SAR Altimetry Processing for Inland Water : Rivers & Lakes

24 February 2017, Florence, Italy

– SAR Altimetry Training Session –

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with contributions from
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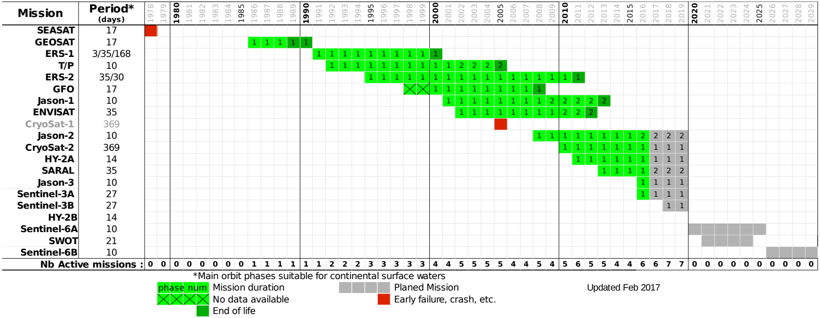
SAR Altimetry for Inland Water : Rivers & Lakes

Structure of the Inland Water training course

- This presentation is **split in two parts** :
  1. SAR Altimetry Processing for Inland Water : Rivers (35')
  2. SAR Altimetry Processing for Inland Water : Lakes (25')
- Questions : few minutes reserved at the end of each presentation
- Presentations share introductory and concluding sections
- Really **for the new comers in alti-hydrology**, but I assume you already know some basics and you have been very assiduous during this training ! :)

Background : Main Technical Evolutions

Chronology of past, present & future altimetry missions



From T/P to Jason-3 : 10+ missions since 1992, 25 years of data available.

Background : Main Technical Evolutions

From LRM to SAR and SARIN modes, from Ku to Ka band...

- **Orbit accuracy** : improved from 1m to few cm !
- **Onboard tracking** : More recent improvements
  E.g., from Topex to Jason-2 (improved close-loop modes), ENVISAT's variable bandwidth, CryoSat-2 SARIN tracking mode, open-loop / DEM-guided modes
- **Retracking algorithms** : Lot of efforts
  From Brown-based retrackers to empirical (OCOG/Ice1, Ice2, Ice3) and to physical (SAMOSA, new CLS retracker) or numerical (CPP/SAR) retrackers.
- **Altimeter modes** : from LRM to SAR and SARIN

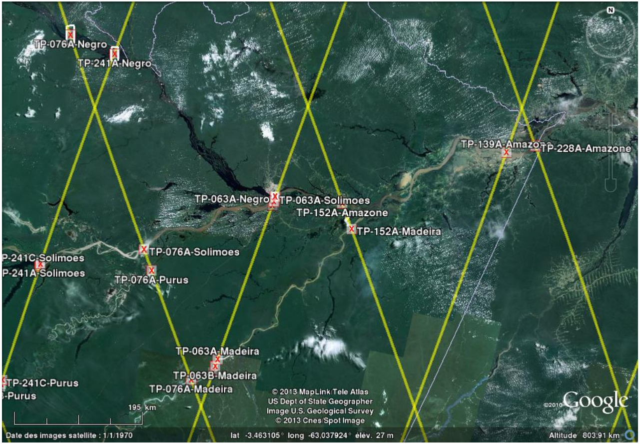
Background : Main Technical Evolutions

- **Altimeter bands** : From Ku (all except...) to Ka (...SARAL)
  - Reduced footprint size (a way to improve the across-track resolution of SAR mode, dixit S. Dinardo during this training)
  - Plus other bands : ENVISAT S-Band, Jason-1/2/3 C-band
- **Geophysical corrections** : Instruments (MWR), methods (GPS) and external data (meteo models) :
  - Improved range corrections : dry, wet and iono (even over land surfaces)
  - Improved Geoid models : EGM96, EGM2008, GRACE, GOCE, EIGEN-6C3, EIGEN-6C4, etc.
- **Various initiatives related or dedicated to hydrology (.../...)**

Initiative	Year(s)	Type	Activity/ Status	Product Type	Mission(s)	Altimetry Mode(s)	Main Innovation
GRLM (USGS)	Since 2003	Service	Running	LWL	TBD	LRM	Automated monitoring
HydroWeb (LEGOS)	Since 2005	Service	Need update (up to 2012)	RWL, LWL, LWS, LWV	T/P, ENVISAT, Jason-2	LRM	Extensive coverage, Long Archive
River & Lake	Since 2003	Project (ESA) Service demo	Ended Still running	L2, RWL	ERS-2, ENVISAT, Jason-2	LRM	Multiple retrackers, NRT Service
CASH	2005-2006	Project (CNES)	Ended	L2 Reproc	T/P	LRM	Envisat retrackers applied to T/P
PISTACH (CNES)	2008-2009	Project (CNES) Operational demo	Ended Still running	L2 for coastal/hydro	Jason-2	LRM	Ice3, L2 corrs
PEACHI (CNES)	2013-2015	Project (CNES) Configurable proto	Ended (renewed) Off-line	L2 (for ice)	SARAL/Ka	LRM	Tunable processor, Ka band
CPP (CNES)	Since 2013	Processor	Off-line	L1b, L2 (focused on ocean)	CryoSat-2	SAR (+PLRM)	DDP
REAPER (ESA)	2014	Product	Ended	Off-line L2	ERS-1 ERS-2	LRM	Reprocessing
LOTUS	2014-2017	Project (FP7)	On-going	TBD	Sentinel-3, CryoSat-2	SAR (+PLRM?)	SAR
CRUCIAL	2014-2016	Project (ESA)	On-going	TBD	CryoSat-2	SAR, SARin	SAR, model
SARVatore (ESA)	Since 2014	On-demand service	Available on G-POD	L1b, L2	CryoSat-2	LRM, SAR, SARin (single channel)	First tunable & on-demand SAR processor
DeDop	2015-2017	Processor	On-going	L1b-s, L1b	Sentinel-3 (+CryoSat-2)	SAR	First Open Source SAR processor
DAHITI (DGFI-TUM)	Since 2013	Service	Running	RWL, LWL	many	LRM	Robust editing and Kalman filtering, extensive validation
DTU/lakes (K. Nielsen)	Since 2015	DTU project On-demand data	On-going? Available	LWL	CryoSat-2	LRM, SAR	Robust processing of lakes water levels
HydroSat (GIS/Univ. Stuttgart)	Since 2016	Service	Running	RWL, RWD, others	many	LRM	Extensive coverage, automated

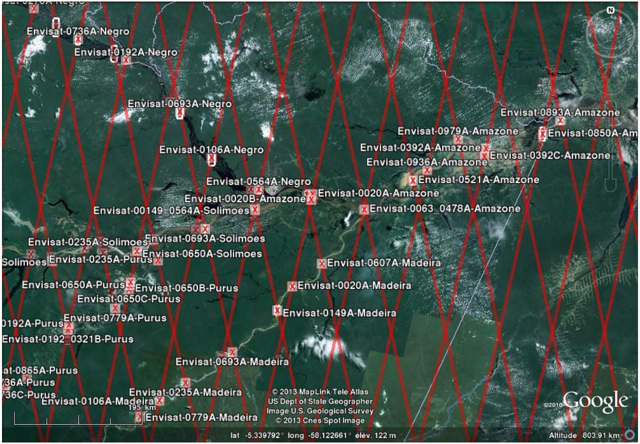
Background : Spatial & Temporal aspects

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



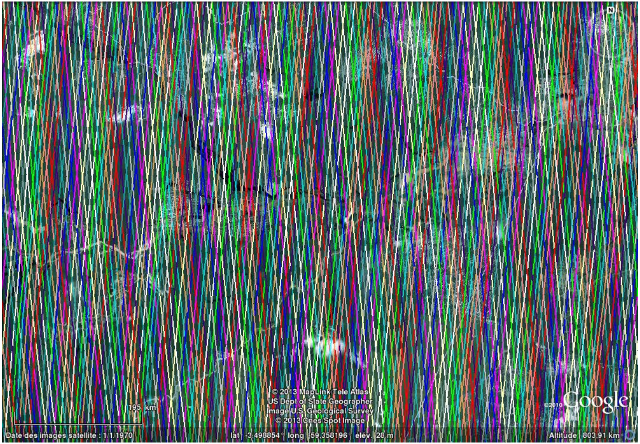
Background : Spatial & Temporal aspects

ERS, ENVISAT, SARAL : 80 km– 35 days



Background : Spatial & Temporal aspects

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



Background : Spatial & Temporal aspects

Consequences of the spatial coverage / tracks pattern

- **Rivers :**
  - More suited to East-West oriented rivers
    (South-North rivers tend to be parallel to satellite tracks. . .)
- **Lakes :**
  - Large lakes are likely to be well covered, possibly by several missions
  - Smaller lakes might be poorly covered or not covered at all !

