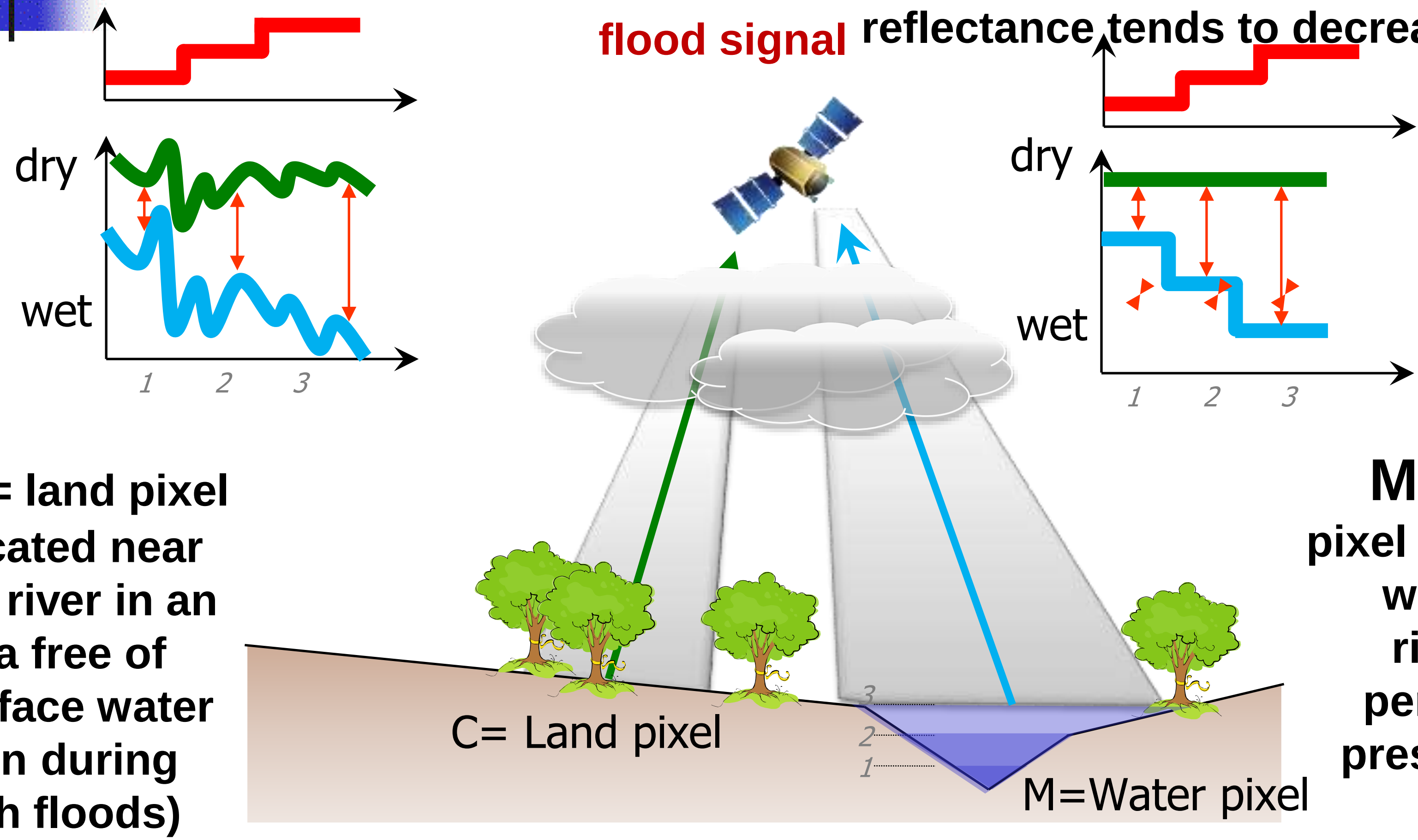
Estimation of flow velocity (V) using sequence of images

When water is present in a pixel or more water is added, its reflectance tends to decrease



