→ 10th COASTAL ALTIMETRY WORKSHOP

SAR Altimetry Training Course

Fully focused SAR processing

Walter H. F. Smith and Alejandro E. Egido

21–24 February 2017 | Florence, Italy

Acknowledgements

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- We thank the Svalbard and Crete transponder teams.
- We thank Rob Cullen, Marco Fornari, Keith Raney, Laurent Rey, Mònica Roca, Duncan Wingham, Ron Abileah and others for stimulating discussion.
- Some figures here are taken from:

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING

Fully Focused SAR Altimetry: Theory and Applications

Alejandro Egido, *Member, IEEE*, and Walter H. F. Smith

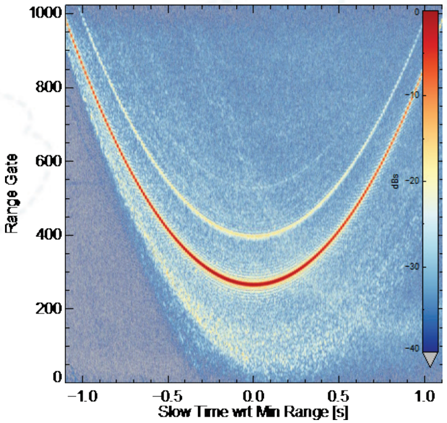
Questions this talk cannot answer:

- What new coastal ocean physics can you see with fully-focused SAR (FF-SAR) altimetry that you cannot see by other altimetry techniques/processing?
  - Our research underway now seeks to answer this.
- When can you give us a complete FF-SAR data set so we can explore it and see for ourselves what it can do?
  - We hope to get there at some point. Please tell us which areas / events / times you want to look at.

Questions this talk aims to answer:

- How is fully focused SAR different from unfocused (delay-Doppler) SAR altimetry?
- What does it mean to “focus” on a pulse-limited area of a rough surface like the ocean? Doesn’t the ocean surface move (de-correlate) while you are looking at it? How can it be in “focus”?
- Isn’t it still pulse-limited across track?
- Why is this useful or worth doing?

Radar range and radar phase



As a radar flies over a fixed point on the Earth, the range (one-way distance) to that point changes from echo to echo. Looking through the instrument's range window at a sequence of pulse echoes, the ground point traces a parabolic trajectory. The total time that the point is "visible" to the radar, T_{vis}, depends on how long the point stays in the window. For CS2 & S3, T_{vis} is ~2 seconds for points near the ground track.

The phase of reflections from that ground point also evolves from echo to echo.

The rate of change of phase reveals a Doppler frequency for that ground point.

Incoherent processing exploits echo power only, ignoring echo phase. It maps a point on the ground to one coordinate only: range.

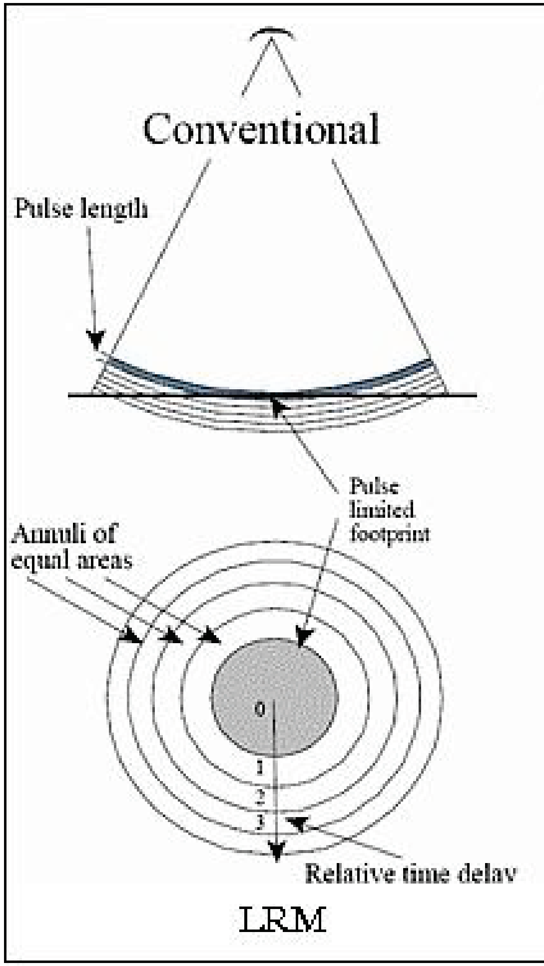
Coherent processing exploits both power and phase through a sequence of echoes. It maps a point on the ground to two coordinates: range and Doppler.

[Details: The range that appears in the range window is not the geometrical range because Doppler shifts alter apparent range in an FM-chirped radar. Our fully focused technique accounts for this and uses a higher-order description of phase evolutions.]

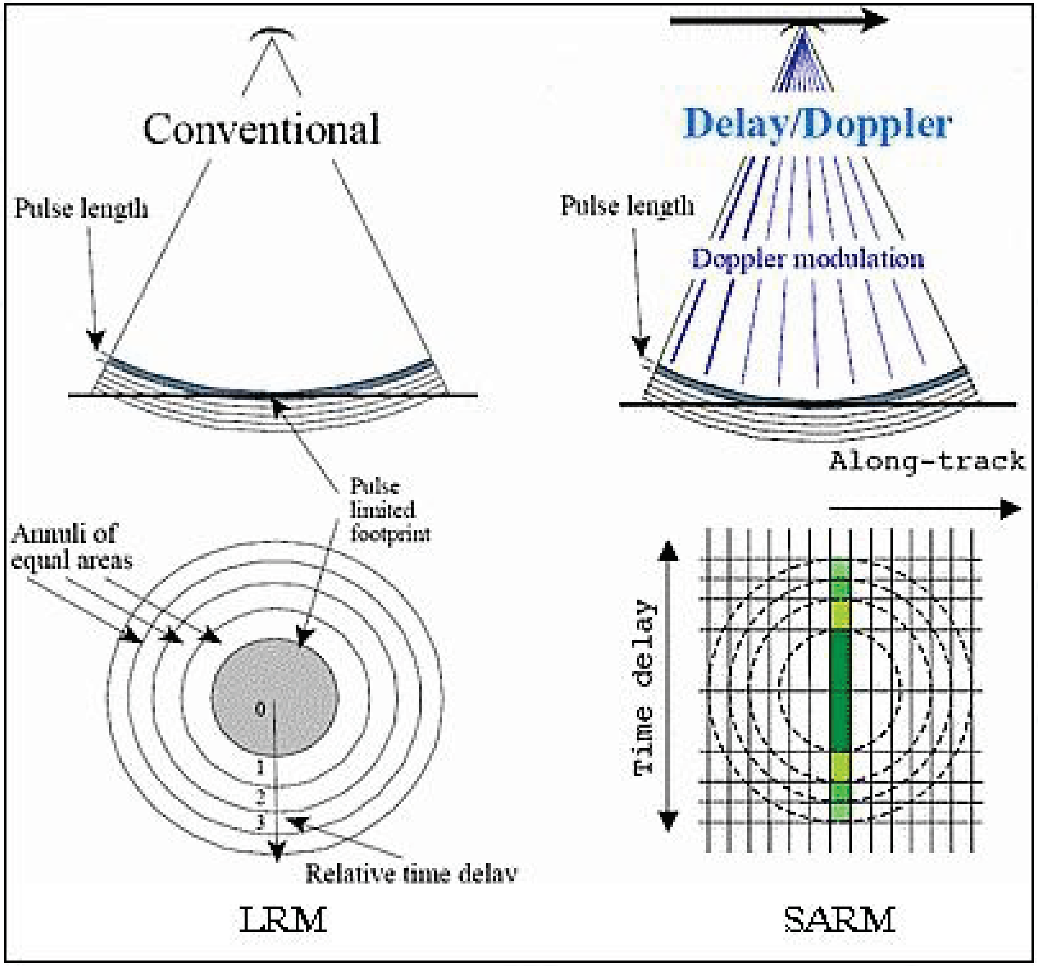
Conventional (incoherent) altimetry

Assumption: the ocean is a “very rough” surface (RMS height greater than radar wavelength) with many random points scattering radar energy. Total pulse echo is the sum of many random point echoes, each with unknowable random phase. Therefore, averages power incoherently, ignoring phase.

