Scientific Applications of Fully-Focused SAR Altimetry

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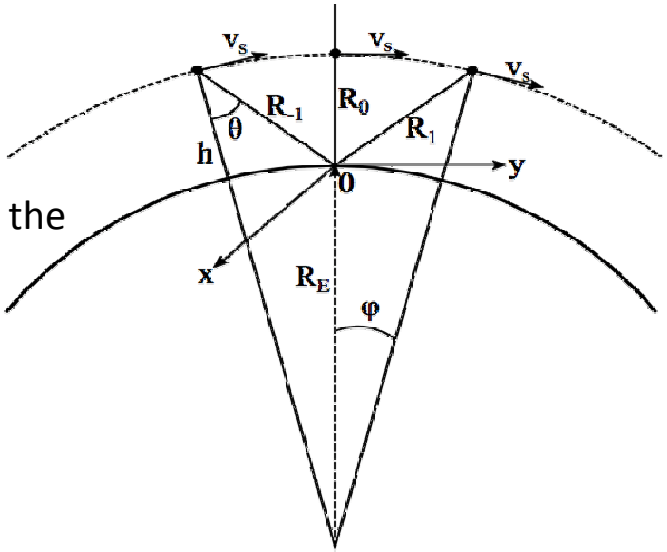
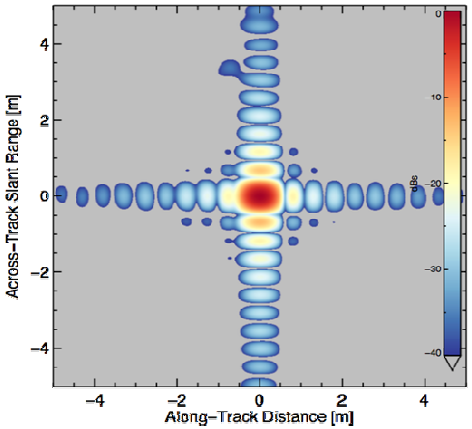
Basics of FF-SAR Altimetry processing

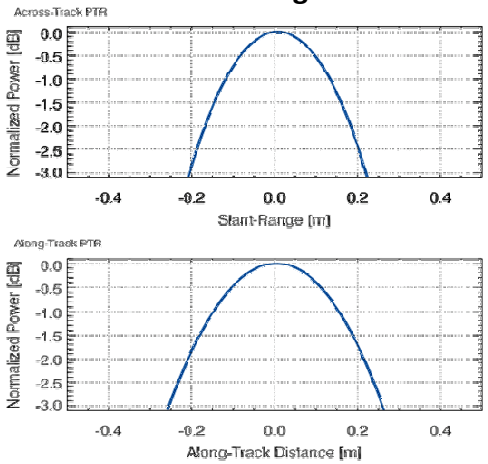
- The Synthetic Aperture Radar (SAR) processing technique combines *coherently* the response of a single point on the surface during its entire illumination time by the radar.
- The target is processed with a synthetic “aperture” of several km.
- The achievable resolution is L/2, L = antenna length.
- The technique can be applied to any kind of SAR Altimeter, provided that the radar is coherent.
- We demonstrated the technique by processing CryoSat-2 FBR SAR Mode data over transponders, [1].
- The closed burst operation of CryoSat and Sentinel-3 (lacunar sampling) leads to multiple side lobes in the along-track PTR.



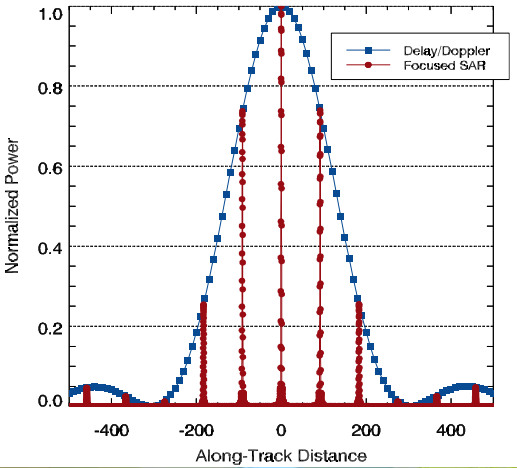
2D SAR Point Target Response



Across-Track and Along-Track Cuts



Full Along-track PTR

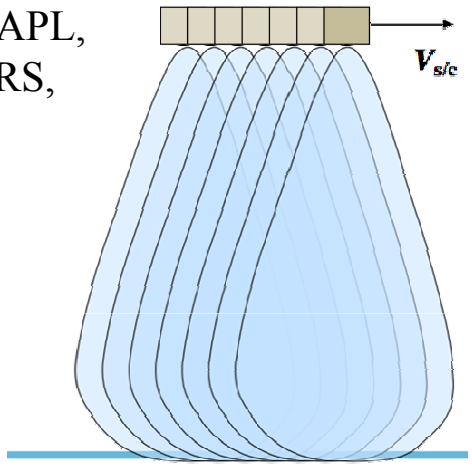


The side lobes will not be present if the sampling is continuous (open burst operation), and will therefore be highly mitigated in the case of **Sentinel-6/Jason-CS.**