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Consequences of the temporal revisit

- **Rivers & Lakes :** Aliasing of the temporal signal (mainly : 10, 27 to 35 days), more critical for rivers which are more dynamic objects

Background : Spatial & Temporal aspects

Adequacy of a given orbit's spatiotemporal trade-off ?

- **Rivers :** Densification of temporal coverage decreases aliasing at the cost of the number of crossings and the capability to estimate rivers slope and longitudinal profile
- **Lakes :** Densification of spatial coverage increases lake crossing probability at the cost of degraded temporal sampling frequency in the time series (aliasing again).

Background : Spatial & Temporal aspects

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- **Lakes :** Densification of spatial coverage increases lake crossing probability at the cost of degraded temporal sampling frequency in the time series (aliasing again).

But multi-mission can help a lot to densify in both space and time.

Background : Technical Challenges

Waveform contamination

- Surrounding land, canopy, banks, etc.
- Other waterbodies, swamps, snaking rivers, arms, islands
- Undesired reflectors (urban structures, boats, rice fields !)

All of them reflecting from near nadir or causing off-nadir & side lobes effects

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Important impact on retracking capability (particularly in LRM !)

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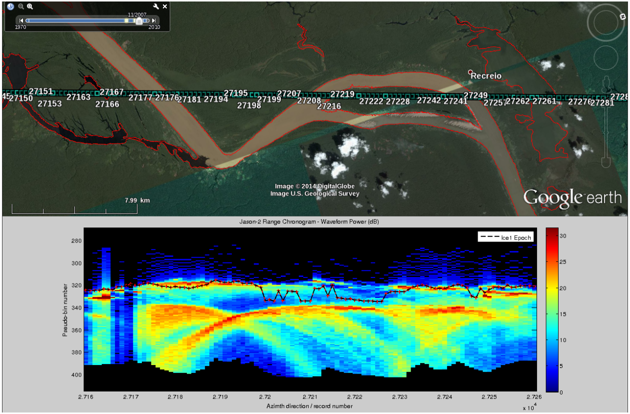
Important impact on retracking capability (particularly in LRM !)

Other issues and sources of errors

- Tracking loss or important hooking = blind to nadir reflectors
- Range corrections (dry & wet tropo vs. syst. bias)

Background : Technical Challenges

Example : LRM Waveforms over the Madeira river
(Jason-2 AVISO/S-GDR)



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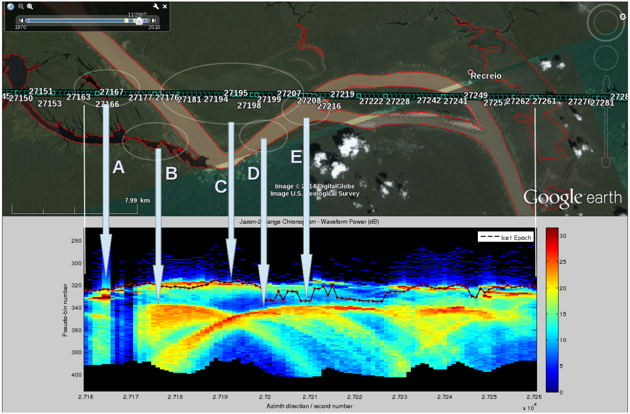


A lot of reflectors contribute from off-nadir directions !

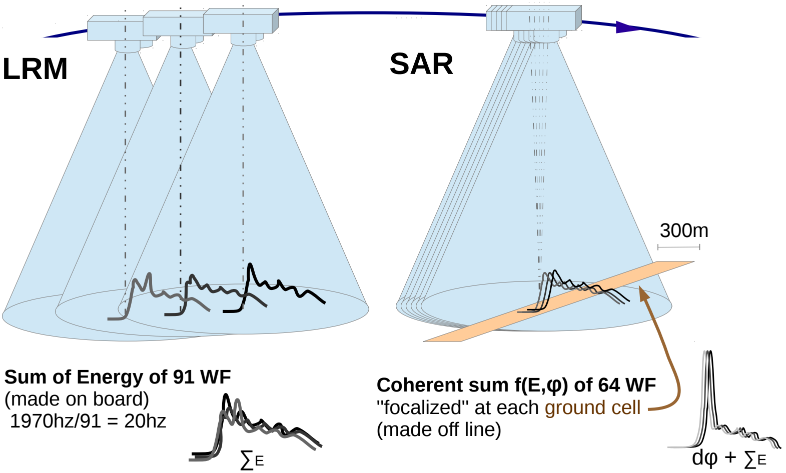
Background : Technical Challenges

Geophysical constraints

- Geoid models : resolution vs. inland waterbodies ?
  - **Rivers :** impact on river slope (this is poorly known actually) and systematic bias
  - **Large lakes :** can lead to non-flat surface (+ systematic bias)
  - **Smaller lakes :** tend to impact systematic bias only
- Barometric effects + wind stress (large lakes only)

SAR altimetry for Rivers : From L1A to L2

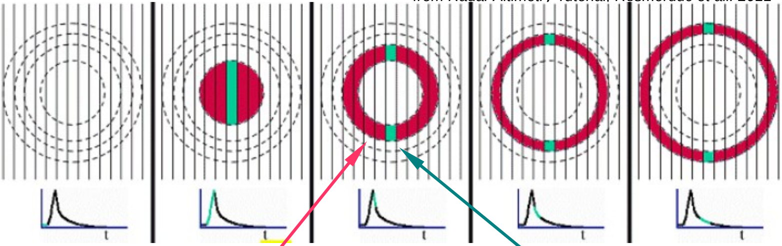
LRM vs. SARM : improved along-track resolution



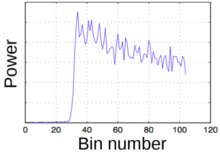
SAR altimetry for Rivers : From L1A to L2

LRM vs. SARM : improved along-track resolution

from Radar Altimetry Tutorial, Rosmorduc et all. 2011

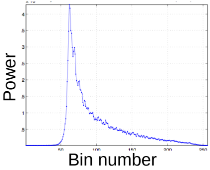


Brown wave-form



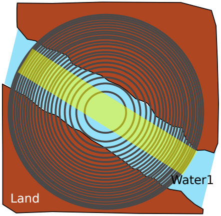
SAR wave-form much more « peaky » than Brown's wave-form (because of surface reduction from internal to external rings)

Doppler wave-form



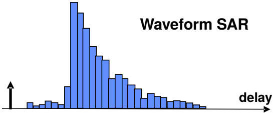
SAR altimetry for Rivers : From L1A to L2

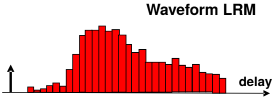
Geometry of the problem : 1 river



1. $\sigma_{0,Land} < \sigma_{0,Water1}$

The waveform shape depends on the water body area in the Doppler band. For any configuration, a simple retracking may work.





Courtesy of Thomas Moreau, CLS, from LPS extract 2013 presentation.

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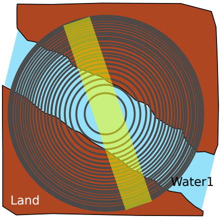

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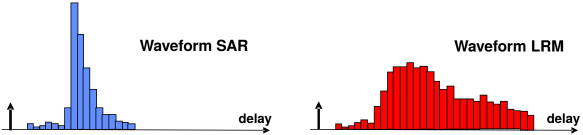

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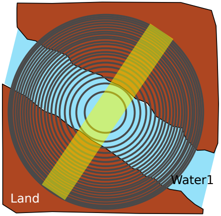

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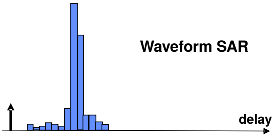

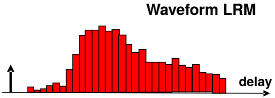

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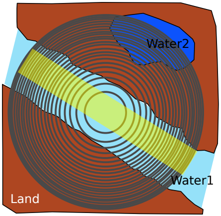
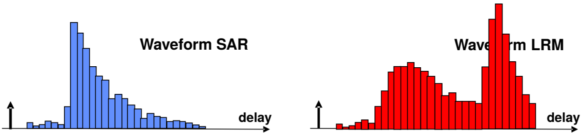
SAR altimetry for Rivers : From L1A to L2

