Some surprisingly wonderful aspects of fully focused SAR (FF-SAR) altimetry

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Fully Focused SAR Altimetry: Theory and Applications

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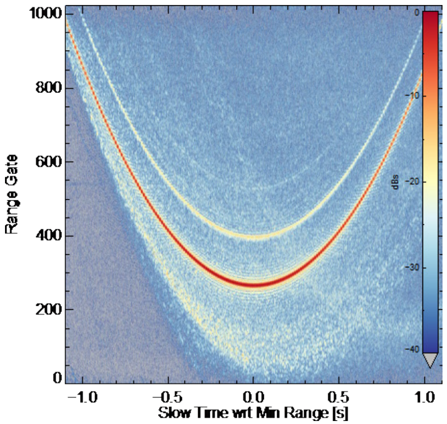
Major themes of this talk

- What is fully focused SAR altimetry?
  - How is CS2/S3/S6-JCS “SAR” (also called Delay-Doppler) different from conventional altimetry?
  - How is fully focused different from D-D “SAR”?
  - What does it mean to “focus” on a rough ocean?
  - What use is it to have a very narrow along-track sampling since we are still pulse-limited across-track?
- What are these wonderful surprises?
  - 0.1 mm range sensitivity at transponders; improved geophysical retrievals over ocean, water & ice surfaces.
  - Sensitivity to along-track width of calm water.
  - 0.5 m along-track resolution of rough ocean! (But what does this really mean in practice?)

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.

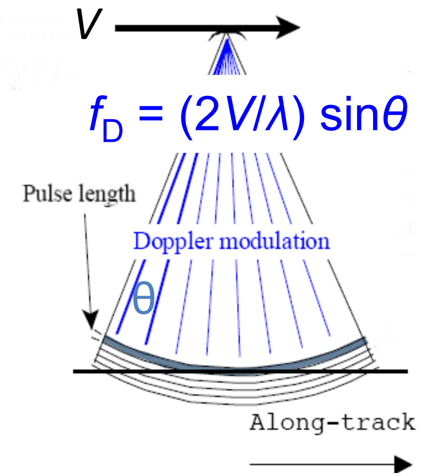
Coherent processing exploits both power and phase through a sequence of echoes. It maps a point on the ground to two coordinates: range and Doppler.

[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.]

Aperture synthesis via coherent processing

As a reflector moves through the range window, Doppler frequency f_D decreases. $f_D = (2V/\lambda) \sin\theta$ for points near the ground track of a nadir-looking altimeter. Doppler coordinate reveals a reflector's along-track position.

Coherent processing over a time T_i resolves Doppler frequency to $\Delta f_D \sim= 1/T_i$. The resulting "Doppler sharpened beam" has θ directivity as of an antenna of length VT_i. This effective antenna is the "synthetic aperture" of a SAR.