From Conventional to Focused SAR Altimetry

Conventional Altimeter

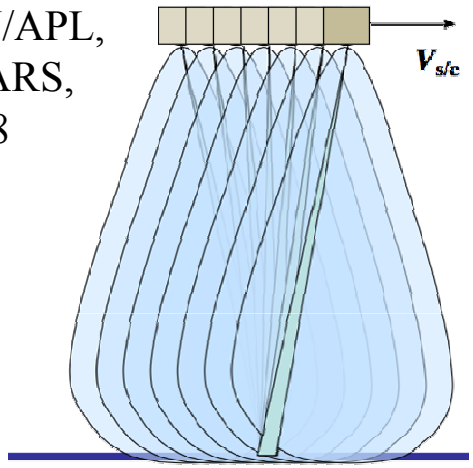
Image K. Raney, JHU/APL, TGARS, 1998



- Low Resolution Mode
- Pulse limited footprint (circular)
- 1.5 / 5 km res. depending on SWH
- Open burst operation
- PRF ~ 2 kHz

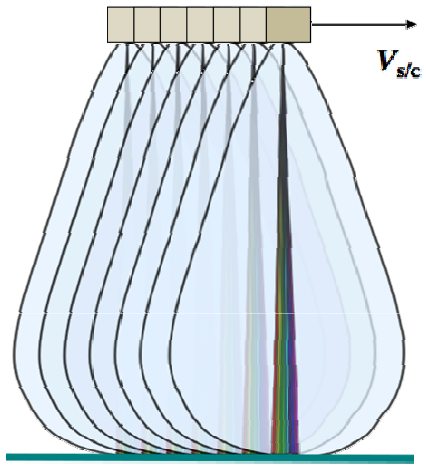
Delay-Doppler Altimeter

Image K. Raney, JHU/APL, TGARS, 1998



- Unfocused SAR processing
- ~300 m resolution Along-Track
- Pulse limited across-track
- Closed Burst
- PRF ~ 18 KHz

Focused SAR Altimeter



- Fully Focused SAR processing Coherent processing for ~2 seconds
- Resolution Along-Track ~ 0.5 m
- Pulse limited across-track
- Closed Burst
- PRF ~ 18 KHz

Hydrology Applications

- Irrigation pond in India
  - In-land calmed water body
  - ~40 x ~40 meter
  - Along-track size < delay-Doppler Resolution

Irrigation pond location and CryoSat-2 sub-satellite track.

Hydrology Applications

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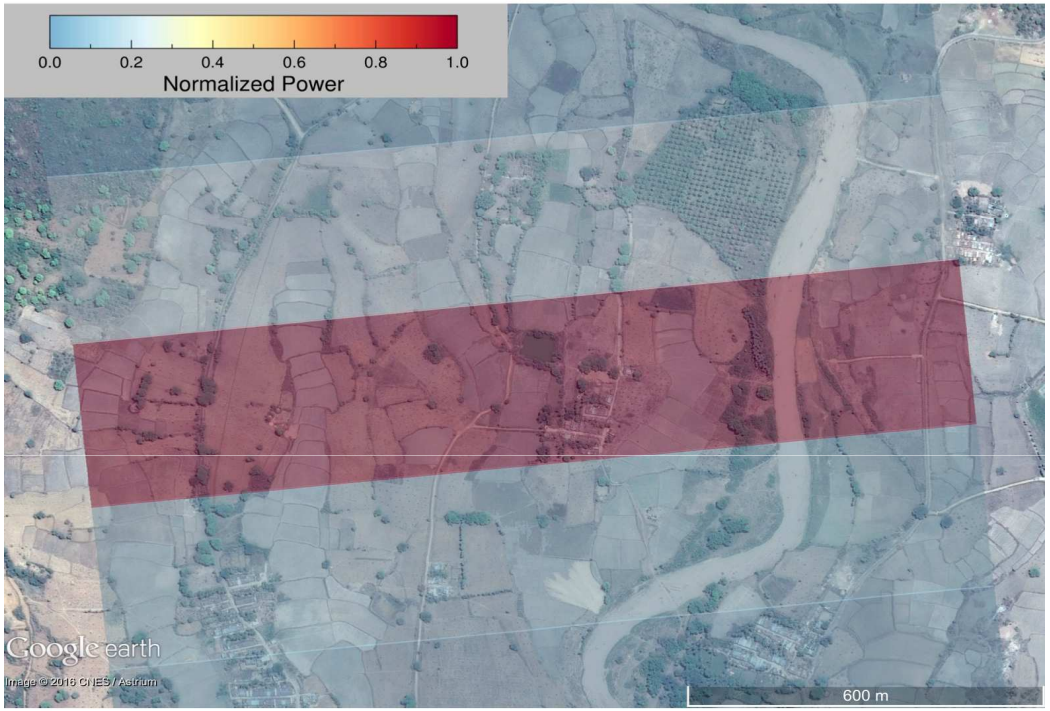
- The pond is detected in the delay/Doppler (unfocused SAR) processing, but…
  - The location of the irrigation of the pond cannot be determined within the resolution cell (...obviously…)
  - The along-track uncertainty in the location of the pond can lead to an error of ±1.5 cm in the determination of the water level



Delay-Doppler Response over the pond, from ESA L1b product.
Normalized Power in color scale. Rectangles represent the DD altimeter footprint, ~300 m along-track by ~1500 m across-track