Geometry of the problem : 1 river + 1 small lake



2. $\sigma_{0,Water2} > \sigma_{0,Water1}$ may occur and the effect is large on the waveform (altering the measurement of the OCOG trackers and retrackers)



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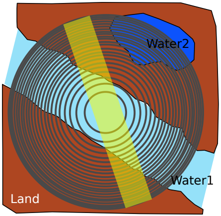

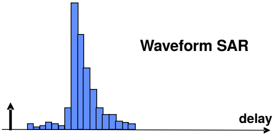

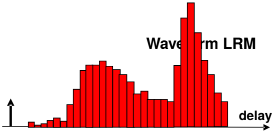

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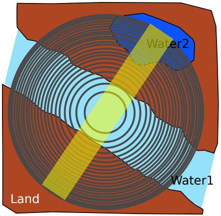

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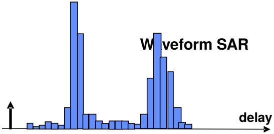
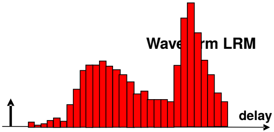




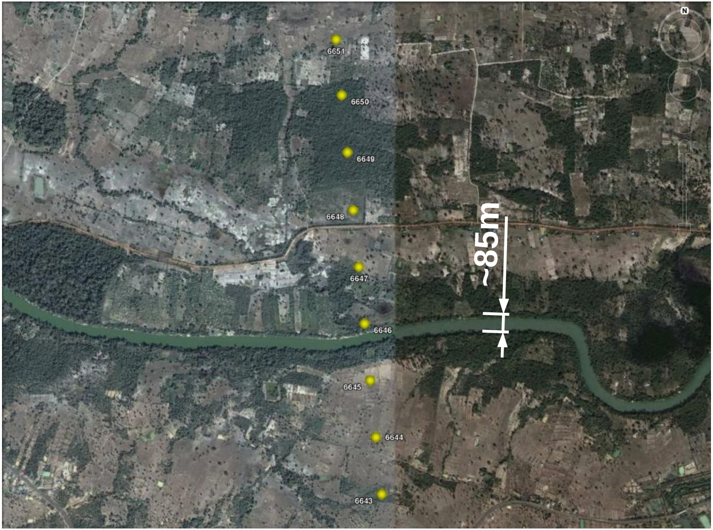
Courtesy of Thomas Moreau, CLS, from LPS extract 2013 presentation.

SAR altimetry for Rivers : From L1A to L2

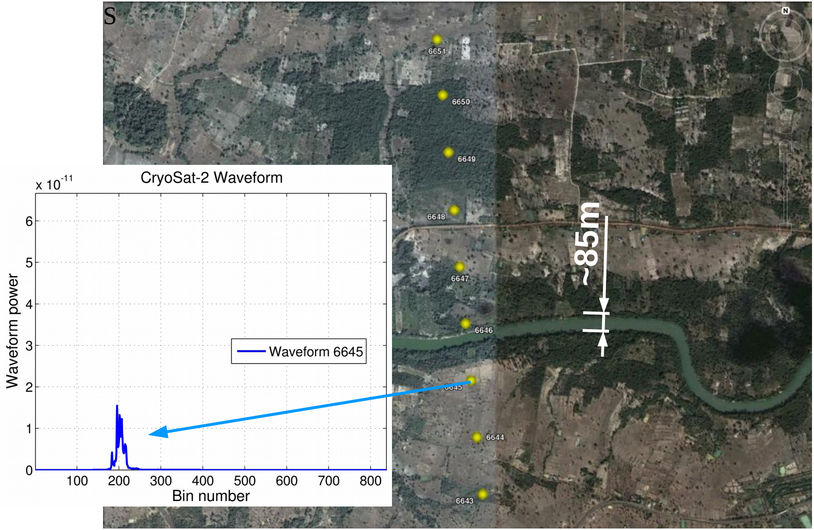
Key idea : SAR mode allows to reprocess the data from lower levels, including from complex echoes or Doppler beams, before the Waveforms to be retracked are formed.

(. . . and that is really cool indeed !)

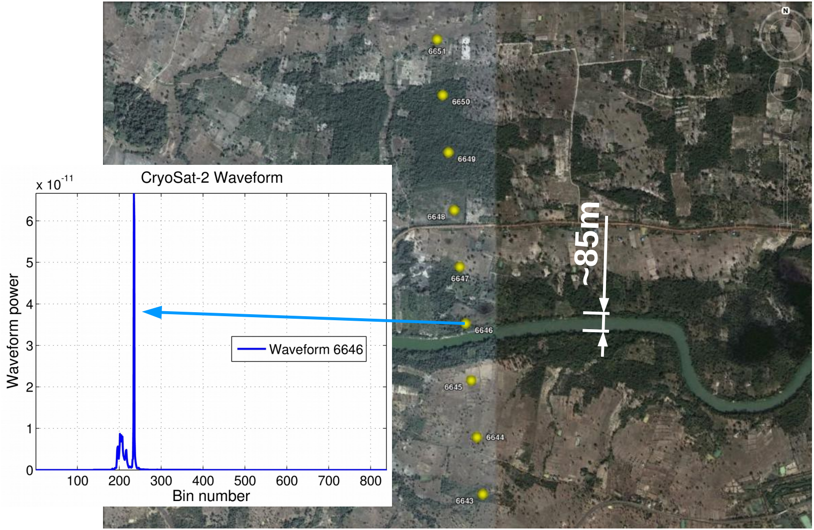
SAR altimetry for Rivers : From L1A to L2



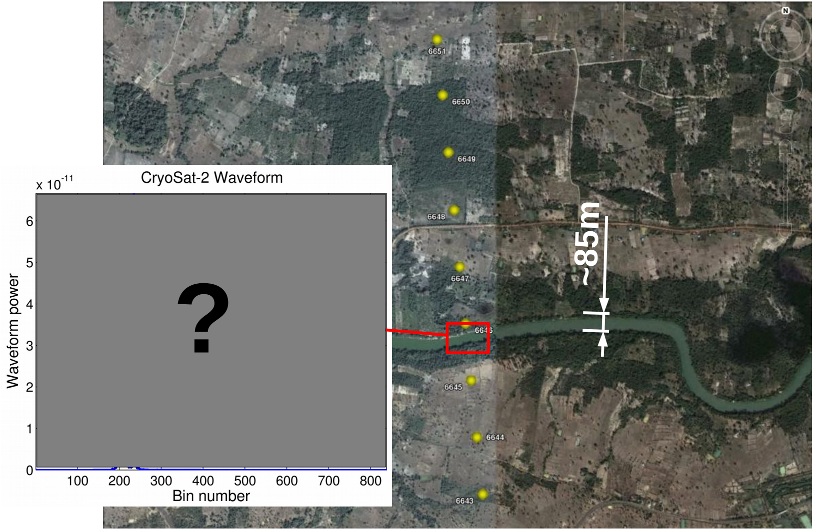
SAR altimetry for Rivers : From L1A to L2



SAR altimetry for Rivers : From L1A to L2



SAR altimetry for Rivers : From L1A to L2



SAR altimetry for Rivers : From L1A to L2

Solution : Beam steering to fixed or arbitrary locations

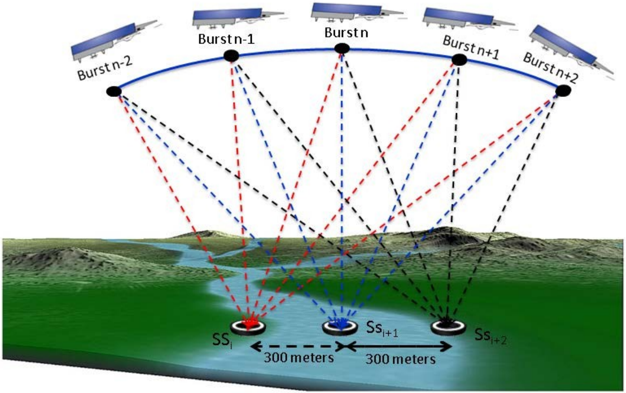
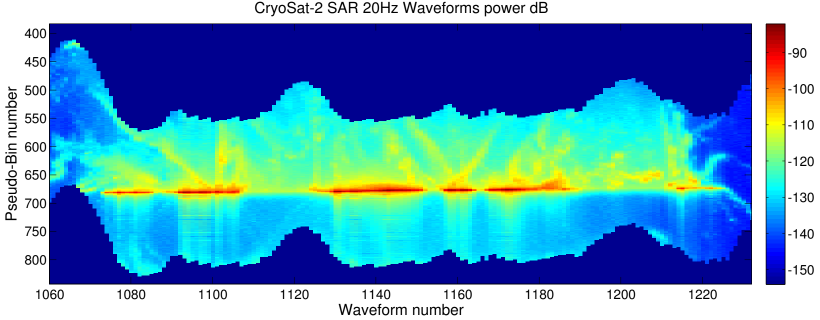


Image from "Guidelines for the SAR (Delay-Doppler) L1b Processing", S. Dinardo, ESA, 2013.