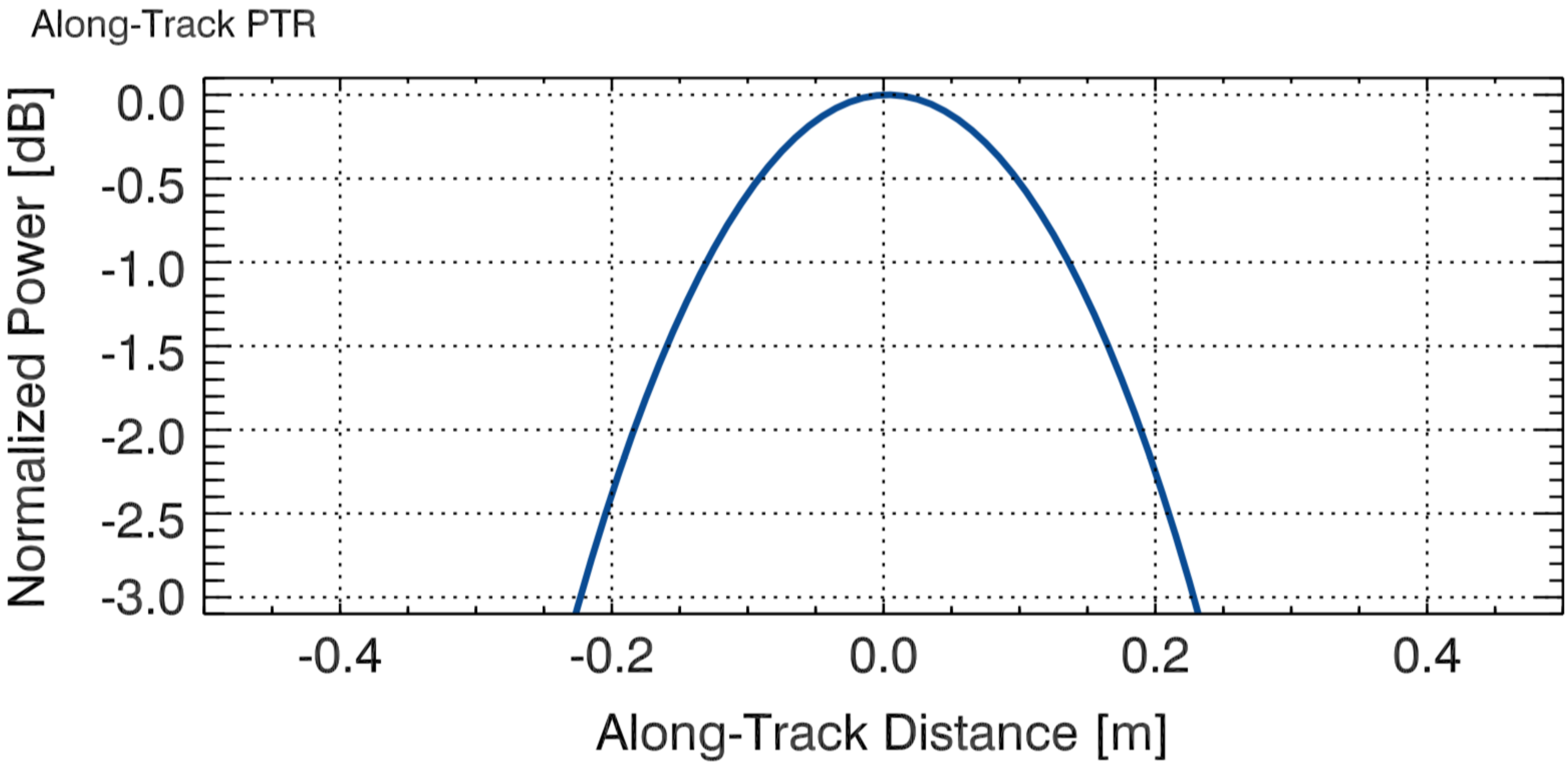


Increasing T_i decreases Δf_D , narrowing the Doppler beam and narrowing the resolution of θ, improving the sensitivity to along-track position.

When T_i is so long that along-track resolution is narrower than a Fresnel zone, the SAR can be "focused". For CryoSat & S-3 orbital altitude the Ku-band Fresnel scale is ~60 m along-track. The processing used in the CryoSat and S-3 "SAR" data product has an along-track scale around ~300 m, and so is "unfocused".

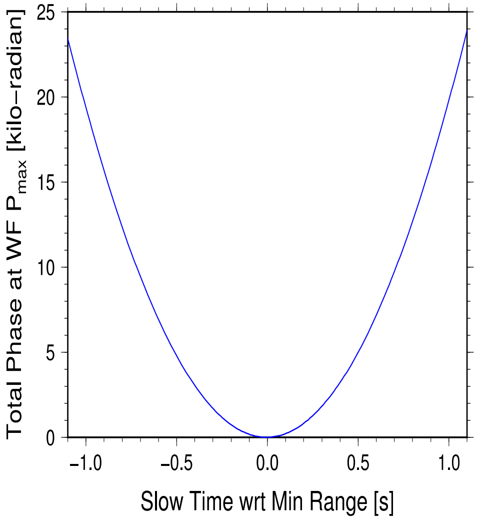
Imaging SAR systems employ $T_i = T_{vis}$ to achieve the best possible along-track resolution, which is of order ½ the actual antenna length, or about 0.5 m. Achieving this requires careful attention to focusing. FF-SAR does this careful focusing also.

Focusing an altimeter on a point



Cryosat SAR FBR data over the Svalbard transponder on 6 May 2014. T_l=T_{vis}. Moving the focal point along-track by a fraction of a meter changes the coherently integrated power. This along-track point target response has full width at half maximum of only 0.45 meter.