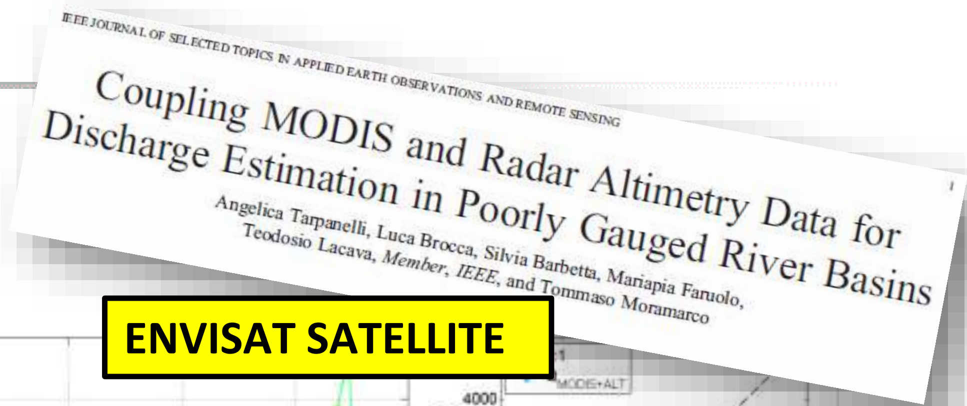
C = land pixel (located near the river in an area free of surface water even during high floods)

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

C/M increases with the presence of water and, hence, of discharge

Brakenridge et al., 2005; 2007

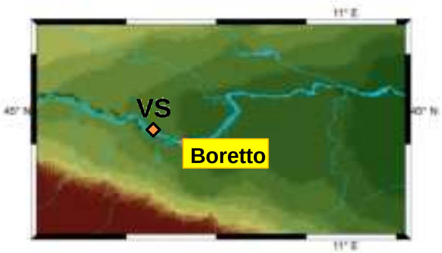
Example using MODIS images amd radar altimetry


IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING

Coupling MODIS and Radar Altimetry Data for Discharge Estimation in Poorly Gauged River Basins

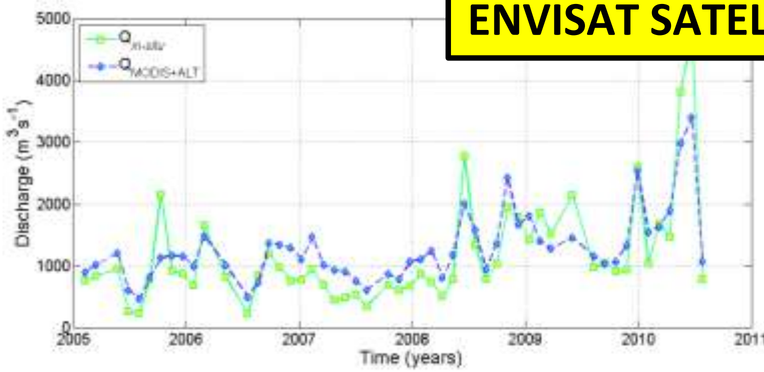
Angelica Tarpanelli, Luca Brocca, Silvia Barbetta, Mariapia Faruolo, Teodosio Lacava, *Member, IEEE*, and Tommaso Moramarco