SAR altimetry for Rivers : From L1A to L2

Solution : Beam steering to fixed or arbitrary locations

Data from S. Dinardo (ESA/ESRIN, 2013)

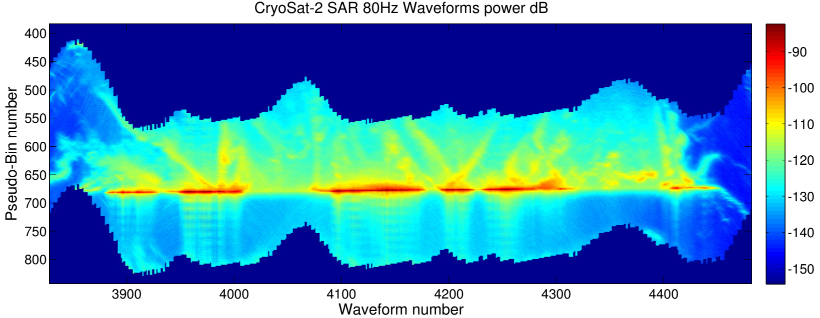


Standard 20Hz Waveform data

SAR altimetry for Rivers : From L1A to L2

Solution : Beam steering to fixed or arbitrary locations

Data from S. Dinardo (ESA/ESRIN, 2013)



Waveform data **reprocessed at 80Hz** (thanks to the presence of 4 bursts per 20Hz cycle)

SAR altimetry for Rivers : From L1A to L2

Solution : Beam steering to fixed or arbitrary locations

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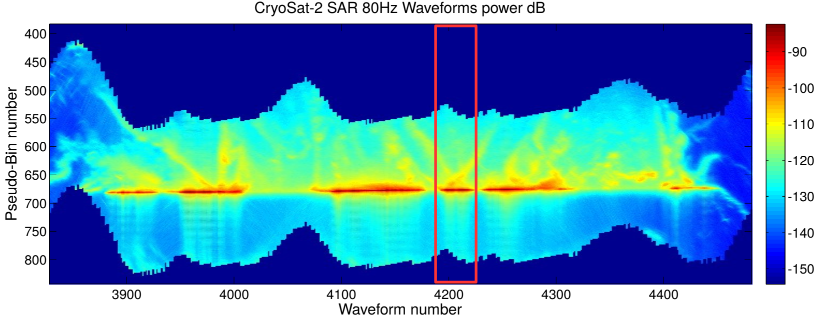
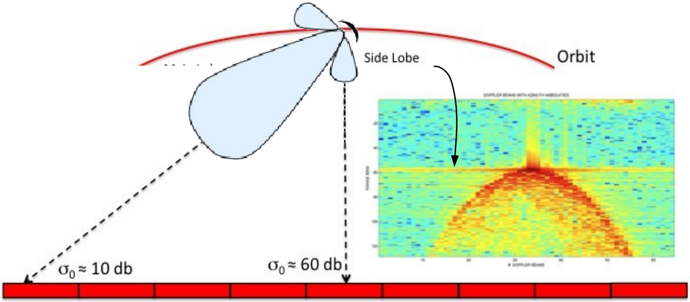


HR water masks (e.g., Sentinel-1) + **SAR 80Hz** (or beam steering) = **Optimal set of multilooked waveforms** + reduce CPU cost to a few records

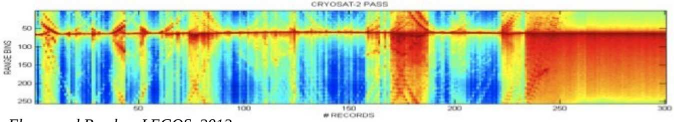
SAR altimetry for Rivers : From L1A to L2

SARM : Stacks and decontamination



Specular surface (rivers, lakes, coastal still waters)
Doppler Cells

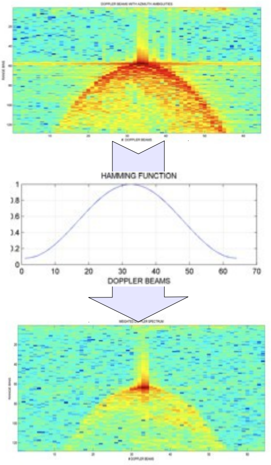
Over the Caspian sea :



From Fleury and Bercher, LEGOS, 2012.

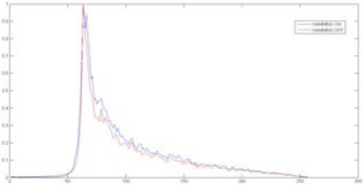
SAR altimetry for Rivers : From L1A to L2

SARM : Stacks and decontamination



From Fleury and Bercher, LEGOS, 2012.

- Systematically applied in ESA products.
- Efficient on cryosphere and hydrosphere (*i.e.*, specular = low RMSS)
- But side effects over open ocean:
  - Degradation of ground cell resolution (450m instead of 300m)
  - Possible bias on SWH
  - Distortion of leading edge
  - Noise and bias in range ?



SAR altimetry for Rivers : From L1A to L2

Key idea : SAR mode allows to decontaminate the Waveforms by editing the Stacks in Delay and Doppler dimensions.

(Something that is not possible using LRM data.)

SAR altimetry for Rivers : From L1A to L2

SARM : Retracking

(An optimistic point of view)

- Thanks to the improved along-track resolution,
- The Waveforms are naturally sharper,
- And they are naturally less contaminated.

At this stage, we may have done all we could to decontaminate the Waveforms and run a **physical retracker**.

SAMOSA (cf. Dinardo in this training, Ray et al. 2014)

- Able to cope with changing roughness (from ocean-like to specular Waveforms)
- Hopefully, decontamination procedures will help to isolate the peak of interest in the Waveforms

SAR altimetry for Rivers : From L1A to L2

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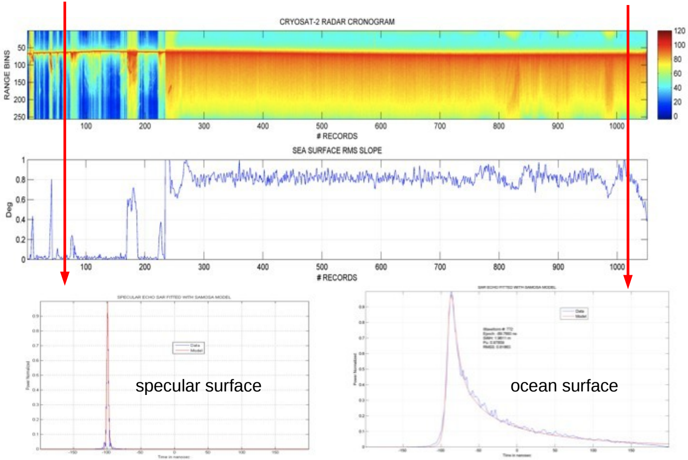
(A pessimistic point of view)

Ice1 retracker might be too sensible to the sharpness of the SAR Waveforms and the high threshold value that has to be for such Waveforms.

SAR altimetry for Rivers : From L1A to L2

SARM : Retracking examples

Caspian sea, data from S. Dinardo (ESA/ESRIN, 2013)



The "unique" SARIN mode of CryoSat-2

Main differences between SAR and SARIN modes

Differences

- SARIN uses two antennas : one to send and two to receive
- Phase difference & coherence between echoes are received via the two antennas (aligned with the waveform samples)
- While SARM emits 4 bursts, SARIN only emits 1 burst
- SARIN has a slightly increased "range noise" than in SARM (but over inland water, somehow. . . we don't care !)
- In the meantime would SARM have emit his 3 extra bursts, SARIN tries very hard to make its tracking very robust (like a 4x4-altimeter so to say !)