Incoherent averaging is circular; insensitive to wind/wave direction; footprint areas are circles of 1 km in radius or more.



Coherent altimetry



Coherent processing exploits echo-to-echo phase changes to map reflector position to Doppler frequency.

Resulting “Doppler beam sharpening” can slice the reflecting area into zones.

These zones remain pulse-limited across-track but the along-track resolution is limited by Doppler resolution.

Increasing the coherent processing time increases the sensitivity to Doppler, narrowing the width of the Doppler beams.

Coherent altimetry, unfocused

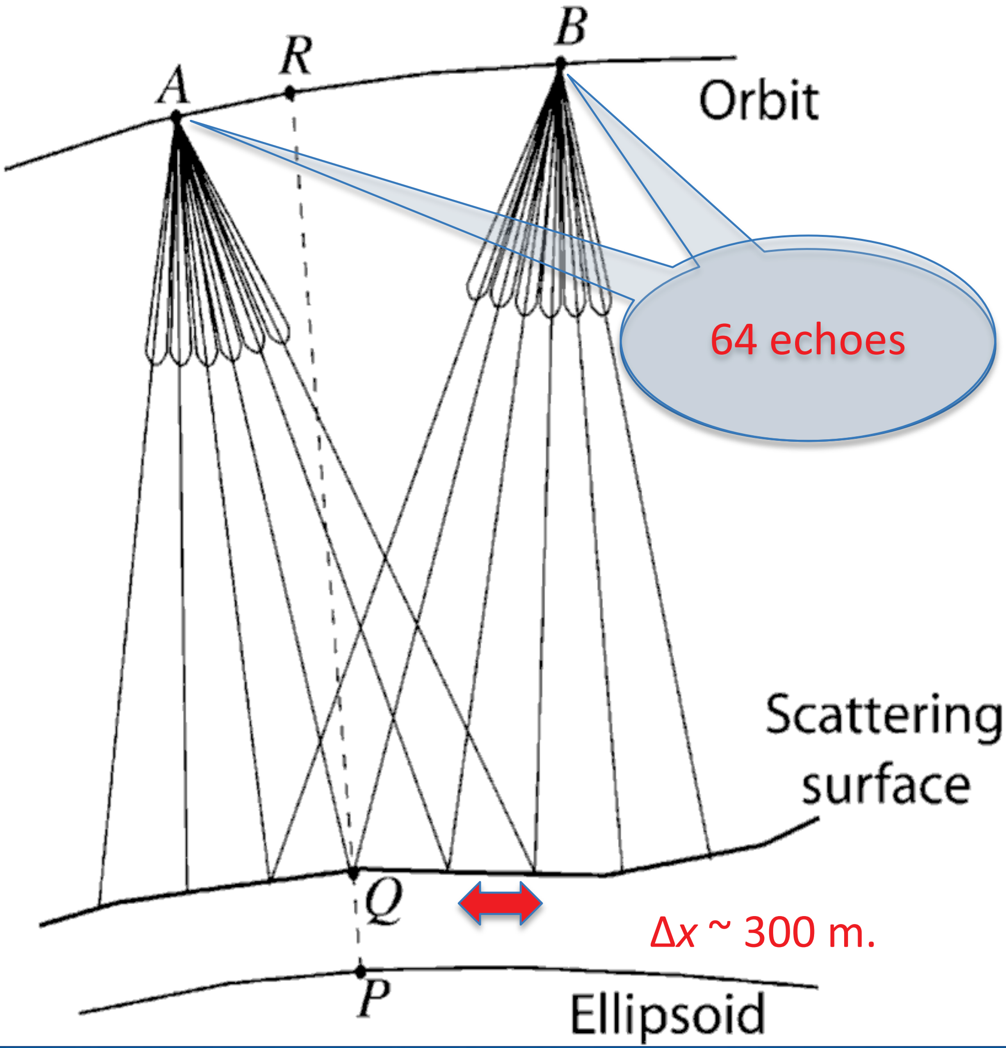


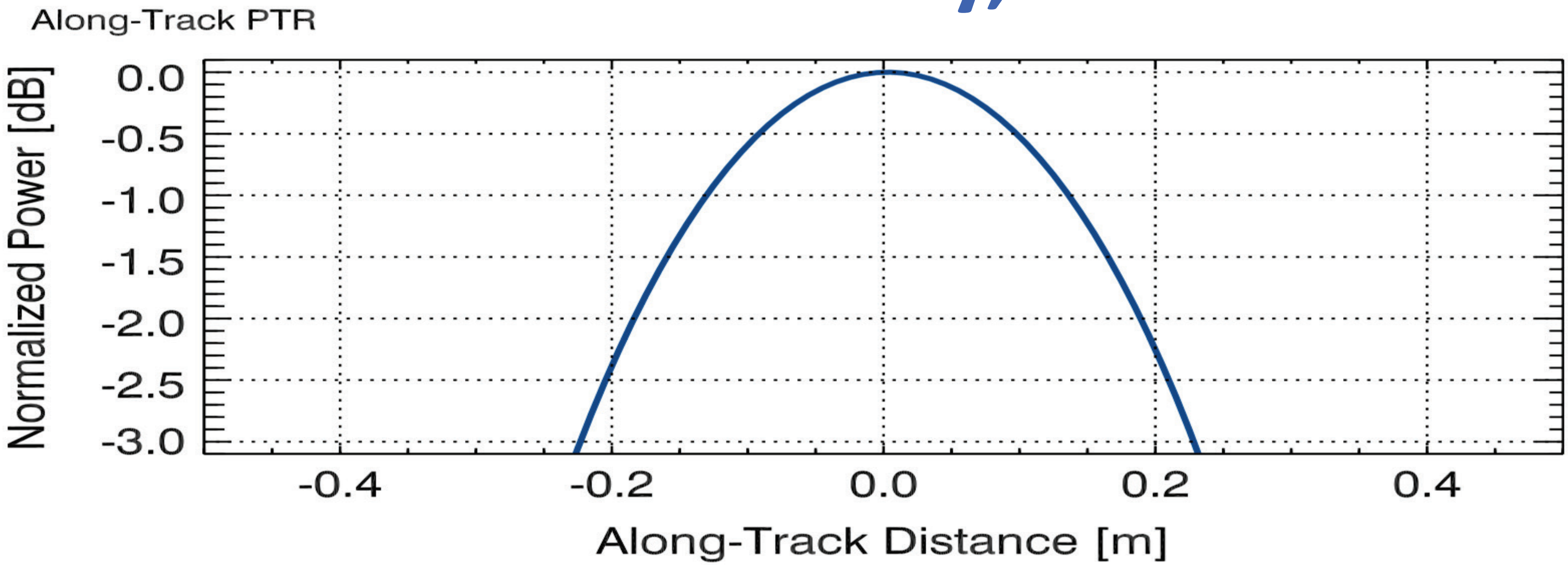
Figure from Wingham et al., 2006, the "multi-looked SAR mode" (also called "Delay/Doppler" [Raney, 1998]) used for Cryosat and Sentinel-3 L1b products applies coherent processing only intra-burst (only 64 echoes at a time, 3.52 msec, ~26 m of aperture). Doppler resolution is $(3.52\ \text{ms})^{-1} = 284$ Hz.