Hydrology Applications

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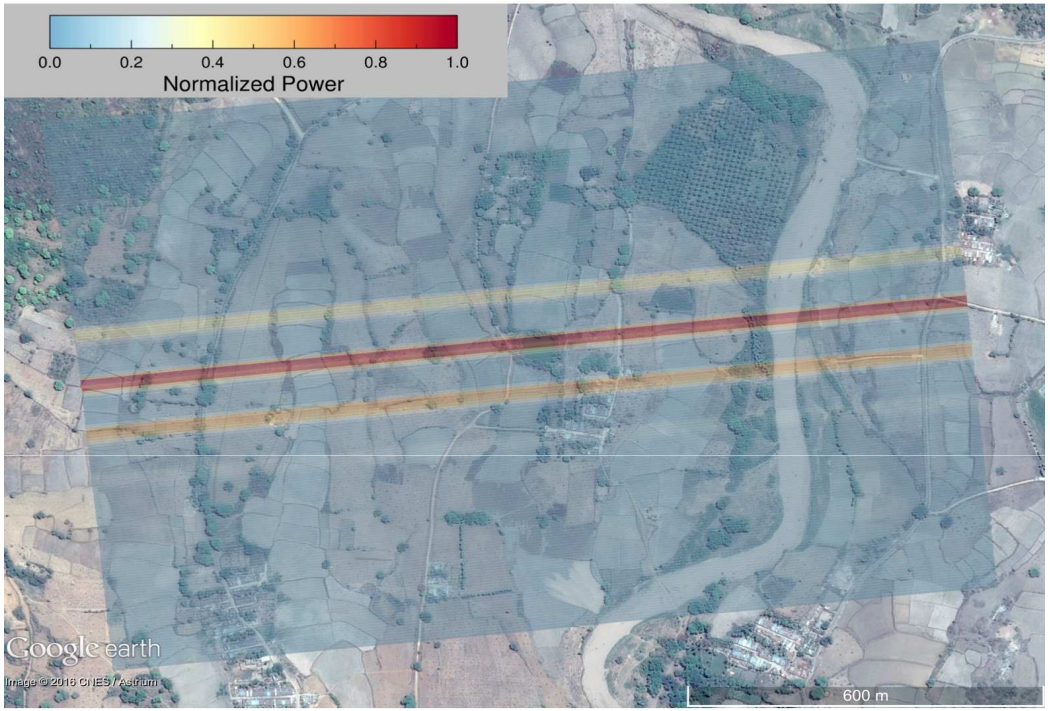
- The pond is clearly resolved in focused SAR Image
- Multiple Impulse responses (ghosts images) due to closed burst operation
- Along-track response could be improved by de-convolution techniques…
- Direct application on hydrology:
  - Better estimation of water levels
  - River mapping
  - Flood mapping



Fully-Focused SAR Response over the pond.
Normalized Power in color scale. Rectangles represent the FF SAR altimeter footprint, ~5 m along-track by ~1500 m across-track