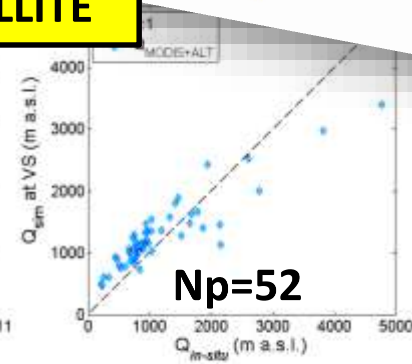
$Q = V \cdot A$



R=0.91
RMSE=423 m^3s^{-1}
RRMSE=36 %

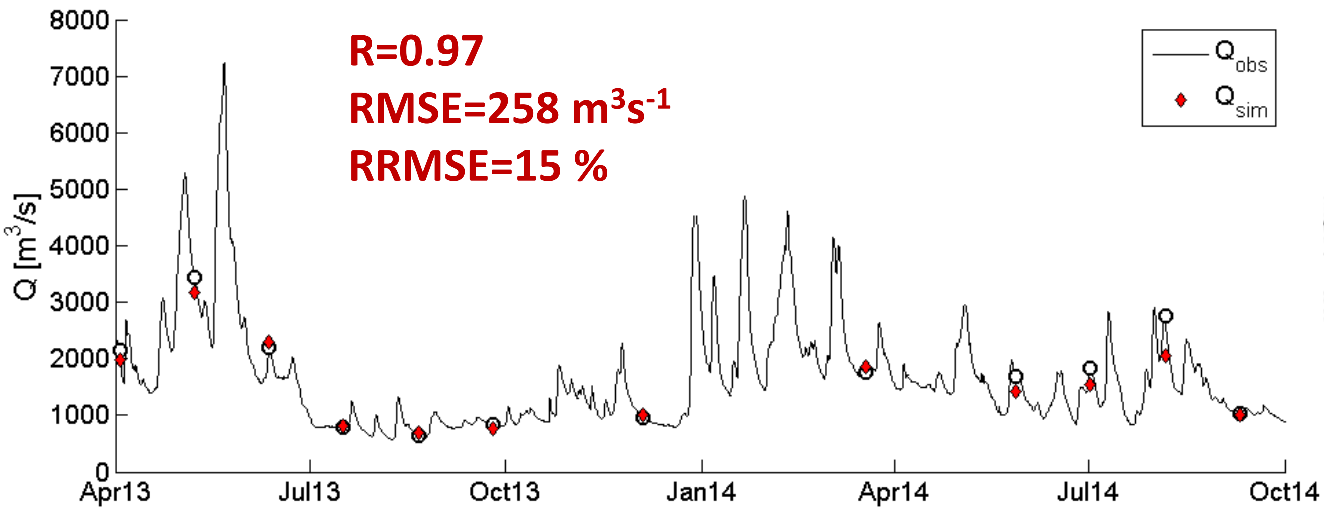
ENVISAT SATELLITE

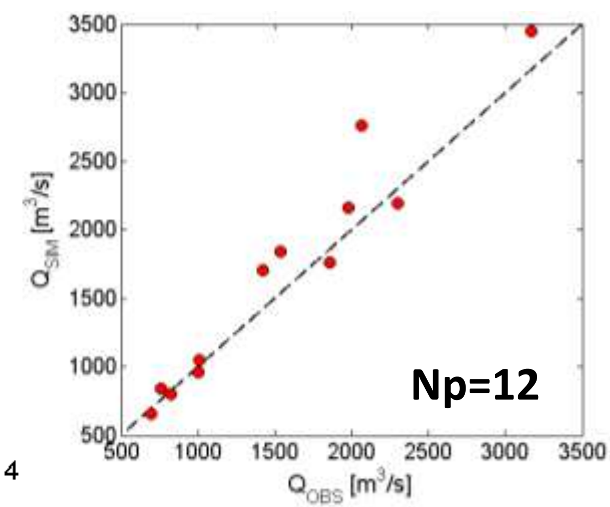




SARAL SATELLITE

R=0.97
RMSE=258 m^3s^{-1}
RRMSE=15 %





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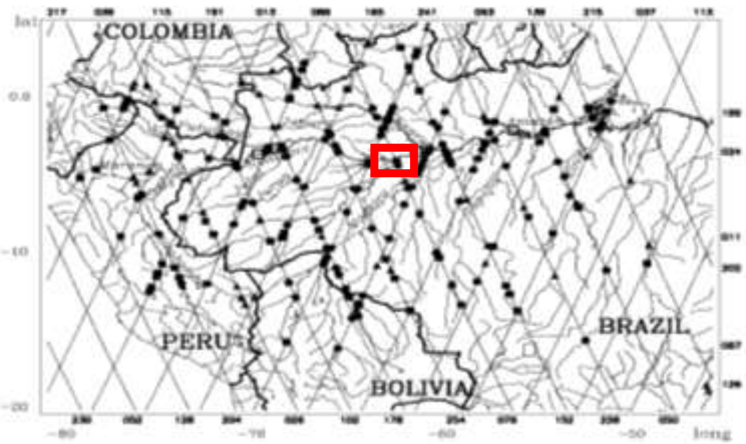
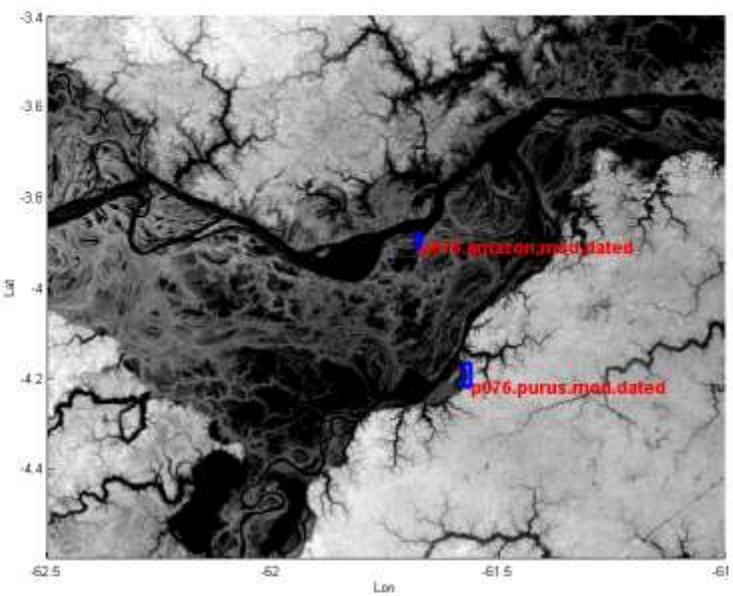
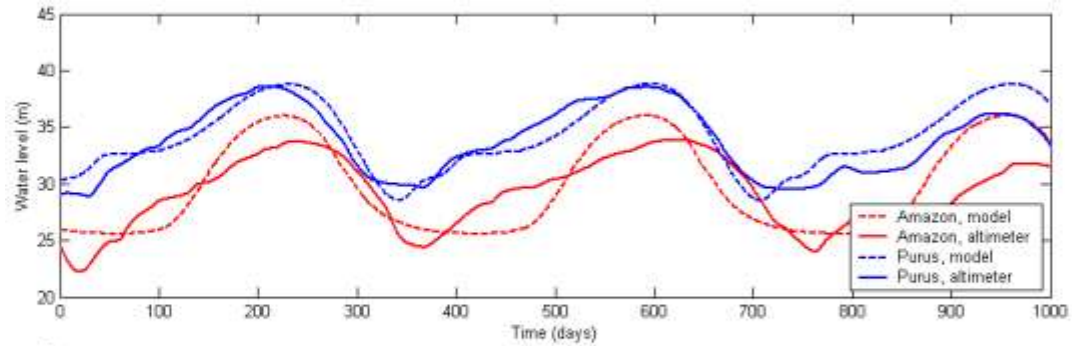
Example of hydraulic modelling of floodplains (I)