Wonderful surprise #1

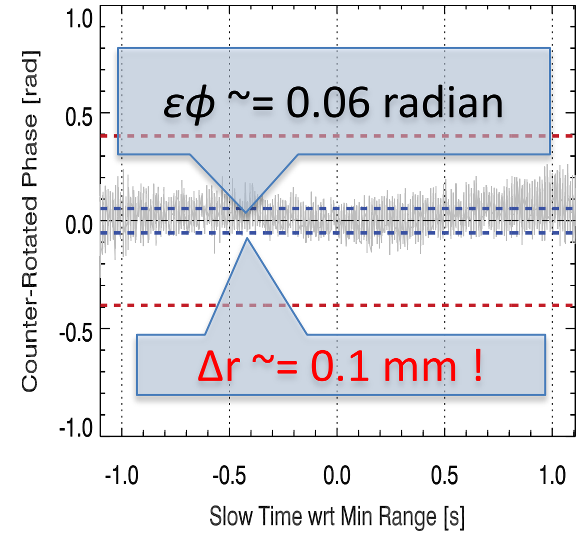


Phase Unwrapping Correction

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. $\varepsilon\phi / \Delta\phi$ ~= $2\text{x}10^{-6}$. $\varepsilon r = \lambda(\varepsilon\phi)/4\pi$ = 0.1 mm !



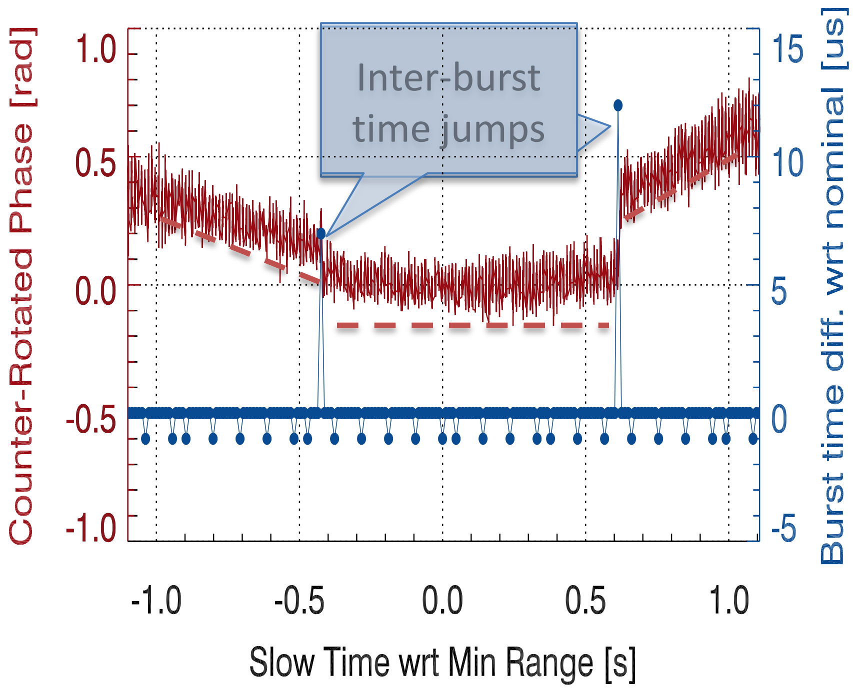
If the FF-SAR calculation employs the maximum possible aperture length ($T_I = T_{vis}$) then it must undo phase changes of the order of 4000 cycles of 2π. After doing this, the residual phase error in each pulse echo is about 0.06 radian, only 2 parts per million of the total change in phase occurring 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.)