Hydrology Applications

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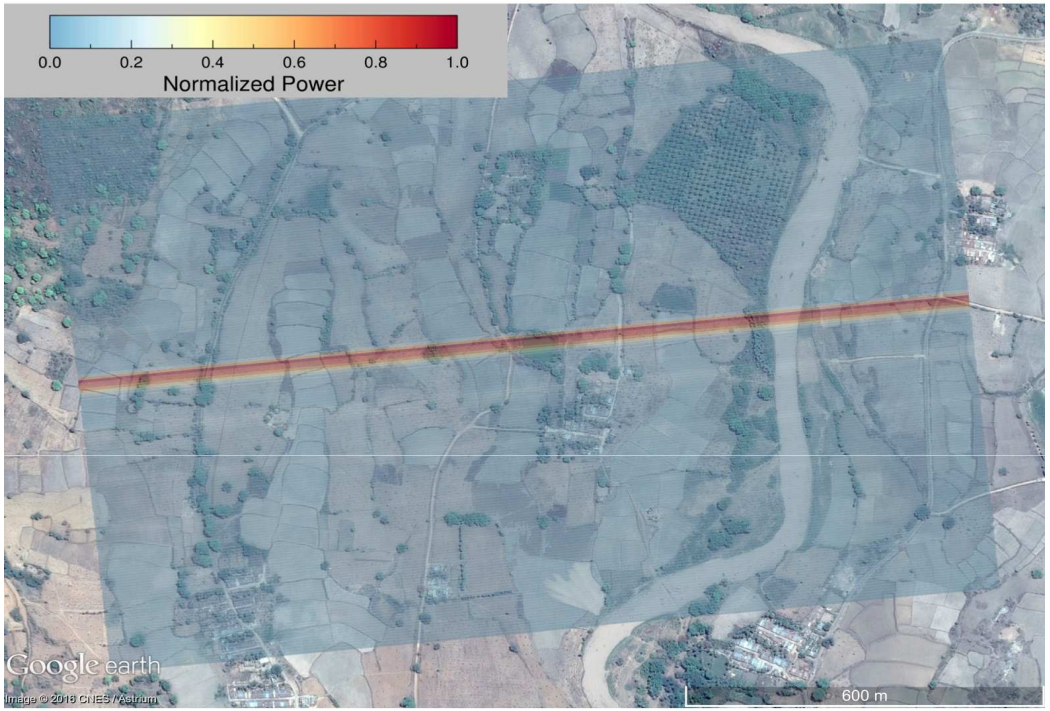
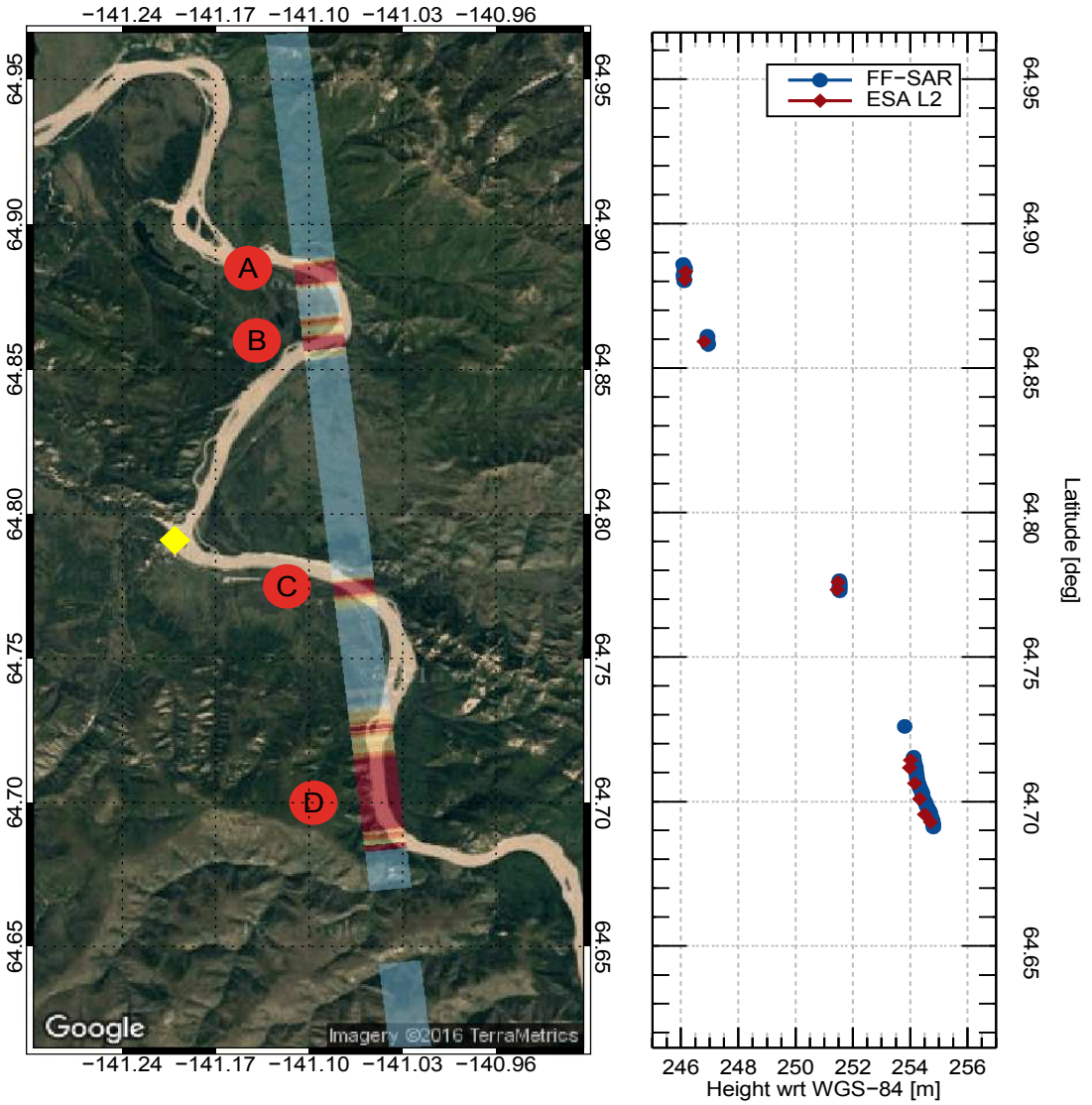


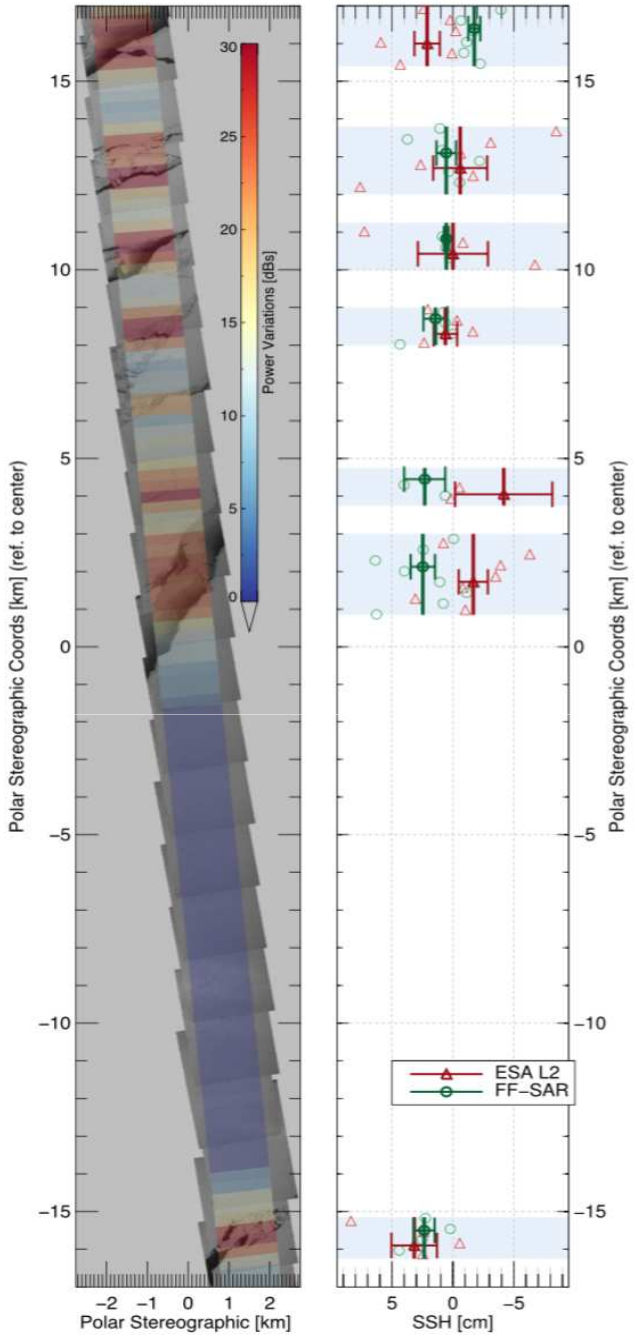
Fully-Focused SAR Response over the pond.
Normalized Power in color scale. Rectangles represent the FF SAR altimeter footprint, ~5 m along-track by ~1500 m across-track