The resulting Doppler beams sample along-track position to Δx ~= 300 m (resolution is ~400 m if Hamming window is applied before along-track FFT, else ~300 m).

Since Δx >> first Fresnel zone, this approach is unfocused [Raney, 2007].

We call this "unfocused SAR".

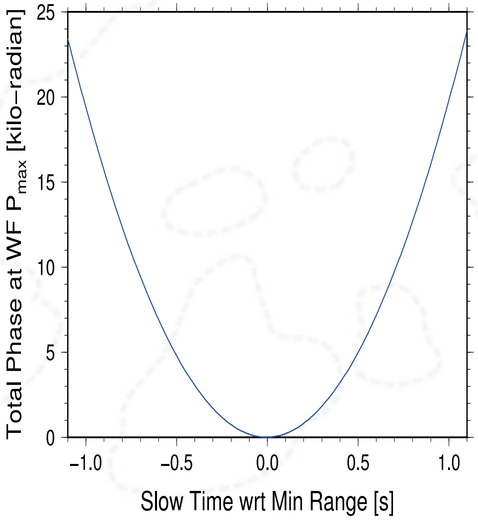
Coherent altimetry, focused



The full time of visibility of this point has been used, $T_I = T_{vis}$, so Doppler resolution is about (2 seconds)$^{-1}$ = 0.5 Hz.

This is an image of CryoSat SAR FBR data taken while flying over the Svalbard transponder on 6 May 2014.

Moving the focal point along-track by a fraction of a meter changes the coherently integrated power. The power is reduced to half-maximum at a full-width along track of 0.45 m.

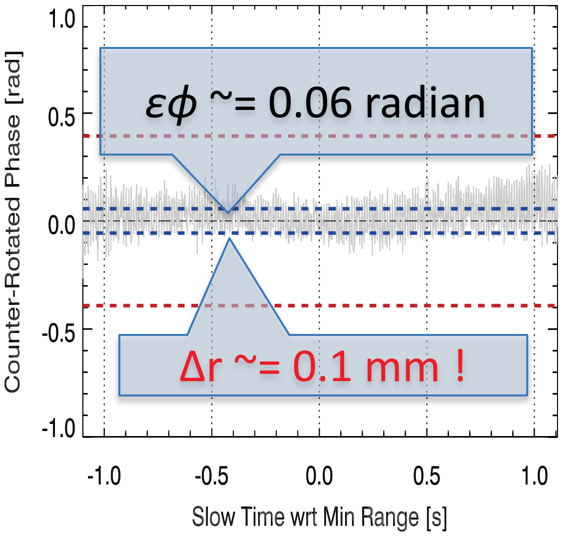


Phase Unwrapping Correction

Phase varies with range as $\Delta\phi = 4\pi\Delta r/\lambda$, to 1st order.

Since Δr ~= 45 m, λ~= 22 mm, $\Delta\phi$ ~ 4000 x (2π).

Unwrapped phase RMS error $\varepsilon\phi$ ~= 0.06 radian. $\varepsilon\phi / \Delta\phi$ ~= 2×10^{-6}. $\varepsilon r = \lambda(\varepsilon\phi)/4\pi$ = 0.1 mm !

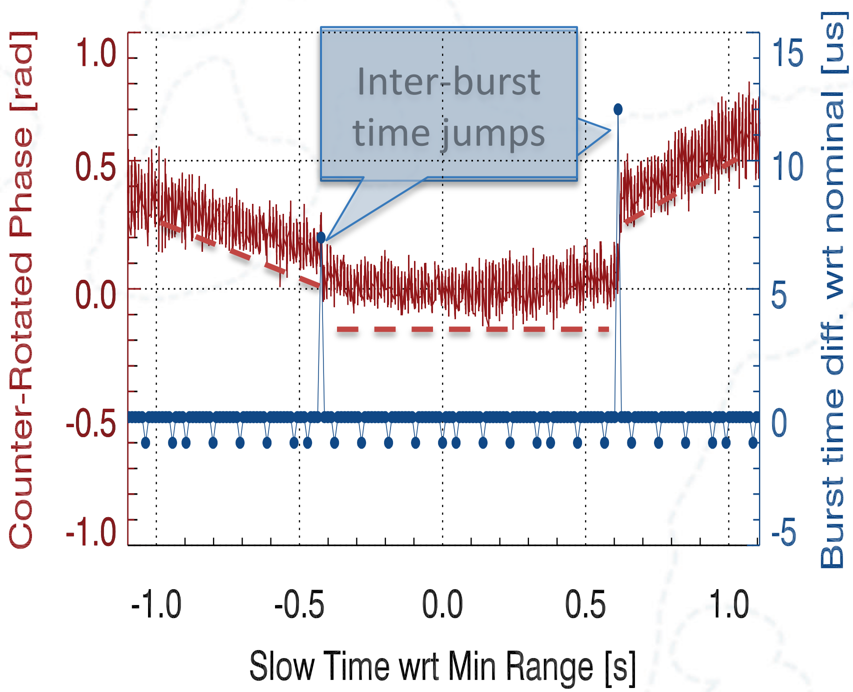


If the FF-SAR calculation employs the maximum possible aperture length ($T_I = T_{vis}$) then it must undo phase changes of the order of 4000 cycles of 2π. After doing this, the residual phase error in each pulse echo is about 0.06 radian, only 2 parts per million of the total change in phase occurring across the aperture. (FF-SAR requires a theory of phase more accurate than just the first-order effect. We account for higher-order effects.)

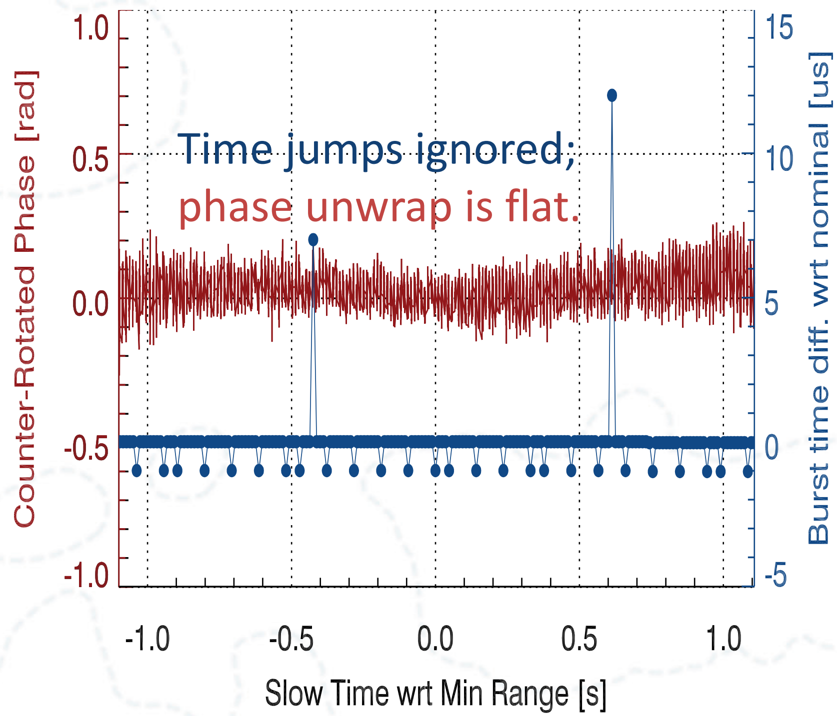
RMS phase error 0.06 radian implies RMS range error ~0.1 mm ! (Also power SNR = 21.4 dB.)

FF-SAR is wonderfully sensitive to range. (Good!) However, this means sensitivity to small errors in datation & position. Note: GDRs usually give height to 1 mm, horizontal position to ~0.1 m, time in floating point Y2k seconds. (Bad!)