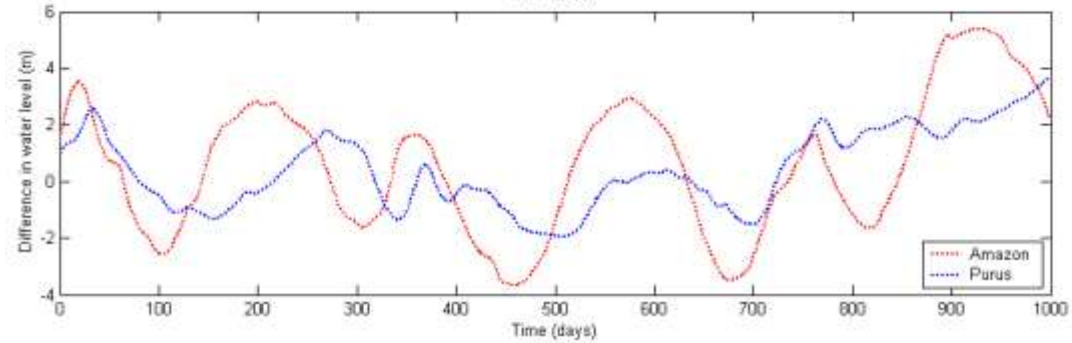
- **Flow on floodplains is controlled by topography and friction**
- Leads to **complex spatial patterns of water depth and velocity** that are **2D in space and dynamic in time**
- Until recently modelling of such flows has only been possible for small river reaches (10-50km)
- New opportunities
  - Large scale modelling has now been made possible by: Simplified 2D hydraulic models, Faster computers, New satellite data sources e.g. SRTM, satellite radars
- New satellite data sources e.g. **SRTM, satellite radars**
- **Simplified 2D model pros**
  - Floodplain flow is solved analytically rather than numerically so very efficient
  - 150-500k cells for full dynamic events should run in less than 1 day on a pc
  - Can use large elements (e.g. 250m – 1000m grids)
  - Intrinsically mass conservative treatment of floodplain flow
- **Simplified 2D model cons**
  - Simplified floodplain flow representation
  - Wetting front propagation may be grid and time step dependent

Example of hydraulic modelling of floodplains (II)









- TOPEX/Poseidon ground track coverage over Amazon
- Comparison of water levels derived from model and altimetry at two places

Courtesy: M. Wilson et al.
http://swot.jpl.nasa.gov/

From raw data sets to information in the hydrological context (I)

- **Satellite altimetry is a piece of the complex hydrology puzzle**
- Understanding, monitoring, assessing in the hydrology context needs an **engineering approach**
- It cannot be in isolation, **team approach is essential** with all relevant players aboard, including final users
- It is important to **be aware about potential limitations, accuracy, processing methods of the various data sets as well as their availability and sustainability in the future**
- **Modelling tools are necessary to integrate data sets and provide finer resolution in space and time**
- **The application of satellite altimetry in small water bodies is still at research stage** as opposed to oceans or large lakes where it is much more consolidated
- The main reason is that **in small water bodies a more sophisticated processing is necessary**