The "unique" SARIN mode of CryoSat-2

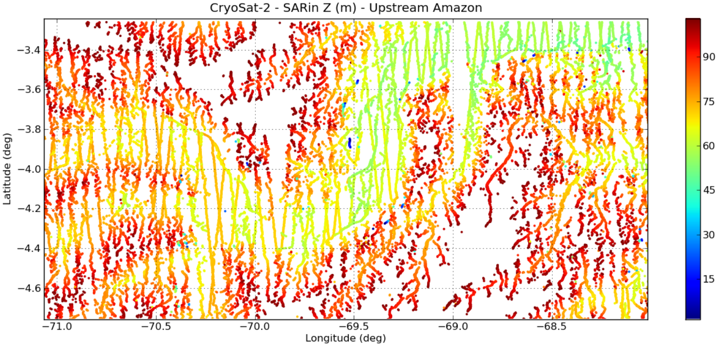
Main Similarities between SAR and SARIN modes

Similarities

- SAR and SARIN share the same Delay-Doppler Scheme, but it is done twice for SARIN
- SAR waveforms have 128 samples, SARIN waveforms have 512
- SAR and SARIN waveforms can be retracked using the same algorithms (though they have to adapt to the different waveform samples)

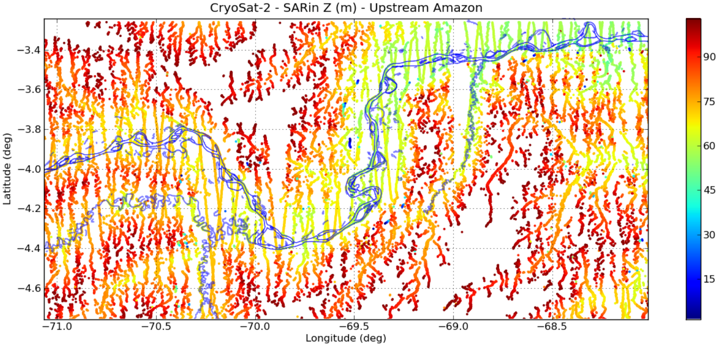
The "unique" SARIN mode of CryoSat-2

Map of SARIN measurements, Solimões river (L2/ESA)



The "unique" SARIN mode of CryoSat-2

Map of SARIN measurements, Solimões river (L2/ESA)



SARIN mode correctly relocates off-nadir measurements (Mapping the hydrographic network ? Help to improve SNR over rivers ?)

River Alti-Hydro products : From L2 to time series

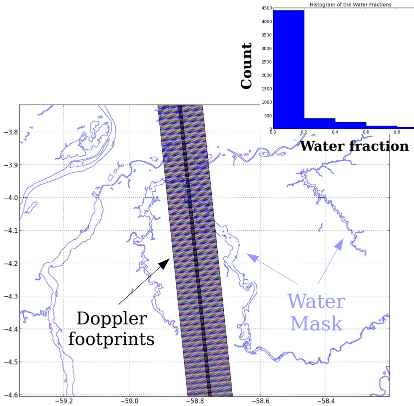
Despite the important improvements brought by of SARM over LRM, **the processing of water level time series** (i.e., the Alti-Hydro products) **is very similar** for both modes.

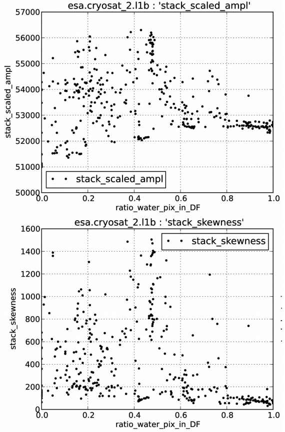
Main steps of the Generic Processing (repeat orbit case)

- **Geo-Selection :**
  - Goal : Using water masks derived from imagery (or predefined virtual stations), collect measurements falling into the area of interest.
- **Editing :**
  - Goal : discard unusable measurements related to instrument and/or L1A–L2 processing states/failures, etc. Based on product "metadata" such as flags, etc.
  - Can be a difficult task, rules are products-dependent
  - Advices : read user's handbook, explore product flags, read netCDF files internal comments, explore your data !
- **Filtering of the time series :**
  - Goal : discard outsider measurements which are not in good agreement with the main water level trend(s) (seasonal, spatial), cf. selected papers.

Selected papers : SARM for hydrology

Fabry et al., 2015 - Characterization of SAR RIP signals

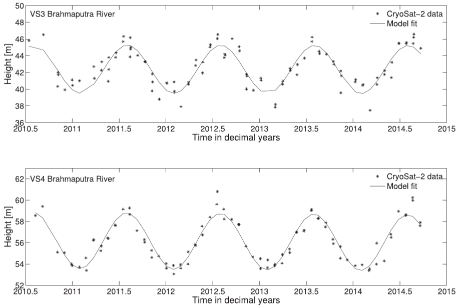




Selected papers : SARM for hydrology

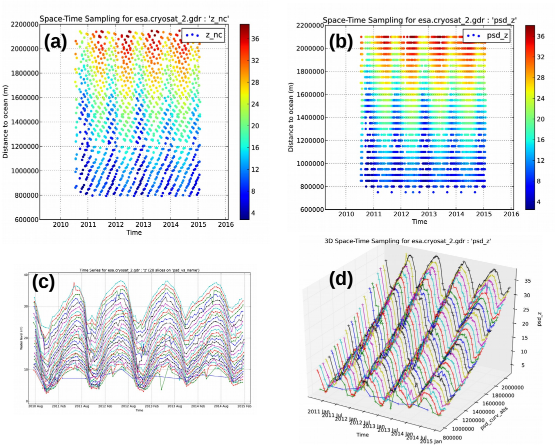
Villadsen et al., 2015

Capture of flood peak amplitude and phase, (CryoSat-2 SARin data, Brahmaputra river)



Selected papers : SARM for hydrology

Bercher et al., 2015 - Estimation of water levels at arbitrary locations along the Amazon river, CryoSat-2 SAR/SARin

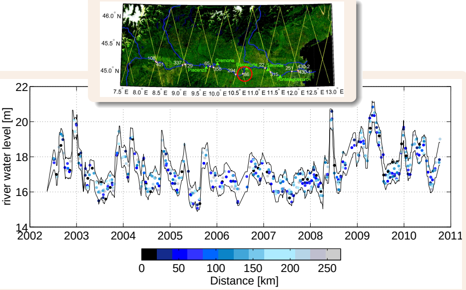


Selected papers : Alti-Hydro processing

Tourian et al., 2015 : developed a method to densify and filter time series mixing data from multiple virtual stations.

Step 5: scaling (back)

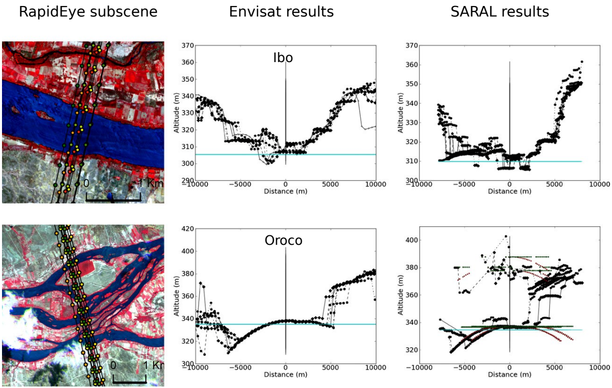
Rescaling the combined altimetric measurements to the considered virtual station



Improving the spatio-temporal resolution of water level time series | Tourian et al. 2014

Selected papers : Alti-Hydro processing

Maillard et al., 2015 : developed a method to use the hooking effect and improve retrieved water levels, continues the work initiated by Silva et al. (2010).



Selected papers : Alti-Hydro processing

Schwatke et al. 2015 : describe in details the internal algorithms of DAHITI web service : Kalman filtering, but also editing rules. Provides extensive validation results.

4354 **C. Schwatke et al.: DAHITI – an innovative approach for estimating water level time series**

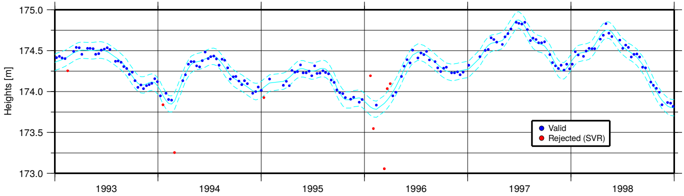


Figure 4. Example of applied SVR using radial base functions for outlier rejection on a resulting water level time series (Lake Erie) of the Kalman filtering step. The estimated regression function (cyan) and its confidence intervals (dotted cyan) are plotted. The result of the regression shows valid (blue) and rejected (red) altimeter heights. Each rejected water level height represents one complete satellite overflight.

Selected papers : other recent papers

- Paiva et al. (2015) – "Spatiotemporal interpolation of discharge across a river network by using synthetic SWOT satellite data"
- Domeneghetti et al. (2015) – "Investigating the uncertainty of satellite altimetry products for hydrodynamic modelling"
- Paris et al., (2016) – "Stage-discharge rating curves based on satellite altimetry and modelled discharge in the Amazon basin"
- Schneider et al. (2016) – "Application of CryoSat-2 altimetry data for river analysis and modelling"
- Tourian et al. (2017) – "River discharge estimation at daily resolution from satellite altimetry over an entire river basin"

Questions related to Part I

–

SAR Altimetry Processing for Inland Water : Rivers

SAR altimetry : Lakes vs. Rivers

The "Background" and "Rivers" sections in **PART I** introduced SARM for rivers.