Using burst datation in FBR



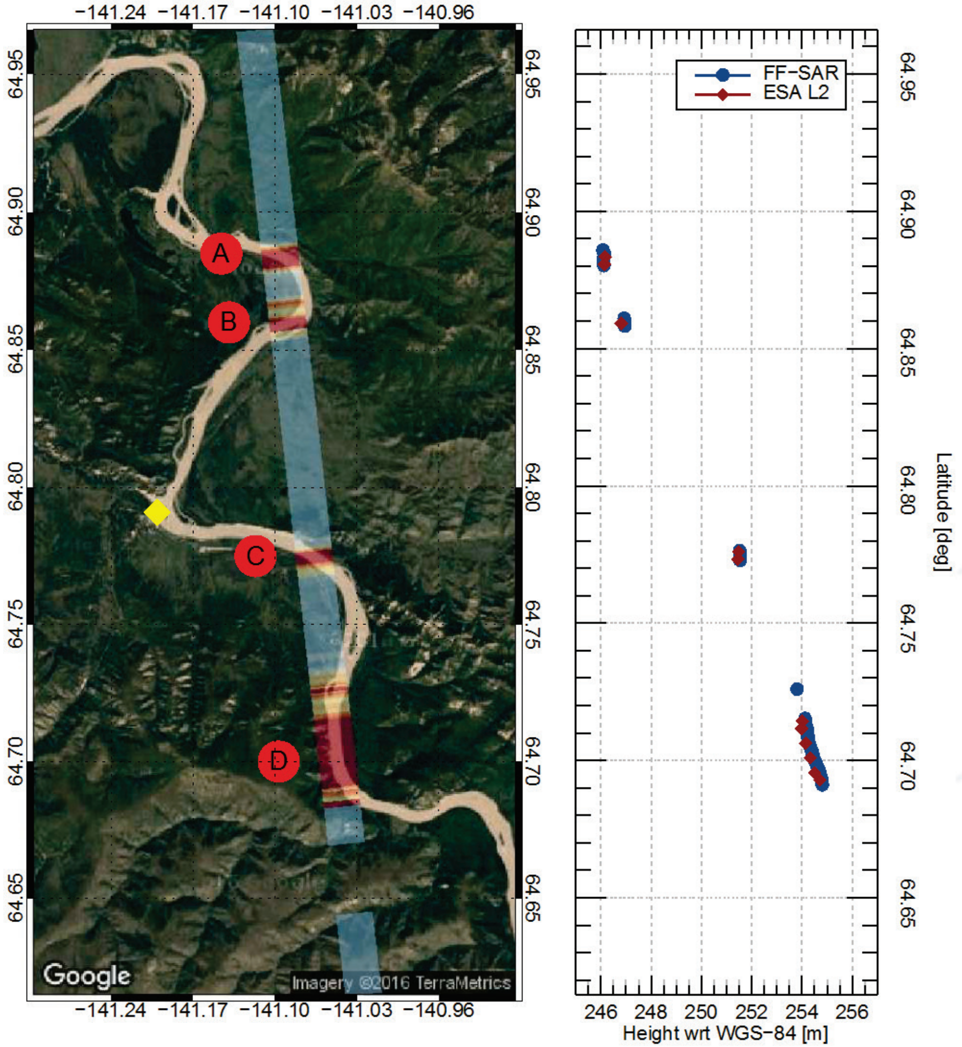
Assuming steady burst rate



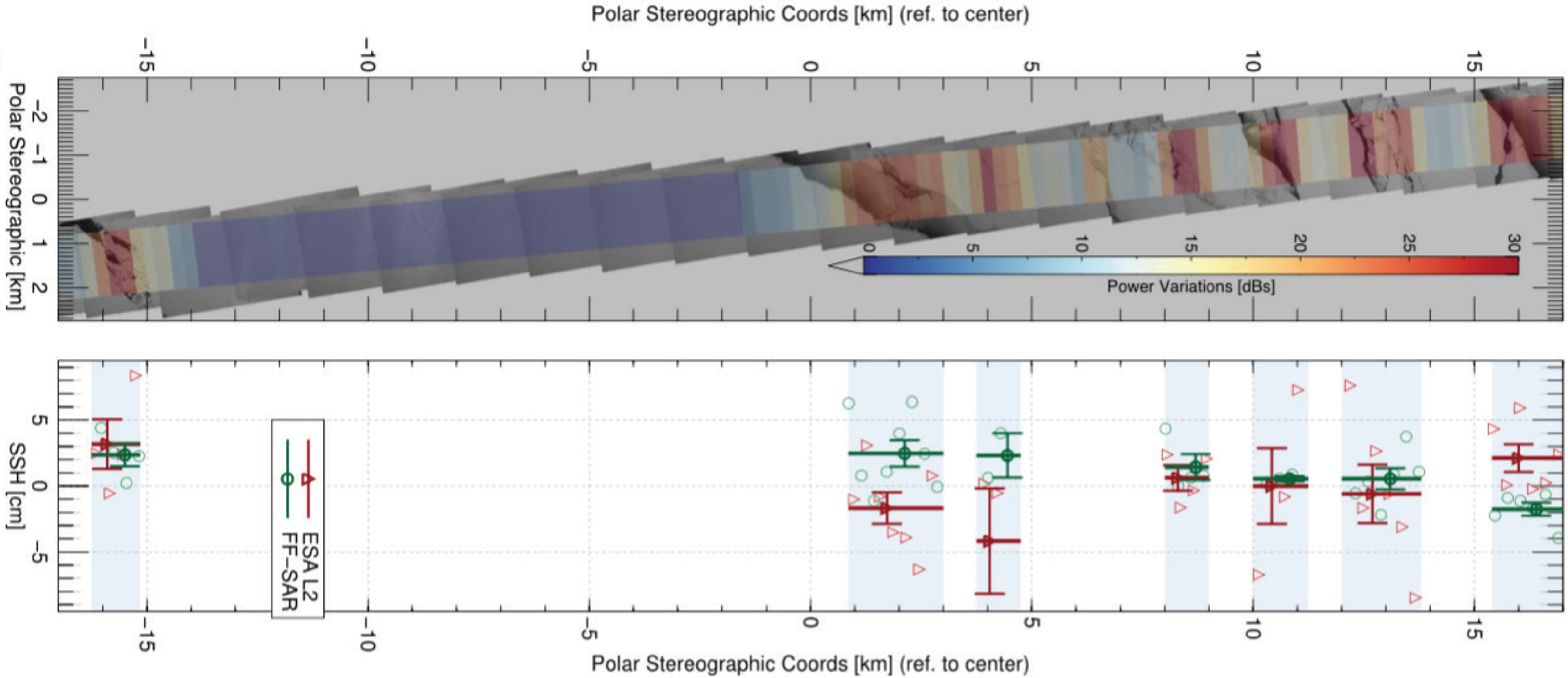
Datation errors of a few microseconds are enough to spoil focus. FF-SAR over a transponder proves that the radar is running steadily even when the datation in the data product shows a jump of a few micro-seconds. To achieve optimal focus we had to correct the datation.

Hydrology Applications

- Yukon River, Alaska, US
- The FF-SAR technique detects the enhanced backscatter when water is in the footprint and gives river height measurement comparable to the ESA L2 product.