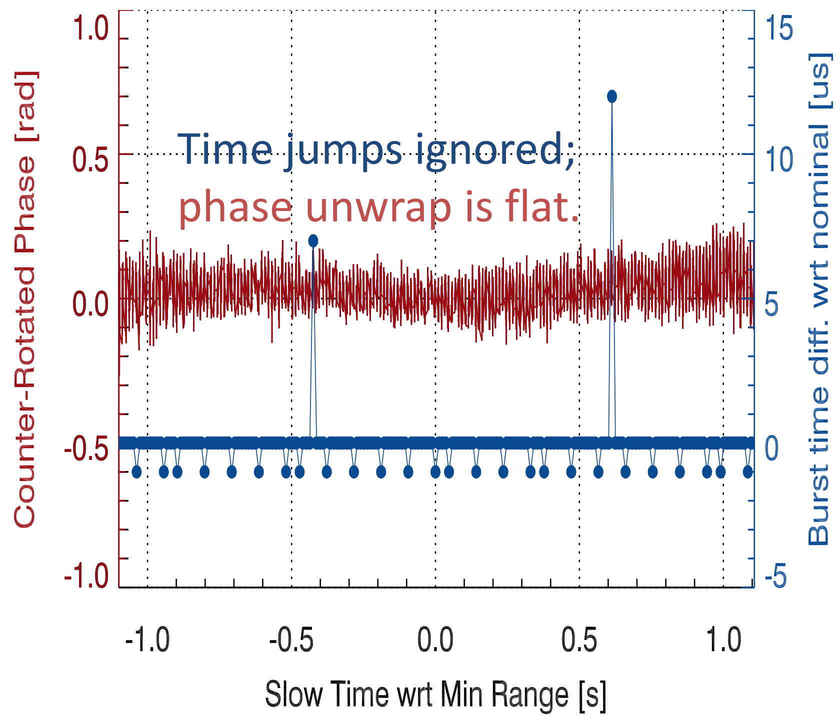
FF-SAR is wonderfully sensitive to range. (Good!) However, this means sensitivity to small errors in datation & position. Note: GDRs usually give height to 1 mm, horizontal position to ~0.1 m, time in floating point Y2k seconds. (Bad!)

Consequence of wonderful surprise #1

Using burst datation in FBR

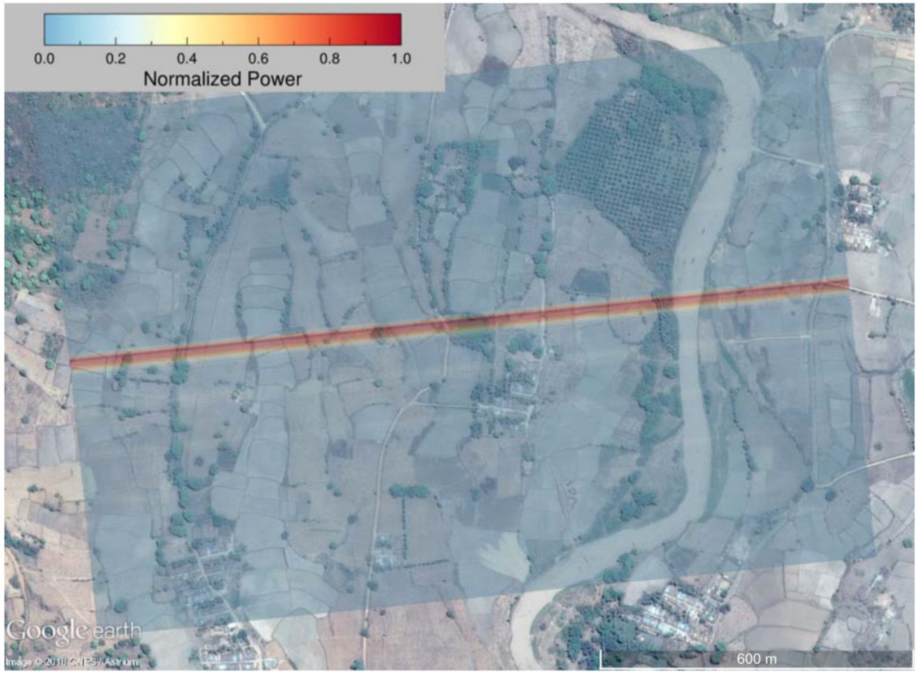


Assuming steady burst rate



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.

Wonderful surprise #2



CryoSat track over a small (~40 m by 40 m) pond (left) and FF-SAR image (right). Although the cross-track sampling is still pulse-limited (very wide), FF-SAR can correctly measure the pond's along-track width. Alejandro has beautiful results from rivers and leads in sea ice.

Earlier work by Abileah, Vignudelli and Scozzari using a quasi-FF-SAR calculation on Envisat RAIES (T_l = 1 s) found that the along-track width of small, smooth water bodies can be measured by resolving the width of their radiation patterns (in effect, they act as radiating antennas). This requires high spatial resolution in the along-track direction (large T_l).