Hydrology Applications

River Level Monitoring

- Fully Focused SAR and delay-Doppler processing applied to track crossing the Yukon River, Alaska, US, close to the Eagle Station, represented as the yellow diamond:
  - FF-SAR at 0.5 meters resolution
  - Multilooking at 80 meters.
- In the figure the CryoSat track is shown overlaid on the Google Earth image, with the waveform power in color scale.
- The height was estimated based on a simple primary peak retracker.
- The estimations are fully consistent with ESA L2 product but at a much higher resolution.





Sea-Ice Applications

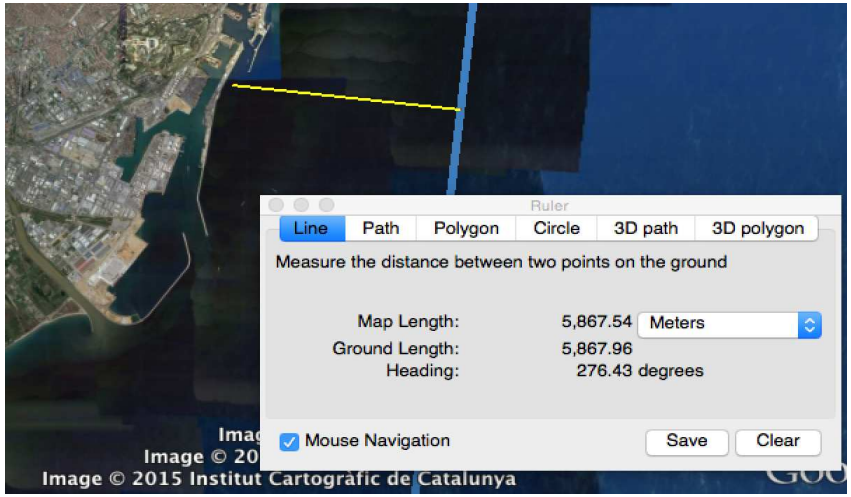
SSH Measurements from Sea-Ice Leads

- Fully Focused SAR processing applied to CryoSat-2 track over sea-ice, for a track coinciding with a NASA Ice-bridge Cryosat-2 under-flight.
  - FF-SAR at 0.5 m resolution
  - Multilooking at 320 m, to compare with ESA's L2 product.
- In the figure, the Digital Mapping System (DMS) data is shown, with the CryoSat-2 track overlaid. In color scale the FF-SAR power variations.
  - As observed, high power returns correspond to sea-ice leads locations; dynamic range > 30 dB
- The SSH measurements are computed from sea-ice leads, determined according to pulse peakiness and stack std:
  - significantly less noise than the ESA L2 product, as shown by errorbars (std of SSH per lead).
  - The error is reduced from 4.4 cm to 3 cm, corresponding to a factor of sqrt(2).

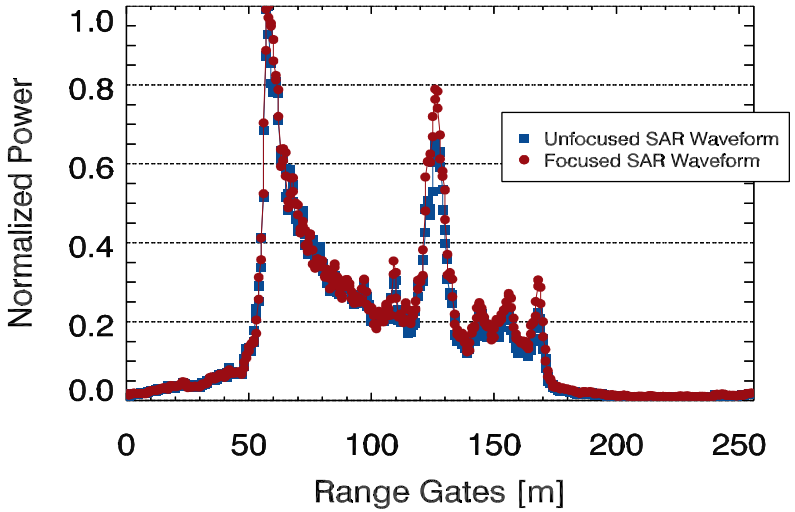
Coastal Applications –

~~Land Contamination Mitigation~~ …maybe not…

- Fully Focused SAR and delay-Doppler processing applied on track off the coast of Barcelona, Catalonia, Spain
- The idea is that after 2 seconds the ocean surface will be completely decorrelated, and all the remaining power will come from static and coherent targets from the ground…However…