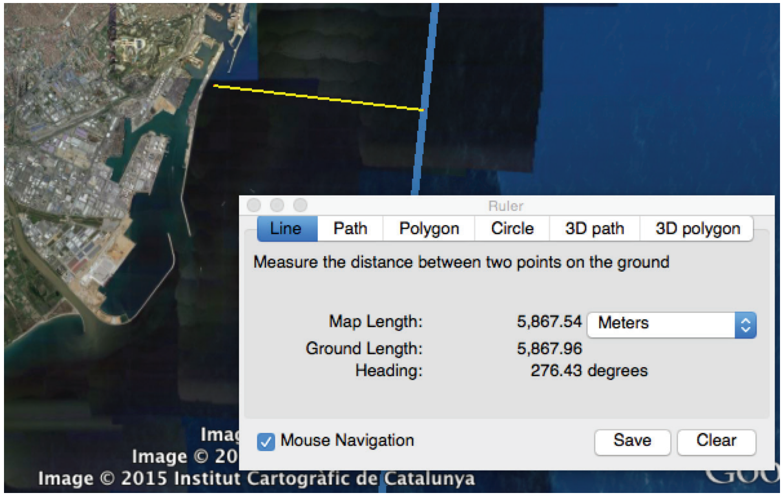
Sea-Ice Applications



FF-SAR detects leads in sea ice and measures sea level in leads more precisely than the ESA L2 product.

Coastal Applications

- Fully Focused SAR and delay-Doppler processing applied on track off the coast of Barcelona, Catalonia, Spain
- We initially supposed that after 2 seconds the ocean surface would be completely decorrelated, and all the remaining power would come from static and coherent targets from the ground. Therefore we thought FF-SAR would allow us to separate coherent and incoherent targets in the scene, and this would be valuable at the coasts.



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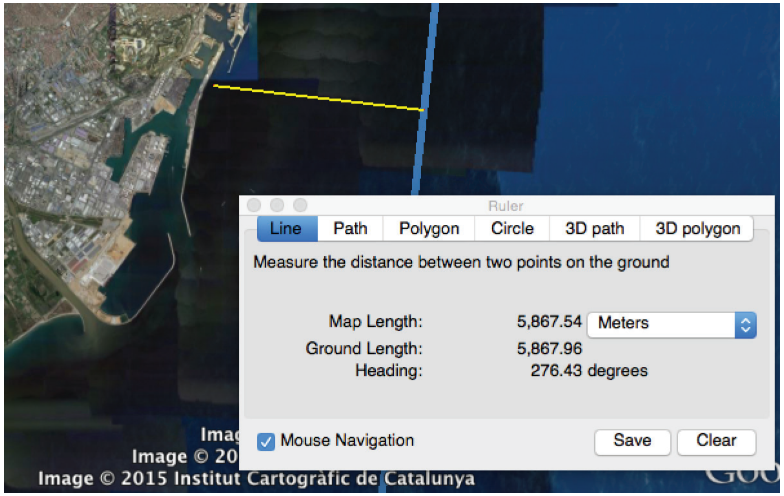

- Both delay/Doppler and fully-focused SAR waveforms have a similar behavior…
- Despite the coherent focusing for 2 seconds the sea return is still present in the waveform…

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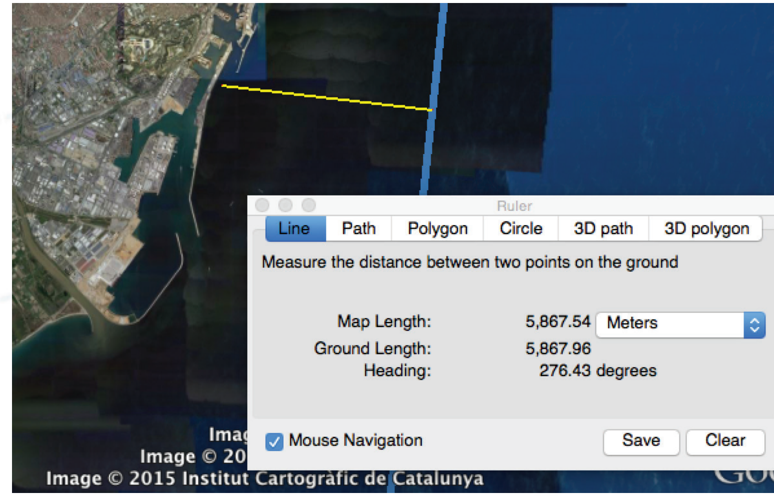
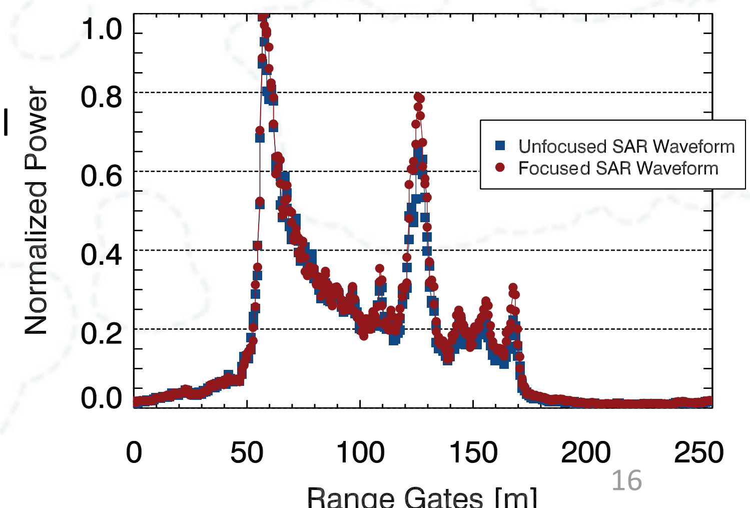
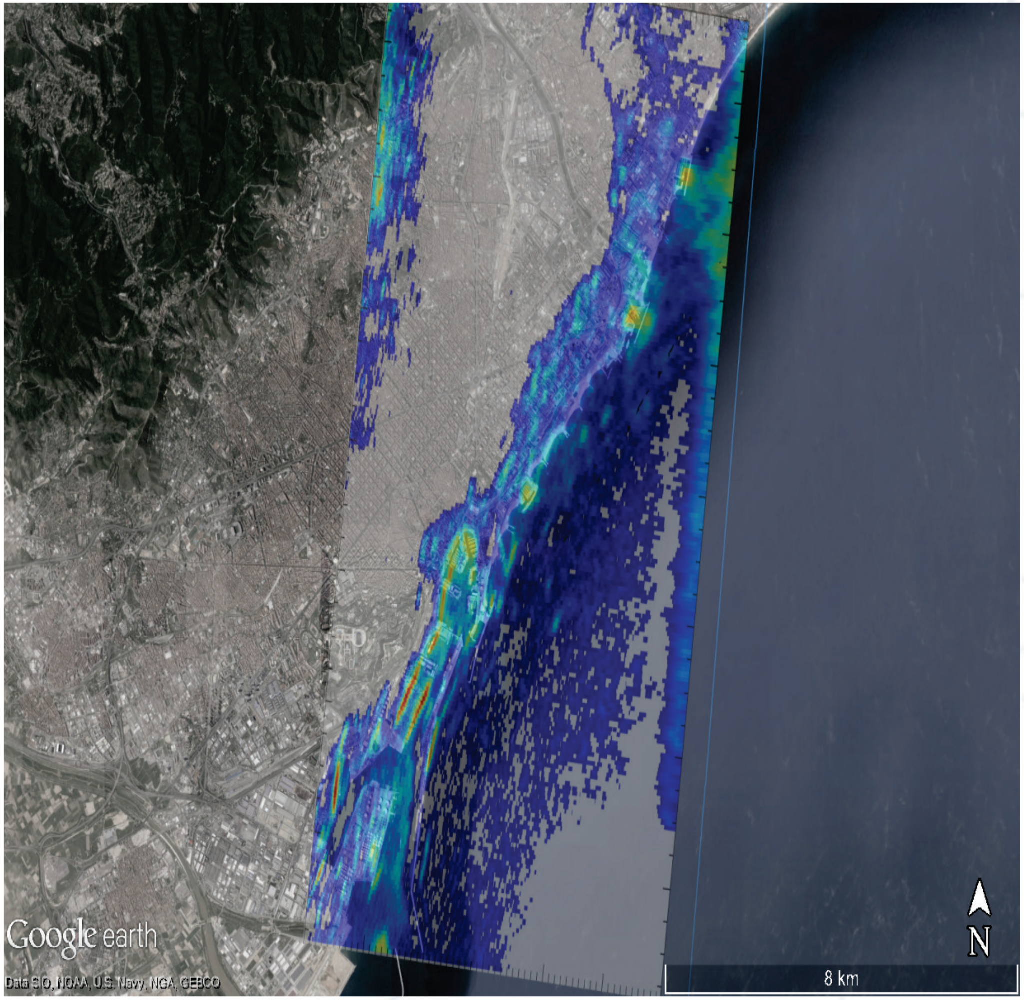