Most of what have been presented so far **remains valid for lakes**. But usually, the more a lake is large, the less the processing is complex.

In **Part II**, we **will highlight the major differences**, **between rivers and lakes**, related to SARM.

SAR altimetry for Lakes : From L1A to L2

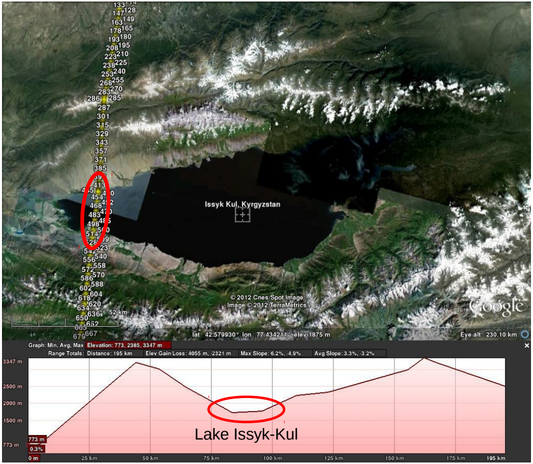
Major differences between rivers and lakes

- **Lakes processing :** Measurement conditions are usually close to those of the ocean (central part) or the coastal zones (closer to the banks)

- **Large lakes :**
  - Waveforms contamination is not an issue, except close to lake banks (less true in SARM than in LRM)
  - The measurement of atmospheric corrections (MWR) is not an issue far enough from the banks
- **Smaller lakes : conditions similar to rivers**
  - Waveforms contamination is likely to be an issue
  - Atmospheric corrections are to be derived from ancillary data (meteo models, GPS)

SAR altimetry for Lakes : From L1A to L2

SARin mode (single channel) over Lake Issyk-Kul



SAR altimetry for Lakes : From L1A to L2

SARin mode (single channel) over Lake Issyk-Kul

SAR altimetry for Lakes : From L1A to L2

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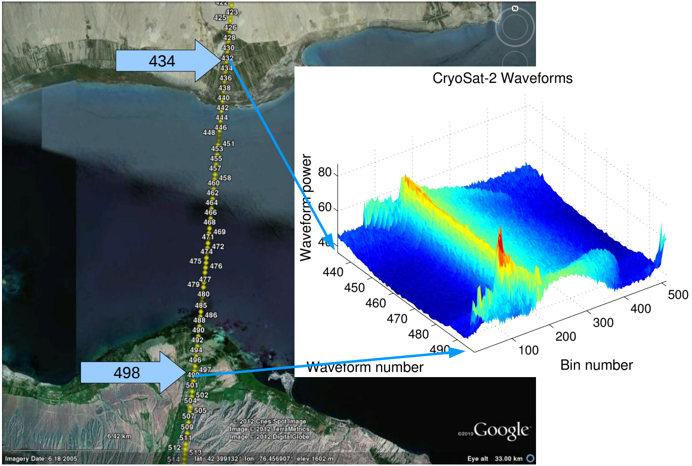
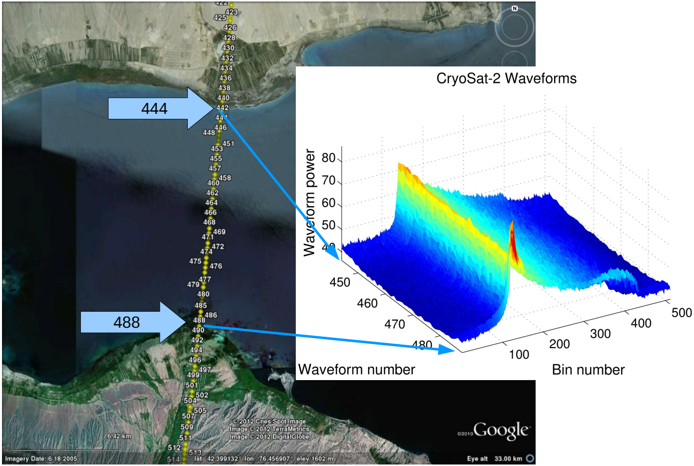


SAR altimetry for Lakes : From L1A to L2

SARin mode (single channel) over Lake Issyk-Kul



SAR altimetry for Lakes : From L1A to L2

Main differences in the Processor configuration

Delay-Doppler Processor

- Editing of the Stacks (Hamming) : might be not required for larger lakes but required for the smaller ones

Retracking

- A physical retracker like SAMOSA might be suitable for all lake sizes
- What about empirical retrackers like Ice1 ?

Atmospherical corrections

- Same issue than for LRM missions. . .

Lake Alti-Hydro products

- **Lakes processing :**
  - Due to larger crossing sections (compared to rivers), a **lot of measurements are collected** after each overflight

- **Large lakes :**
  - The larger crossing sections allows/requires the refinement on the **estimation of the local geoid** using altimetry data
  - Usually good spatial coverage & temporal sampling (multi-mission) : "simplified" processing of the water level time series
- **Smaller lakes :**
  - The constraints are similar to those of rivers
  - The resulting time series might **expose larger bias** than for large lakes

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

h_sat : satellite altitude above ellipsoid.

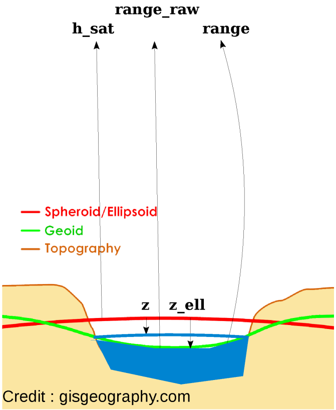
range = range_raw + atm : retracked waveform : satellite-to-surface range incl. atmo. path delays.

atm = corr_tropo_dry + corr_tropo_wet : most of the atmospheric path delays.

z_ell = h_sat – range : surface elevation above ellipsoid (WGS84) incl. surface deformation due to the geoid.

geoid : shape that water surfaces would take under the influence of Earth's gravity alone (no wind, no current effects) → oceans, lakes and rivers have bumps and holes (not iso range to the ellipsoid).

z = z_ell – geoid : surface height



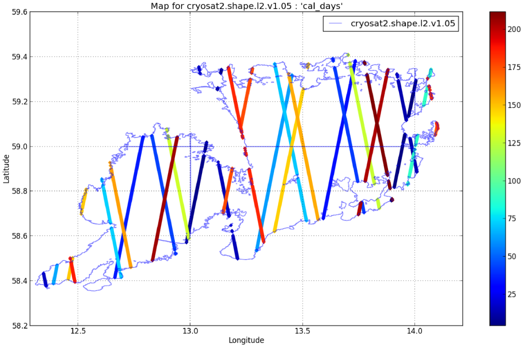
Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

SHAPE PROCESSOR : Lake Vänern from 01/01/2016 to 30/07/2016

A collection of tracks each one indexed by a time **t** vector and two position vectors **x** and **y** so that the **i**-th track provides : **h_sat(t_i,x_i,y_i)** and **range(t_i,x_i,y_i)**.



Pierre Fabry & Nicolas Bercher, ALONG-TRACK, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

We are looking for : **z = h_sat - range - atm - geoid**

Problems :

- Q : Do we know **atm** good enough ? A : Pretty well : accuracy = few cm
- Q : Do we know **geoid** good enough ? A : Not sure : accuracy = few 10 cm

To mitigate the impact of geoid accuracy, why not inter-calibrating all of the tracks overflying the lake by exploiting the network of crossings (**thanks to the geodetic orbit**) ?