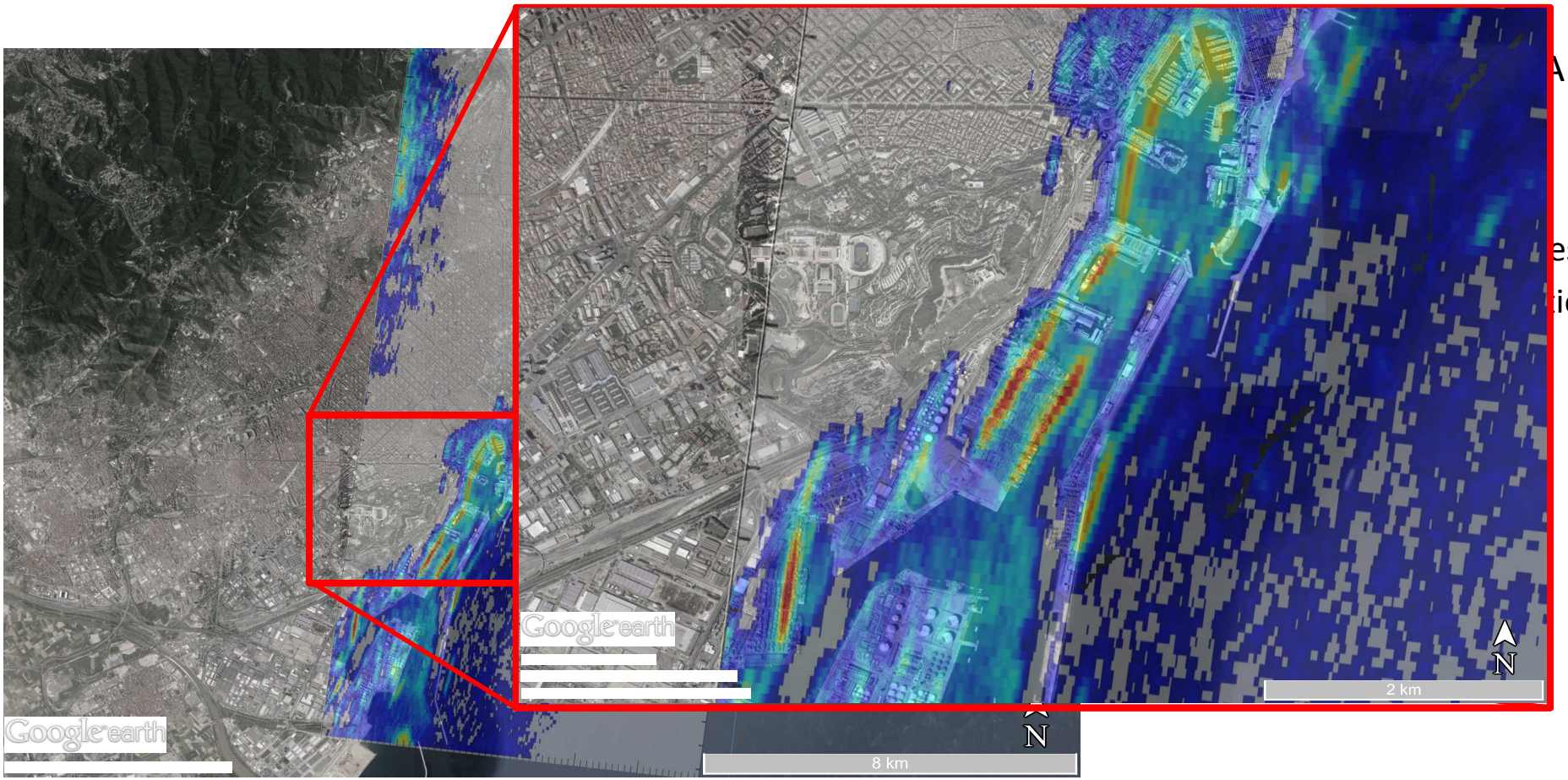


- Both delay/Doppler and fully-focused SAR waveforms have a similar behavior…
- Despite the coherent focusing for 2 seconds the sea return is still present in the waveform…
- …but why?
  - Shouldn't the surface of the ocean decorrelate after 2 seconds?
  - Could this actually be used to measure the ocean surface?
- What would be the performance of the fully focused SAR Altimeter over the ocean?