- Both delay/Doppler and fully-focused SAR waveforms have a similar behavior…
- Despite the coherent focusing for 2 seconds the sea return is still present in the waveform…
- …but why?
  - Shouldn’t the surface of the ocean decorrelate after 2 seconds?
  - Could this actually be used to measure the ocean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



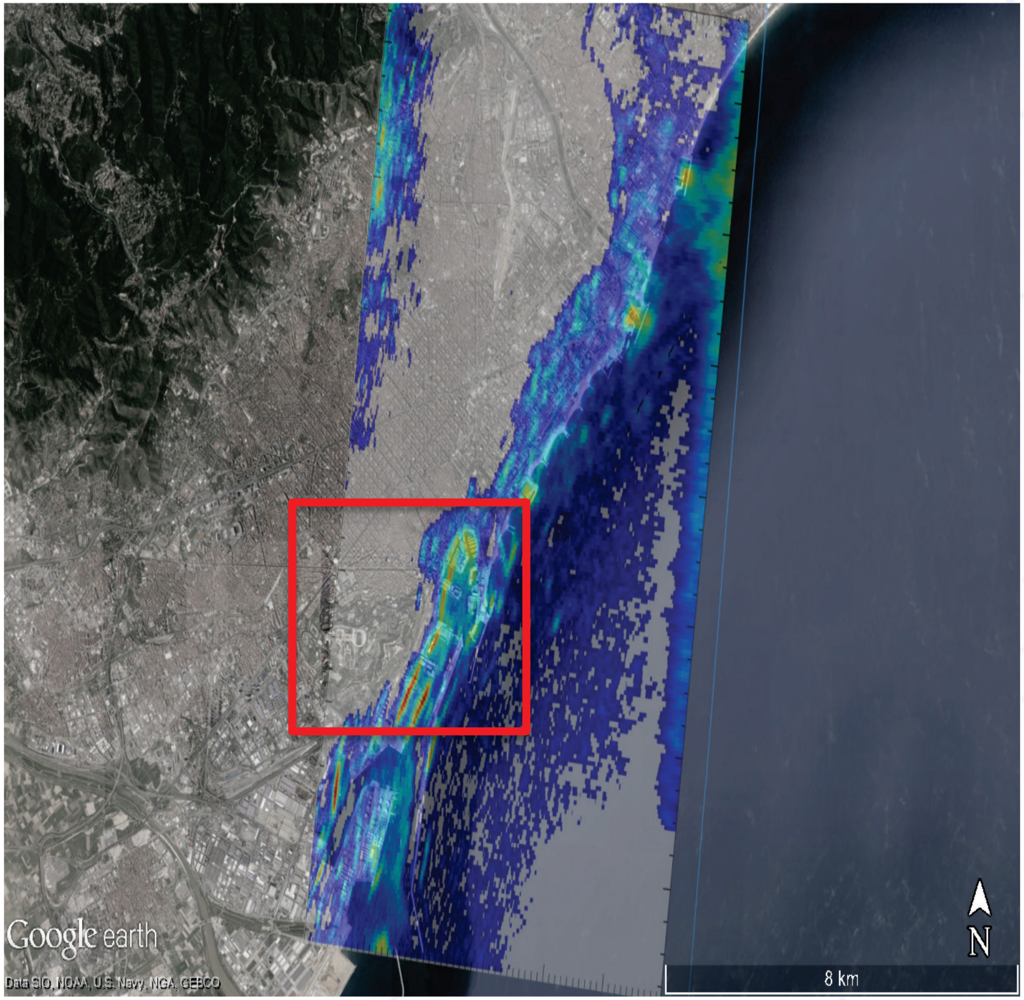
Coastal Applications



CryoSat-2 Fully focused SAR "Image" off the coast of Barcelona, Spain

- 2 seconds coherent processing ~ 0.5 m along-track resolution
- Multi-looking @150 m

Coastal Applications



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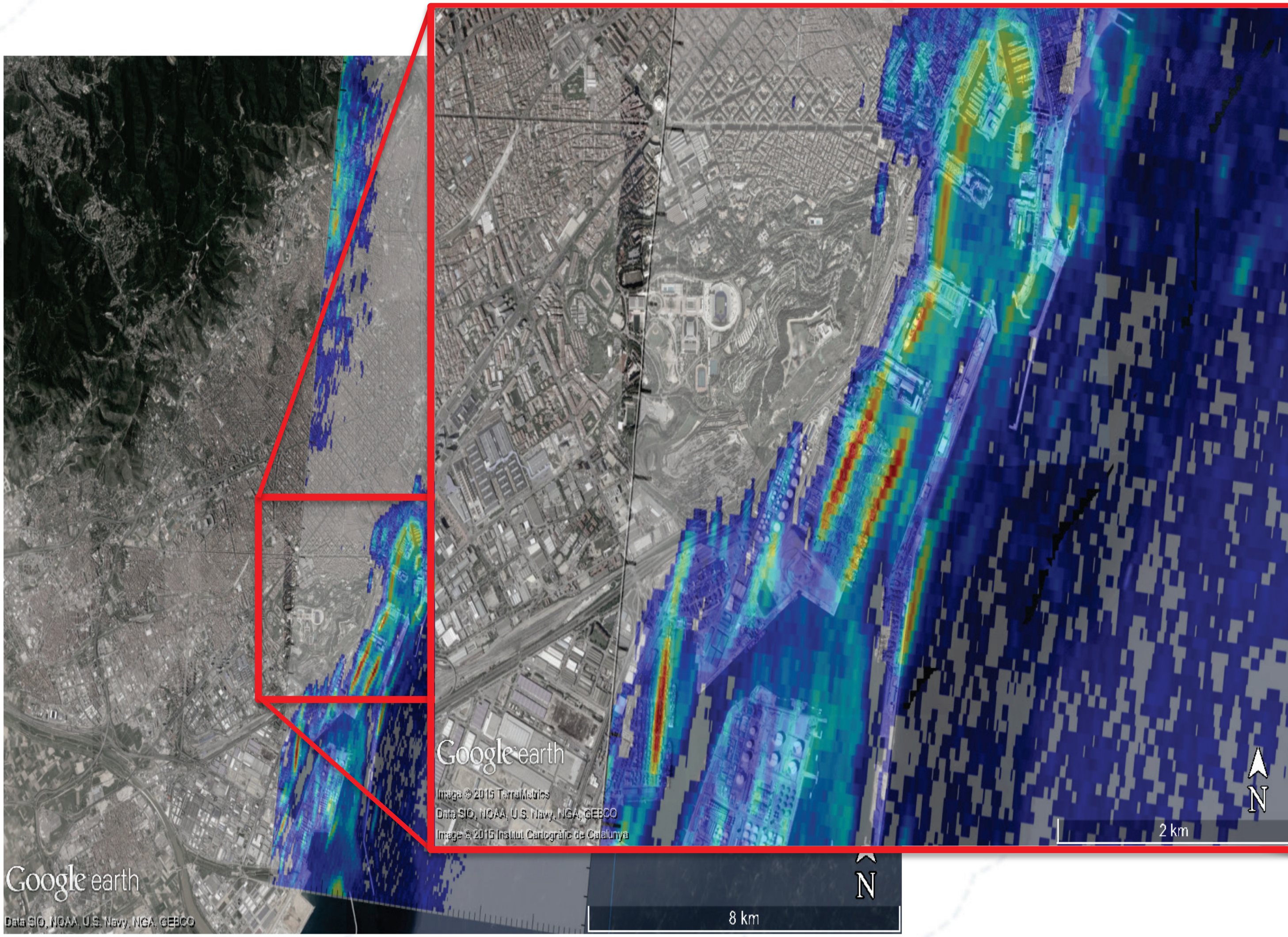

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So how can the ocean give an FF-SAR echo?