(1) $$z(t_i,x_i,y_i) = h\_sat(t_i,x_i,y_i) - range(t_i,x_i,y_i) - atm(t_i,x_i,y_i) - geoid(x_i,y_i)$$

(2) $$z(t_k,x_k,y_k) = h\_sat(t_k,x_k,y_k) - range(t_k,x_k,y_k) - atm(t_k,x_k,y_k) - geoid(x_k,y_k)$$

Crossing of tracks **i** and **k** → selection of records within a **vicinity geobox** defined as a subset of (x_i,y_i) and a subset of (x_k,y_k) that verify :

$$\sqrt{[(x_i-x_k)^2 + (y_i-y_k)^2]} < d \Rightarrow geoid(x_i,y_i) \approx geoid(x_k,y_k)$$

Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

At the vicinity geobox : (1) – (2) = $\Delta z(\mathbf{t_i},\mathbf{t_k}) \approx \Delta h(\mathbf{t_i},\mathbf{t_k}) - \Delta range(\mathbf{t_i},\mathbf{t_k}) - \Delta atm(\mathbf{t_i},\mathbf{t_k})$

Several things shall be noted :

- $\Delta z(\mathbf{t_i},\mathbf{t_k}) = \Delta z\_ell(\mathbf{t_i},\mathbf{t_k})$ is an inter-track calibration value (scalar)
- This framework is geoid error free if the vicinity boxes are small enough (few 100 m radius)
- Fair assumption : the calibration value applies to all records of track (even outside the geobox) and it brings the two tracks to the same date where only the spatial component remains :

$$\mathbf{z}(t_k,x_k,y_k) + \Delta z(t_i,t_k) \approx \mathbf{z}(t_i,x_k,y_k)$$

- With enough crossings we can propagate the inter-calibration from any starting point to any ending point and **this cancels the time variability of altimetric measurements over large lakes** ⇒ **measuring the spatial variability**

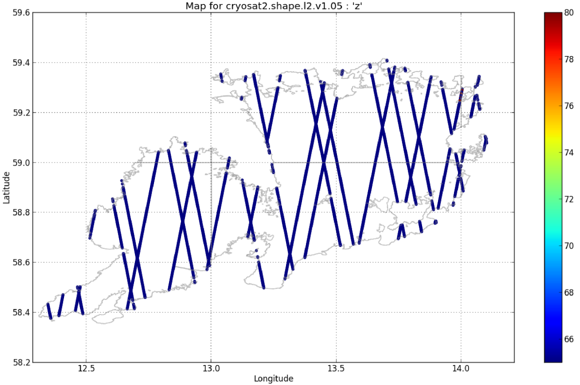
⇒ **measuring the geoid + a constant bias**.

Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Let's compare **z** to **z_ell**



Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

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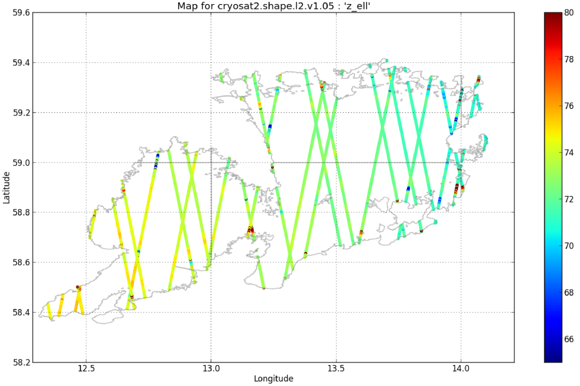
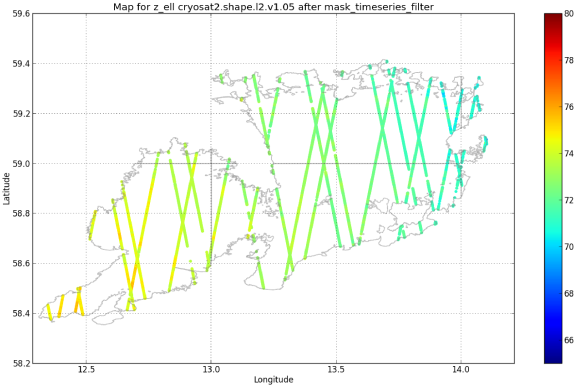


Pierre Fabry & Nicolas Bercher, ALONG-TRACK, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Application of 3sigma gaussian filter for outliers rejection :



Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

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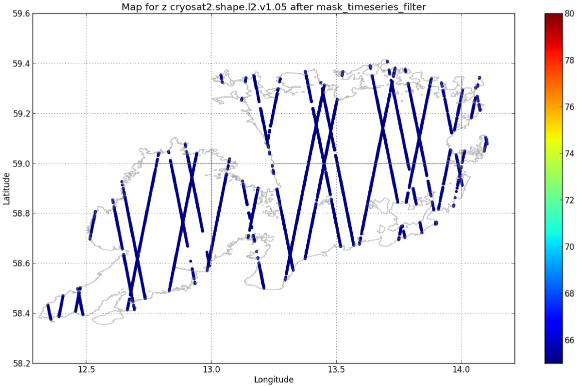
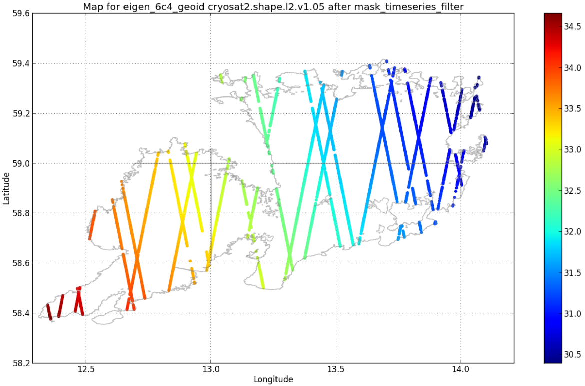


Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Let's compare with eigen6c4 geoid:

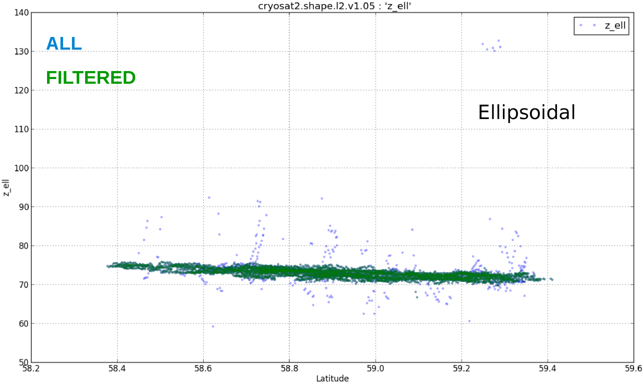


Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Also **plots vs lat** provide the trends (look at the absolute levels):



Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

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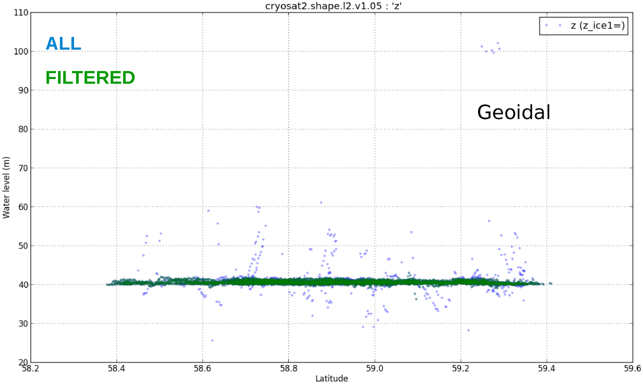

Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

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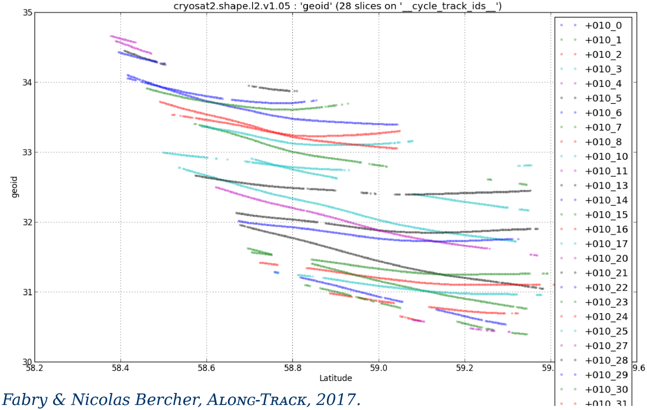


Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Inter-overflight calibration method :

- Select only records over the watermask
- Apply 3sigma Gaussian Outlier Rejection Filter
- Identify all crossings 'XINGS' : **cycle-track1, cycle-track2, lon, lat**
- Compute the distance (records to XING) for all records of both cycle-tracks (computation on Earth tangential plane at mean lake level from ALL records)
- Select only records @ vicinity geobox and compute **local mean z_ell** for **both cycle-track**
- **Δz = mean z_ell (cycle-track1, cycle-track2)**
- Keep the XING If we have **at least one record** for each cycle-track : green dots (cf. map)
- Apply the correction from cycle-track to cycle-track as described earlier, while taking care of correction a cycle-track only once :

$$z(t_k, x_k, y_k) + \Delta z(t_i, t_k)$$

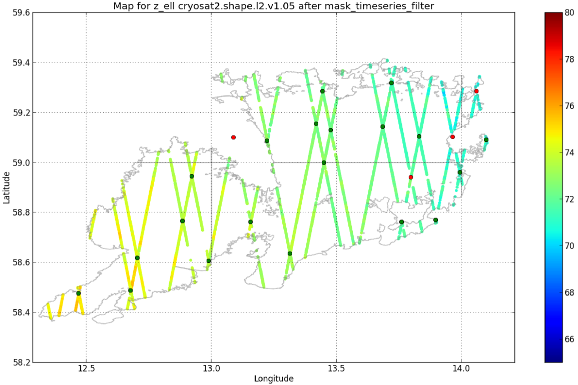
- Identify separated clusters if needed and cross calibrate them from gauging stations if needed
- Compare to geoid : the diff should be quite flat (the constant bias)