From raw data sets to information in the hydrological context (II)

- **Many data sets**
  - Many sources: In-situ, satellite, data bases, etc.
  - Various types: Meteorological, socioeconomic, etc.
  - Many variables: water level, flood area/volume, snow cover, glaciers, frozen ground…
  - Water fluxes: precipitation, evaporation, transpiration, snow melt, soil water depletion, river discharge, etc.
- **Growing complexity of satellite data sets**
  - No water variables available in these data files
  - Specific processing chains to extract information relevan to water
  - Space and time resolution as well as coverage not immediate to understand
  - Differences between products (e.g. L1, L2)
  - Differences between missions

From raw data sets to information in the hydrological context (III)

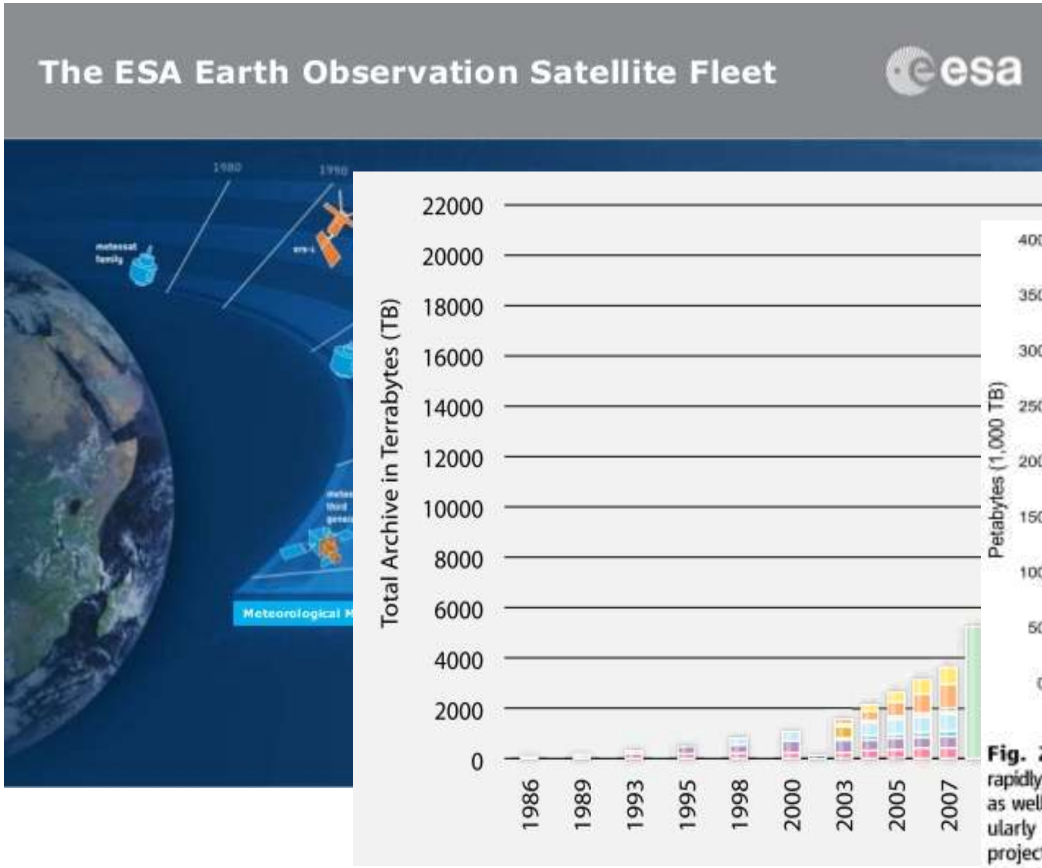
- **Many users, e.g.,**
  - Universities/Research Centers
  - Water Authorities, Water Operators, Private Companies,
  - International Organisations, NGOs,
- **Many applications, e.g.,**
  - Water Resource Management
  - Environment Monitoring,
  - Disaster Monitoring
  - Agriculture
  - Etc.
- **Many regions of interest**
  - E.g., Global, Trans-boundary, etc.
- **Many types of analysis**
  - E.g., Climate Change, Water Cycle studies
- **Many domains**
  - e.g. floods, droughts, hydropower, irrigation, etc.