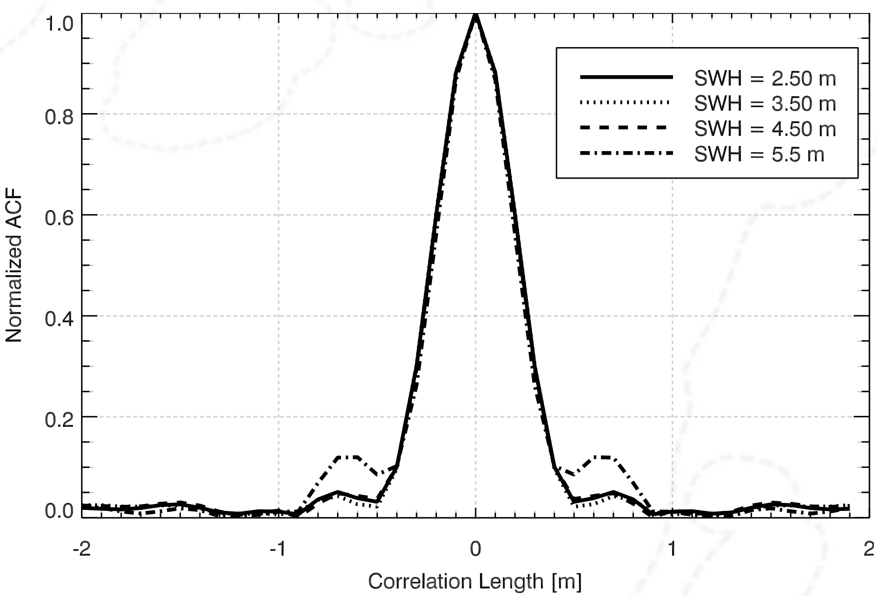
The ocean is “very rough”, meaning (SWH/4) >> λ, so in each pulse echo the power and phase each are independent random variables, and each echo is a realization of “speckle noise”. The surface is also in motion, and may move enough to decorrelate to Ku λ in ~4 msec.

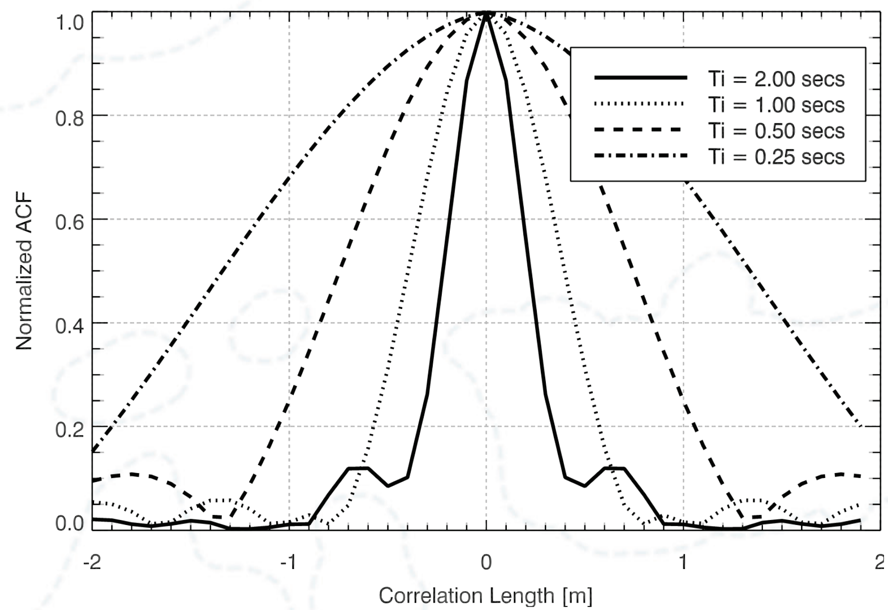
So what happens when we do FF-SAR over the ocean?

The answer is empirical: each 0.5 m along track gives a statistically independent realization of random noise, corresponding to an independent Doppler-sharpened “look” angle.

Along-track correlation of ocean speckle in FF-SAR

Speckle noise power fluctuations decorrelate as the focus point moves a distance determined by the Doppler resolution. This length is independent of SWH (left) but depends on coherent integration time, T_i, (right). For T_i = 2 s the speckle decorrelation scale is ~0.5 m and resembles the transponder point target response.

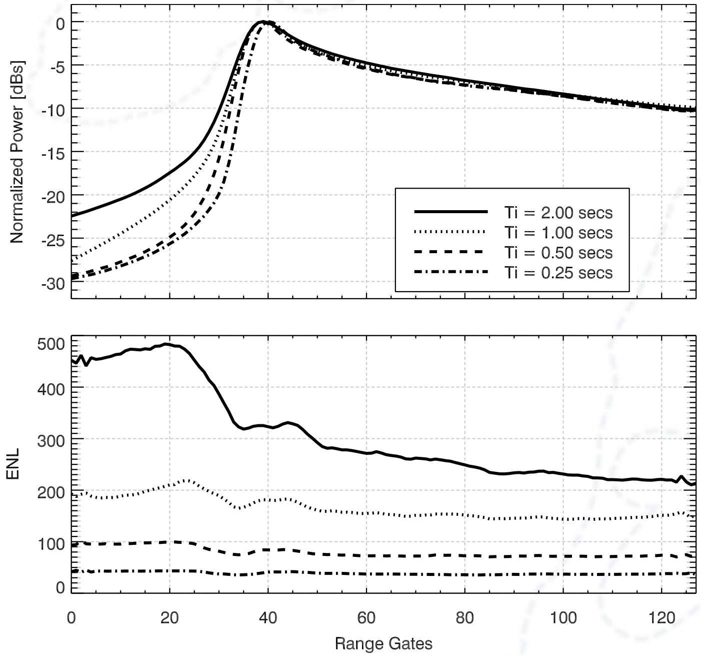




Thus FF-SAR can get statistically independent looks at the ocean every ~0.5 m along track, or ~13,500 per second. [Almost. The lacunar sampling of closed burst mode causes some small degradation in this, by introducing small side lobes in the along-track PTR.]

FF-SAR "multi-looked" to 20 Hz rate.

To compare the FF-SAR waveform to the CryoSat2 Level1b "multi-looked SAR" waveform, we create an FF-SAR waveform every 0.5 m along track, then incoherently average the individual FF-SAR waveforms over the distance the sub-satellite point flies between "20 Hz" samples. This distance, ~318 m, roughly equals the resolution of the unfocused D/D SAR waveform produced for the CryoSat2 L1b product (and, we assume, Sentinel-3).