Coastal Applications

Coastal Mapping



AR

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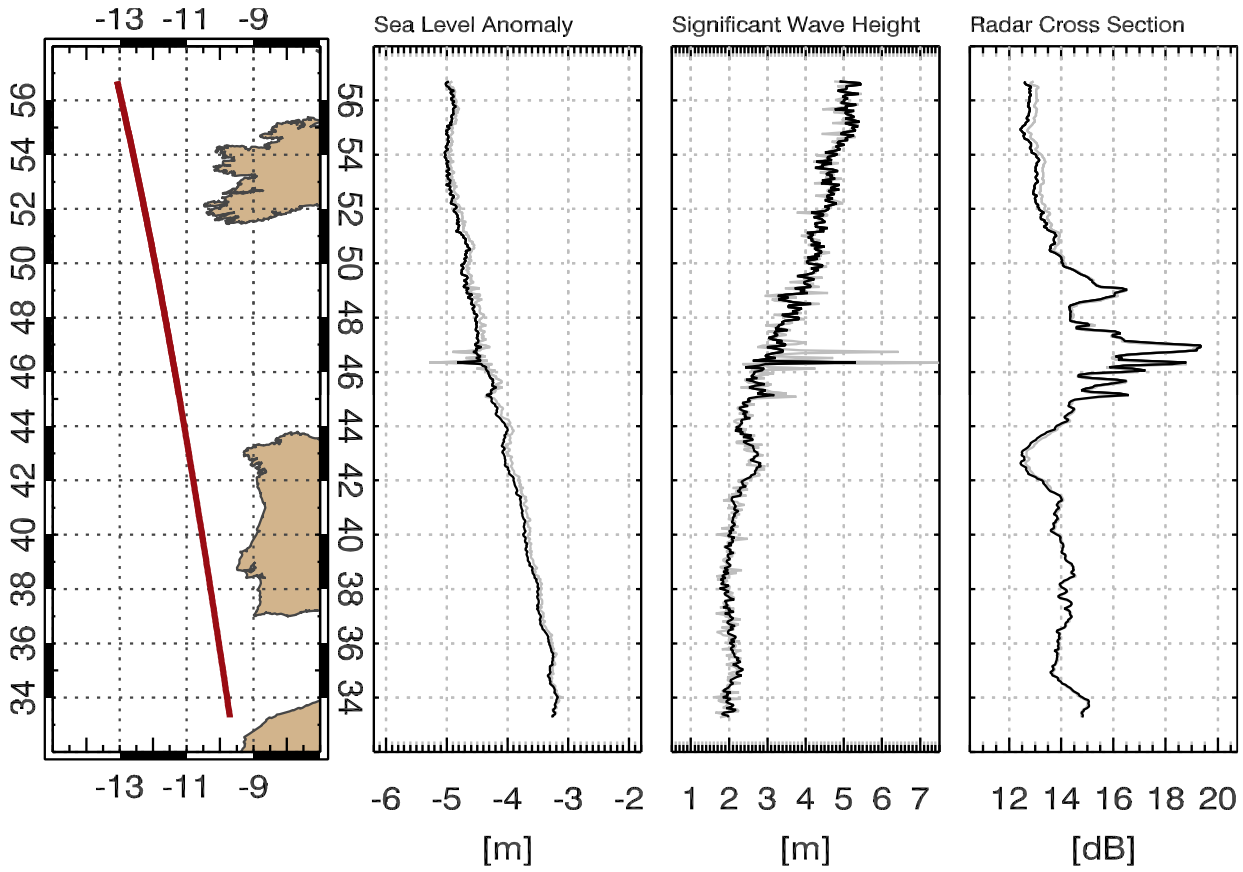
Could we think about a combined SAR altimeter & imager mission?

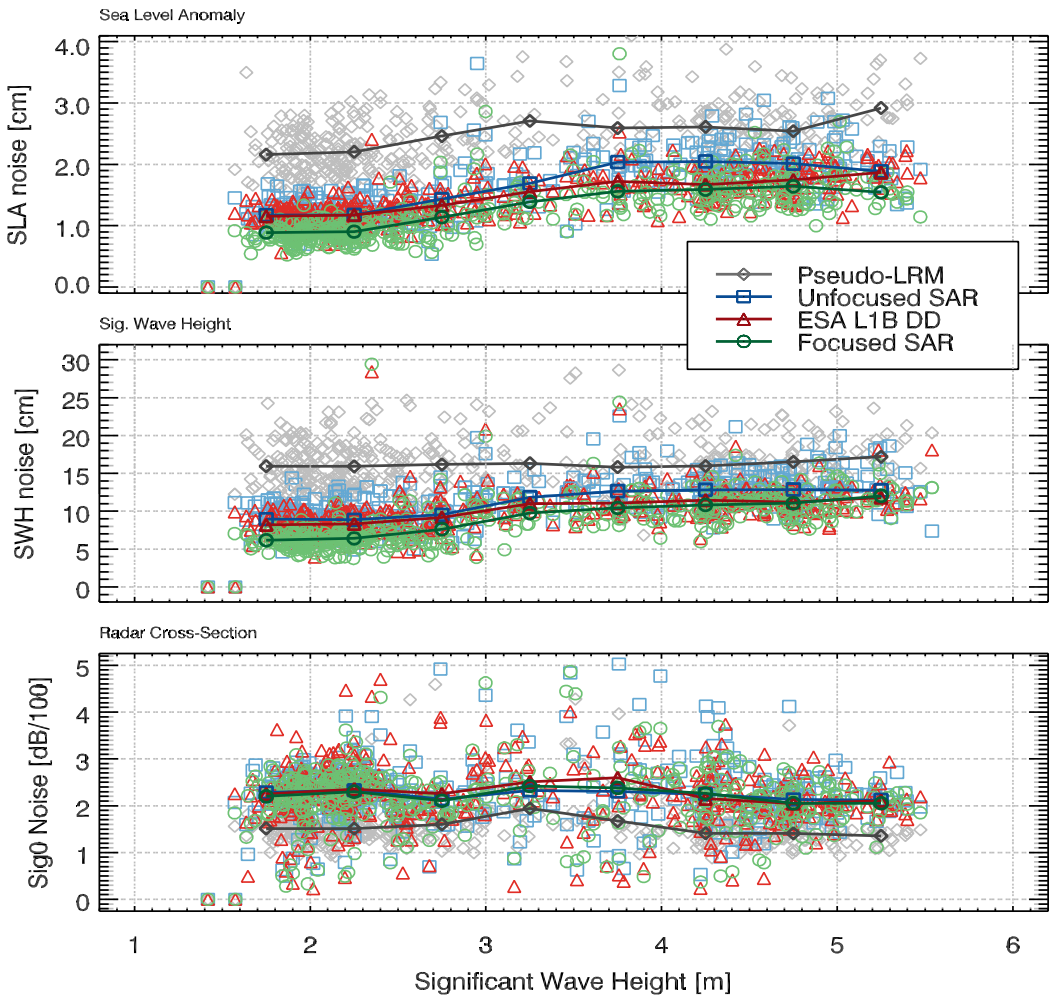
Open Ocean Applications

- CryoSat-2 SAR Mode track over North-East Atlantic.
- The panels show the satellite track and the geophysical parameters retracking results for both PLRM (in gray) and fully-focused SAR data (in black) at 1 Hz.
  - The geophysical parameters were obtained with a MLE3 retracker for PLRM (as done for RADS), and with a modified SAMOSA retracker for FF-SAR.
- These results show that FF-SAR Altimetry can provide consistent estimations of SSH, SWH and sig0
- So what is the performance…?