The state-of-the-art

- **Uploading and processing of satellite data sets in hydrological model is not easy to do**
- Accessing to all available satellite data sets, services and toolboxes for hydrology is not user-friendly
- **Integration of datasets, services and toolboxes is now possible for a limited number of people**
- Comparison of results between different groups is not easy missing a common processing protocol
- People spend lot of time in IT tasks
- **People do not have the necessary IT resources at their laboratories**
- The three pillars of the hydrology community
  - **Having room** where to share information, knowledge, algorithms, tools, results, products, services, etc.
  - **Having a portal** providing data sets and services tailored for hydrological applications
  - **Having functionalities** to discover, access, process, visualise, and compare various datasets as well as integrate their own hydrological models and data

A paradigm change with the development of thematic platforms

https://tep.eo.esa.int/



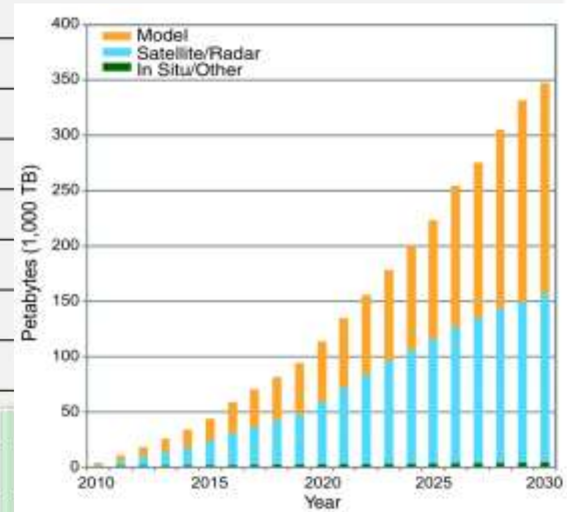
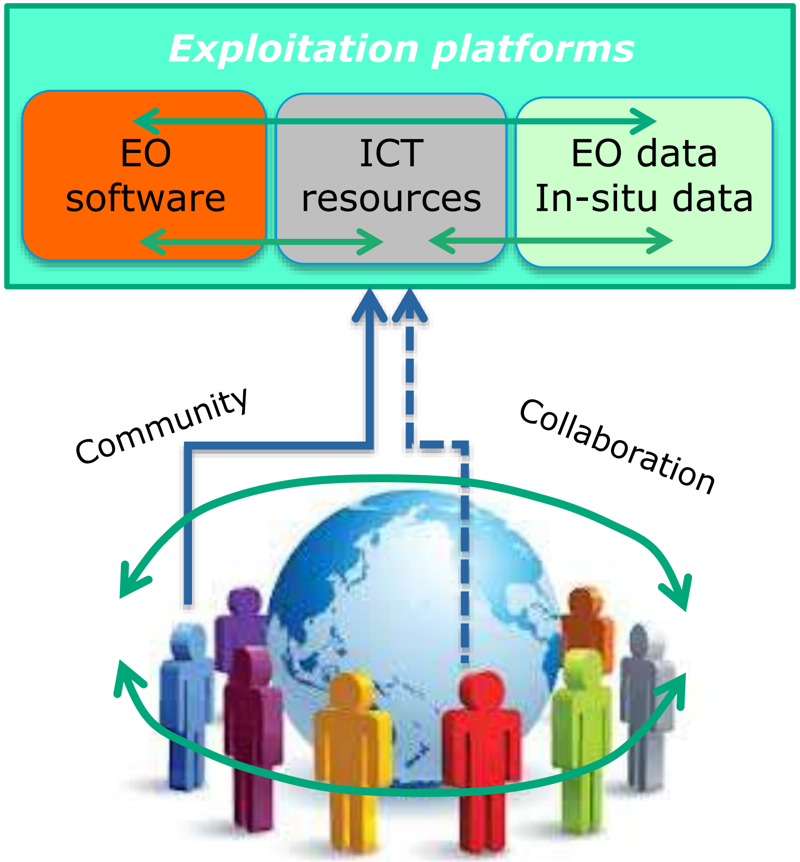


Fig. 2. The volume of worldwide climate data is expanding rapidly, creating challenges for both physical archiving and sharing, as well as for ease of access and finding what's needed, particularly if you are not a climate scientist. The figure shows the projected increase in global climate data holdings for climate models, remotely sensed data, and in situ instrumental/proxy data.

What is a Thematic Exploitation Platform?