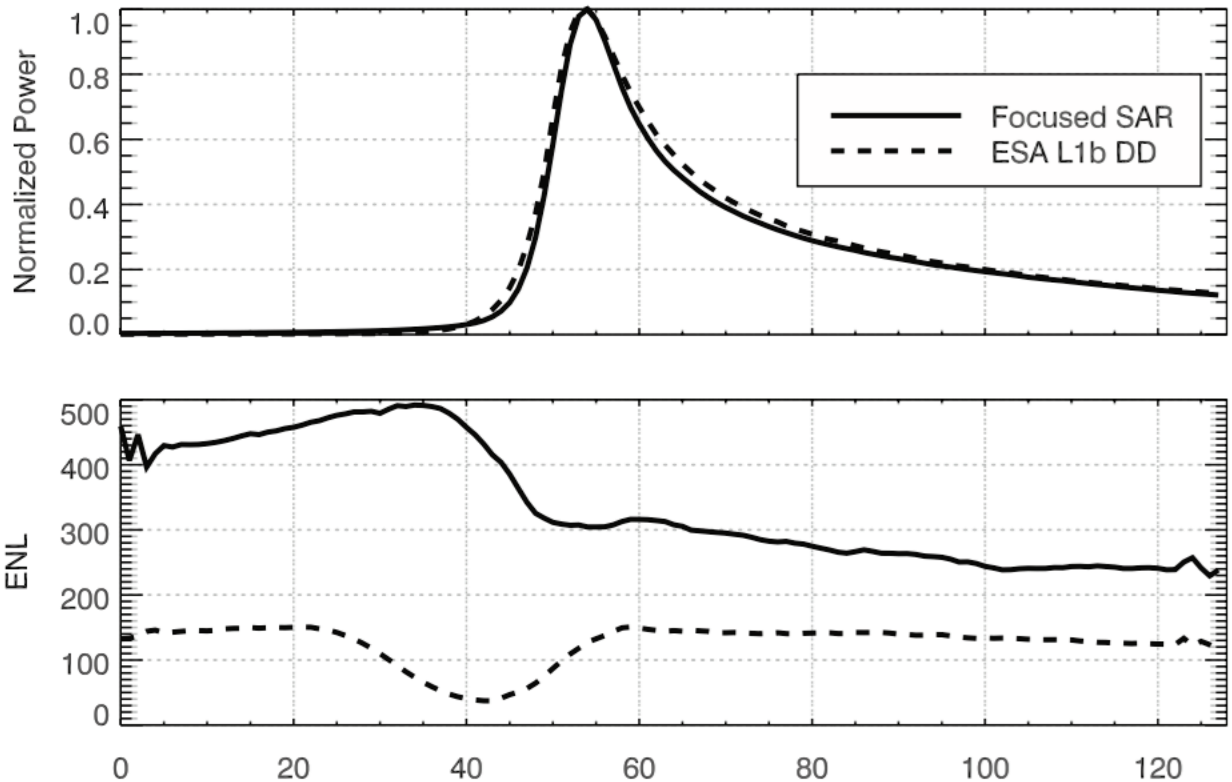
The mean waveform shape depends on the coherent integration time T_i. T_i = 2 s gives a broad "toe" about 23 dB below peak. Reducing T_i makes the rise steeper and brings the toe down 30 dB below peak.

[Note that, since the same pulse echoes are processed in different ways, the "thermal noise" is the same for all waveforms. The noise in the toe is "clutter noise".]

Dividing the square of the mean by the variance gives the Effective Number of [statistically independent] Looks, ENL. The ENL is close to 500 for T_i = 2 s and drops to around 50 for T_i = 0.25 s.

[Note that if the FF-SAR waveform were perfectly decorrelated in exactly 0.5 m, then averaging over ~318 m should give ENL ~=636, not ~500. The decorrelation isn't perfect, due to lacunar Doppler sampling (?), so ~9k ENL/s, not 13k/s.]

Comparing FF-SAR and D/D “SAR” 20 Hz waveforms

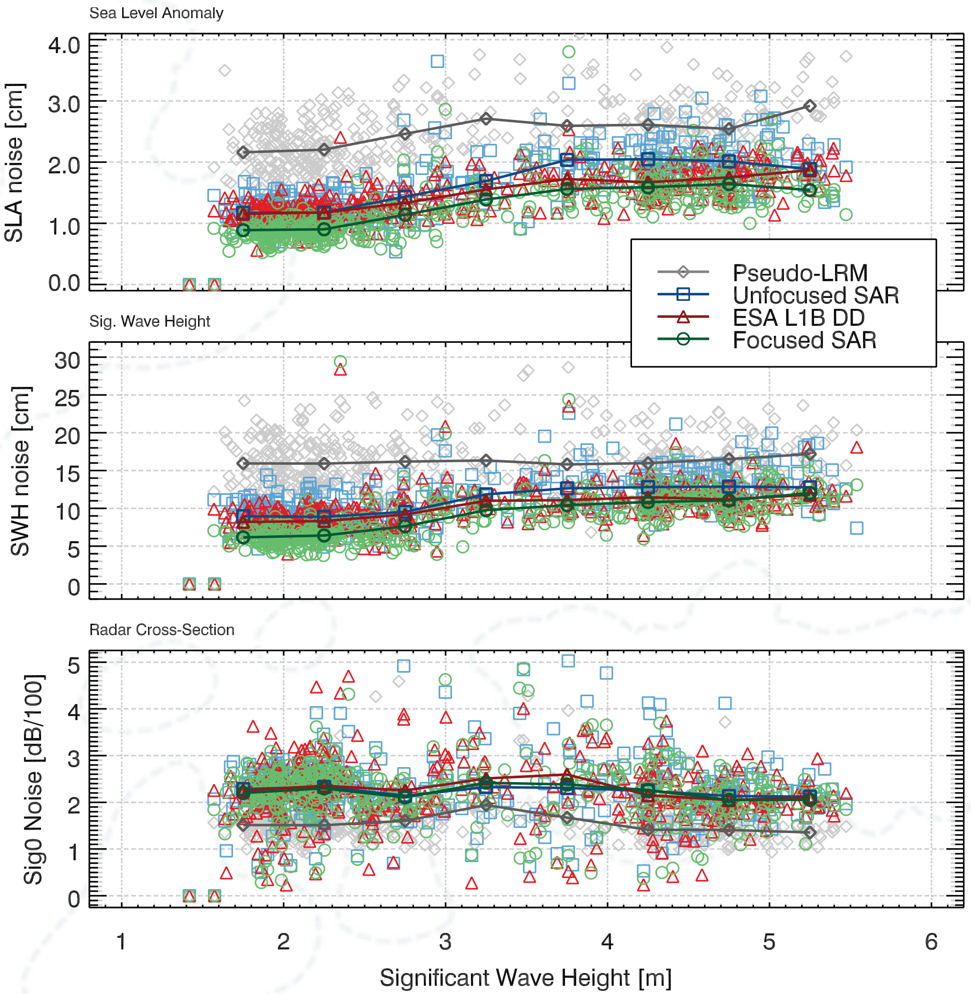


After multi-looking to 20 Hz, so the two can be compared, the mean waveforms of FF-SAR and unfocused D/D SAR (Cryosat L1b) have similar shapes. FF is a little more peaked. The main advantage is that FF ENL is higher than D/D ENL by a factor of 2 to 3, depending on range gate.

If the SNR in each waveform type is the same then the higher ENL should give FF-SAR a precision advantage over unfocused SAR for geophysical estimates. And in fact this is what we observe.

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
  - The comparison with the L1b ESA product is consistent for low SWH but changes towards higher SWH due to ESA's data editing and windowing.
- 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.



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.
- The focused SAR multi-looked waveforms @ 1 Hz show an increase in the ENL by a factor of 2 with respect the "conventional" delay/Doppler processing (20 Hz processing)
- Improvement by a factor of sqrt(2) @ 1Hz wrt DDA:
  - SLA noise @ 1Hz around 0.7cm (conservative)
- Detailed description of technique in:

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