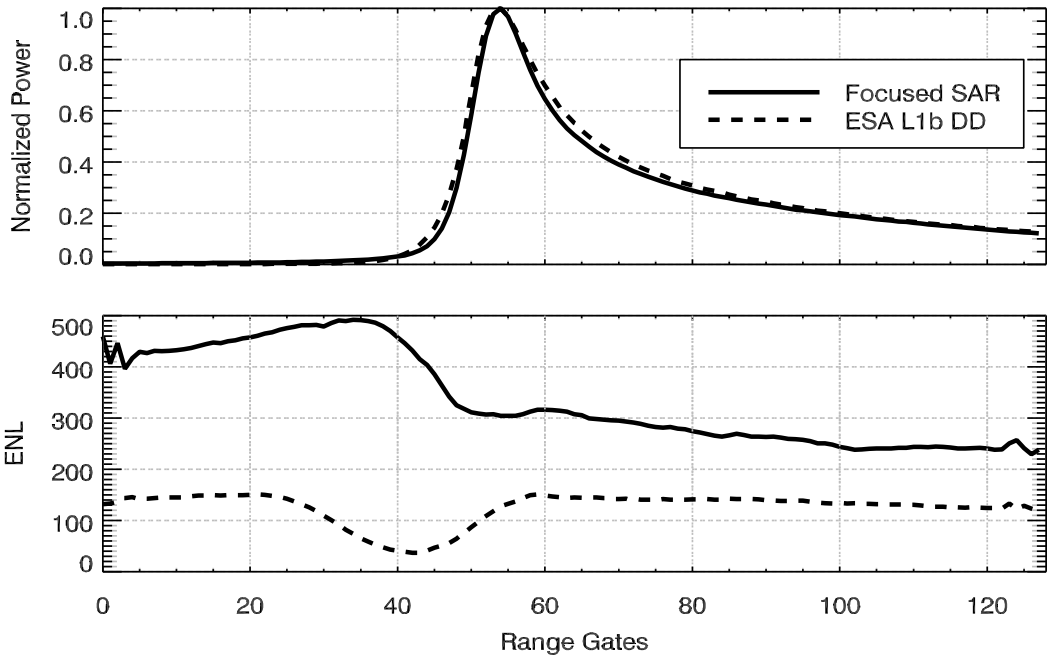
Open Ocean Applications

- Performance estimation of geophysical parameters by different processing approaches.
  - 1 Hz noise estimates of geophysical parameters
- The Fully Focused SAR shows an improvement of sqrt(2) wrt unfocused SAR in the estimation of SSH and SWH:
  - For SSH, from ~1.2 cm 1Hs error for DDA L1b @ 2m SWH to 0.78 cm for FF-SAR.
- An improvement in the performance leads to:
  - Less noise with the same resolution
  - Better resolution with the same noise
- The reason for the performance improvement is linked to an increase in the number of independent looks of the surface.



Open Ocean Applications

- As mentioned before...the performance improvement of geophysical parameters comes from the increase of Effective Number of Looks
- This is thanks to the (partial) independency of the single looks processed with the full aperture.
  - Figure showing FF-SAR and ESA L1b (DD) averaged waveforms for ~30 seconds and
  - 20 Hz ENL for both FF-SAR and ESA L1b



- The ENL of the multilook FF-SAR waveform increases by a factor of 2 wrt ESA L1b DD leading to the sqrt(2) improvement in the estimation of geophysical parameters
- However, this is not as large as if they were completely independent (300 m / 0.5 m = 600) due to:
  - CryoSat's Closed Burst Mode (lacunar sampling), that leads to the side lobes of the AT-PTR, but this will be different in Sentinel-6/Jason-CS with the interleaved mode

Conclusions

- Development of both unfocused delay/Doppler and fully focused SAR L1 processor
  - Measured along-track resolution in agreement with theoretical expectations, i.e. ~0.5 meters
  - Direct application on hydrology, sea-ice, and open ocean.
- For hydrology and sea-ice applications the FF-SAR shows a much better capability to sample the surface thanks to its improved along-track resolution…
- and for oceanographic applications, the focused SAR multi-looked waveforms @ 1 Hz show an increase in the ENL by a factor of 2 with respect the delay/Doppler processing.
  - Improvement by a factor of sqrt(2) @ 1Hz wrt DDA:
  - SLA noise @ 1Hz around 0.75cm (conservative)
- Detailed description of technique in [1]:
  - A. Egido; W. H. F. Smith, "Fully Focused SAR Altimetry: Theory and Applications," in *IEEE Transactions on Geoscience and Remote Sensing* , vol.PP, no.99, pp.1-15, doi: 10.1109/TGRS.2016.2607122
- Huge amount of work still remains to be done in the field of FF-SAR…