Bringing together

- EO data
- In-situ data
- Computing resources & hosted processing
- Processing tools
- Collaboration mechanisms

Exploitation Platforms for different communities

ESA is currently implementing seven Thematic Exploitation Platforms (TEPs), in support of seven thematic communities:

- Coastal
- Forestry
- Geohazards
- Hydrology
- Polar
- Urban

- Food Security coming soo

Coastal Thematic Platform

coastal
tep

Unlocking coastal knowledge and innovation using satellite imagery and cloud processing

https://coastal-tep.eo.esa.int/

Eimear Tuohy, MaREI, UCC
eimear.tuohy@ucc.ie

Thematic hydrology platform

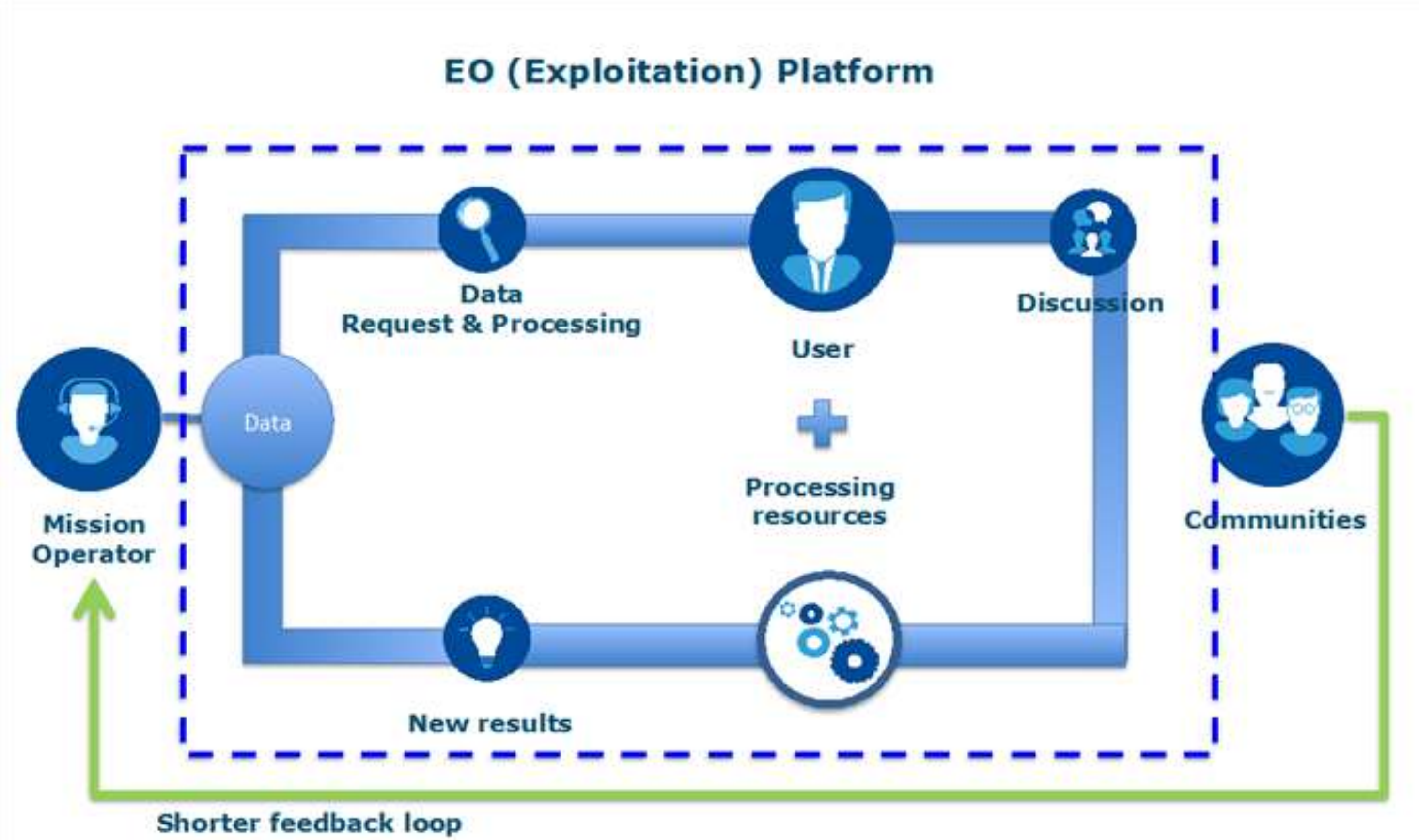
hydrology tep

https://hydrology-tep.eo.esa.int/

- **A set of services based mainly on the exploitation of different satellite datasets and tools that will be available to the hydrology community**
- The aim of these services is to make **easier the access, exploitation, processing and visualization of different type of datasets** (satellite, in-situ, socioeconomic databases) to the expert and non expert users
- Examples of services include **water resource management**, **floods monitoring**, **drought monitoring**, etc.
- The platform responds to the need for integrated and open access to different areas and categories of users (**government decision makers**, **scientists**, **businesses and citizens**)
- **These needs are particularly high in the developing countries where there is not enough ground truth data coverage**
- The platform brings together **IT tools, cloud processing, data sets and services tailored to the hydrology community requirements**
- The platform should enable the inclusion of satellite datasets in existing and new decision support tools for water managers and decision makers