Pierre Fabry & Nicolas Bercher, ALONG-TRACK, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Map with vicinity radius = 2000m

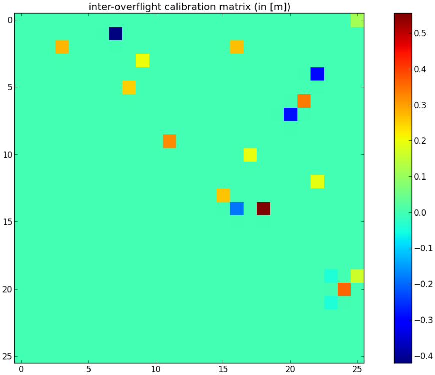


Pierre Fabry & Nicolas Bercher, ALONG-TRACK, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Calibration Matrix with vicinity radius = 2000m

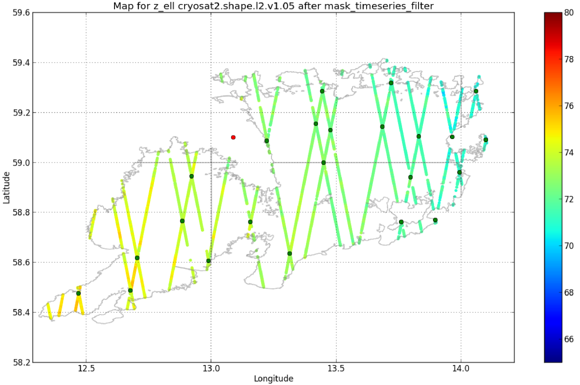


Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Map with vicinity radius = 5000m

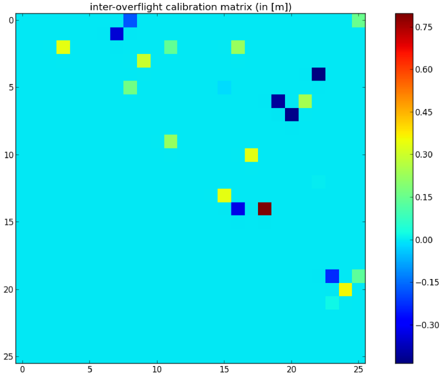


Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Calibration Matrix with vicinity radius = 5000m



Pierre Fabry & Nicolas Bercher, Along-Track, 2017.

Geoid estimation from CryoSat-2 geodetic orbit

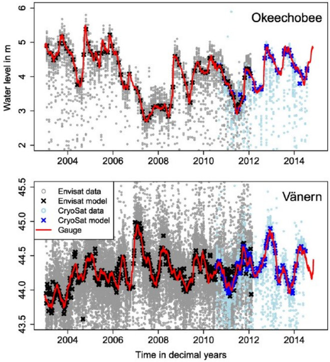
Vänern lake (Sentinel-3-like baseline run on FBR/C products)

Perspectives :

- Complete the job and study error propagation from cycle-track to cycle-track
- Study sensitivity to geobox size (vicinity radius)
- Compare (the time series) with **mission_geoid** and **SHAPE_geoid**
- Apply the method to multi-mission (intercalibration of multi-missions)
- Produce multi-mission time series over lakes and assess their consistency
- Use this framework to compare retrackers over lakes : useful for empirical-threshold retrackers calibration and sensitivity to sea state
- Maybe more …

any idea or remark ?

Selected papers



Nielsen et al., 2015

Robust estimation of lake water levels, CryoSat-2 SAR data, lake Vänern + 4 others.

An open source "R" package is available online, it implements an along-track filter, based on the description of the meas. noise.

Selected papers

Arsen et al., 2014 : Validation of SARAL over medium and small lakes, derived a trend between vertical RMS Error and lake-track cross-sections. Though not in SAR mode, the results clearly depict the benefit of a reduced footprint size.

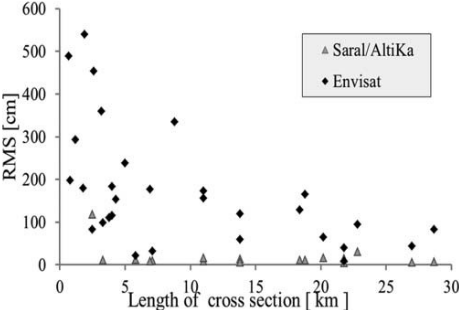


Figure 7.Accuracy with respect to the length of the cross sections.

Selected papers : other recent papers

- Tourian et al., 2015 – "A spaceborne multisensor approach to monitor the desiccation of Lake Urmia in Iran"
- Cretaux et al. 2016 – "Lake Volume Monitoring from Space"
- Göttl et al. 2016 – "Lake Level Estimation Based on CryoSat-2 SAR Altimetry and Multi-Looked Waveform Classification"
- Shen et al. 2016 – "Estimate the fluctuation of Poyang Lake water level using Cryosat-2 data"
- Jiang et al. 2017 – "Monitoring recent lake level variations on the Tibetan Plateau using CryoSat-2 SARIn mode data"

Online Resources

- **www.altimetry.info** : Documentation and much more ! Topics : Toolbox, Code, Data Access, Links, Altimetry Tutorial, Use Cases, Missions, Helpdesk

- **Data access :**
  - L1b/L2 : ESA, AVISO+ (incl. PEACHI), LEGOS/CTOH, NASA/PO.DAAC, PISTACH
  - Alti-Hydro portals : HydroSat, DAHITI, HydroWeb, River&Lake

- **Software and toolboxes :** BRAT, MAPS, VALS, K. Nielsen's "R" tool for lakes processing

Conclusion

Satellite Altimetry

- Already 25 years of data from 12 missions
- Important improvements in vertical noise, orbit, etc.
- Several innovative projects, services
- SARM : Several alternative Delay-Doppler processors

Altimetry and Hydrology

- Trade-off & limitations related to space & time
- Lots of technical challenges due to land surfaces
- Rivers & Lakes : different cases...

Conclusion

Altimetry, SARM & Rivers monitoring

- Rivers : complex, dynamic objects (water level variations, topography, morphology)
- Require specific processing at each stage, from L1A to L2, and to Alti-Hydro Products (time series)
- Waveforms contamination is the biggest challenge
- Atmospherical corrections are derived from models

Conclusion

Altimetry, SARM & Lakes monitoring

- Lakes are less complex than rivers, though smaller lakes requires similar care than rivers
- Extended cross-sections allow/require to refine the local geoid model
- Waveforms contamination is of mitigated impact, depending on lake size
- Atmospherical can be measured over central sections of the larger lakes, or corrections derived from models

Acknowledgement

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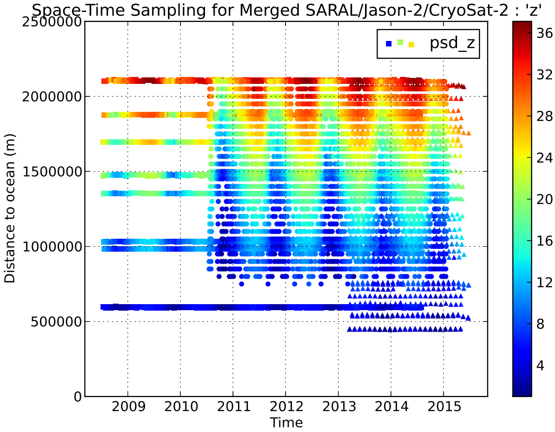
- Philippe Maillard
- Sara Fleury
- Salvatore Dinardo
- M. J. Tourian
- Mònica Roca
- Thomas Moreau
- Pierre Fabry
- . . . and ESA for the invitation !

– Thank you ! –



Space-Time Sampling for Merged SARAL/Jason-2/CryoSat-2 : 'z'
psd_z
Distance to ocean (m)
Time
0
500000
1000000
1500000
2000000
2500000
2009
2010
2011
2012
2013
2014
2015
4
8
12
16
20
24
28
32
36

Questions related to Part II

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SAR Altimetry Processing for Inland Water : Lakes