The new concept

https://hydrology-tep.eo.esa.int/



Source: ESA

- Hidrological services that will be implemented:
  - **Flood monitoring and small water bodies mapping**
  - **Water quality and level**
  - **Hydrological modelling**

Final comments (I)

- While the demand on water continues to grow, **more and more catchments are becoming ungauged** as in-situ gauges falls out of repair
- Using the remote measurement capability of altimetry, it is now possible for water resource managers to access some data and its context - **decadal historical information**
- **The technology can be applied as well in the oceanic coastal zone (similar difficulties in retrieval due to contamination by surrounding land)**
- **The scientific challenge is to fully extend to the global inland water bodies the success of altimetry in monitoring the global open ocean.**
- To satisfy hydrologist requirements we need:
  - **Improve the processing** (that is work in progress)
  - **better spatial/temporal sampling** (SWOT or constellations)
  - **integration of measurements and synergy with modelling tools** (thematic processing platforms)

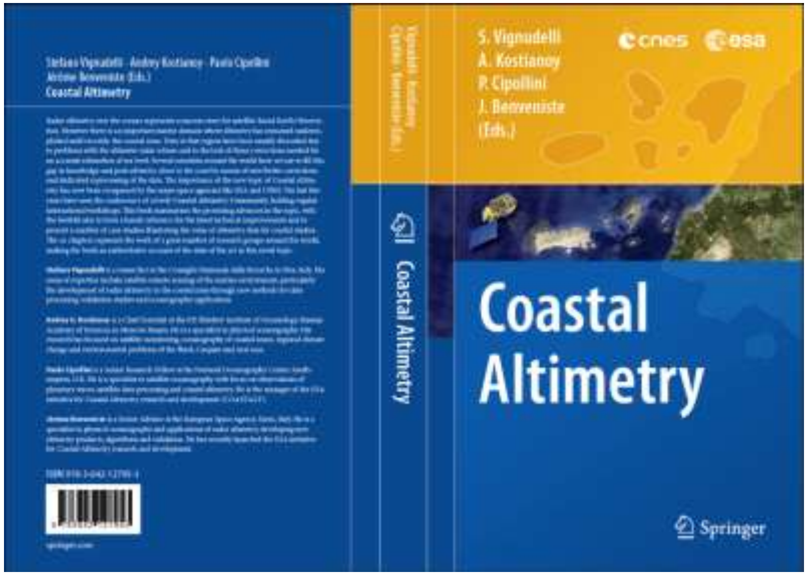
Final comments (II)

- **Landsat imagery and satellite radar altimetry can be combined over a period of several years**
- This fusion process provides several related products, including the estimation of **water volume changes** and **bathymetry**
- However, **the practical use of this multi-sensor approach requires a proper quantification of the error sources**
- **Lake Nasser was an especially appropriate test site for the exploitation of the fusion of Landsat and radar altimetry in the Sahara region, and areas suffering from water scarcity in general, which make use of large surface reservoirs**
- I will show results from this case-study tomorrow

“Inland Water Altimetry” a Springer Book in progress that complements the “Coastal Altimetry” book

Editors: Benveniste (ESA),Vignudelli (CNR, Italy), Kostianoy (SIO, Russia)

- 19 chapters
- Tens of people involved in authoring
- Chapter 18 “*Fusion of Radar Altimetry with Imaging Satellites for Monitoring Water Volume Changes*” by R. Abileah, S. Vignudelli, A. Scozzari



https://sites.google.com/site/hydrospacebook/home

Paper just submitted to "Remote Sensing" journal

Authors: Ron Abileah (JomegaK), Andrea Scozzari and Stefano Vignudelli (CNR)

Envisat RA-2 Individual Echoes: a unique dataset for a better understanding of inland water altimetry potentialities

remote sensing

MDPI

Envisat RA-2 Individual Echoes: a unique dataset for a better understanding of inland water altimetry potentialities

Thank you for your attention!

http://www.coastalaltimetry.org/
http://www.coastalt.eu/

E-mail: vignudelli@pi.ibf.cnr.it
Skype: vignudell_stefano

There is a very simple and concise bottom message:

….radar altimeters from satellites give us a convenient and privileged viewpoint [to study inland waters]