Wonderful surprise #3

Transponders and small water bodies are coherent targets, so you might not be surprised that one can focus on them. But you might be surprised to learn that SSH, SWH, & σ^0 estimates from FF-SAR over ocean surfaces seem to be more precise than those from the "SAR" products of Cryosat (& presumably S-3 and J-CS/S-6 as well?). Alejandro will show the data analysis. I will now try to explain how we think FF-SAR works on a rough ocean.

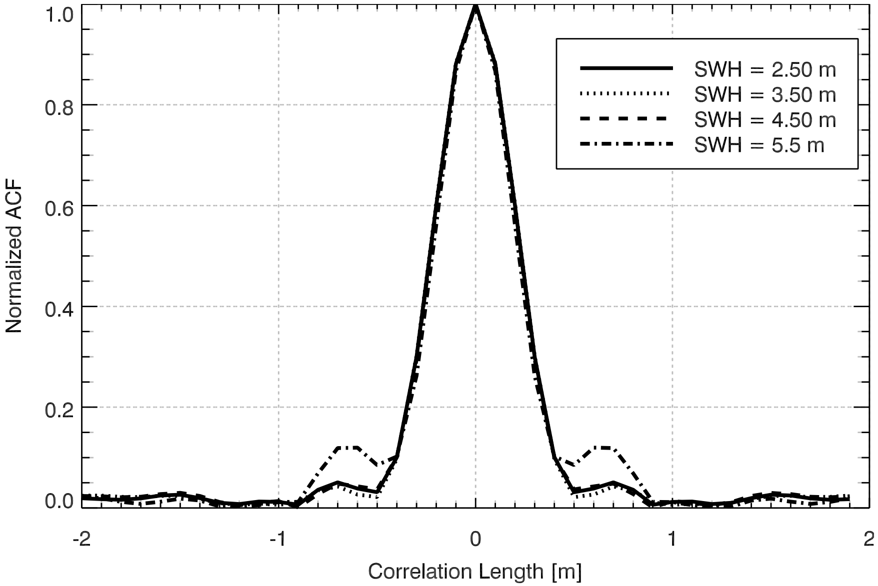
The ocean is "very rough", meaning (SWH/4) >> λ, and there are very many scatterers within the pulse limited footprint, so the power and phase of each pulse echo are each independent random variables, a phenomenon called "speckle noise".

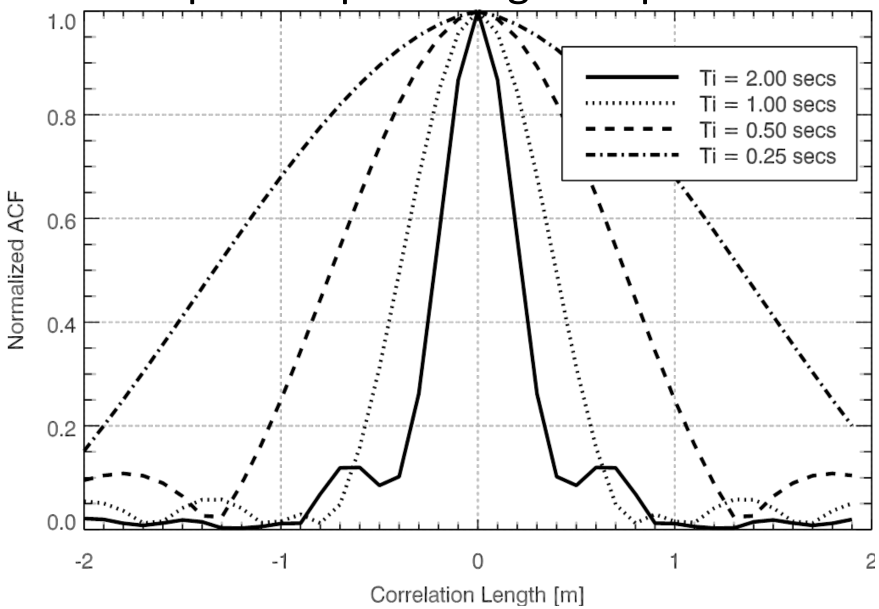
The surface is also in motion, and may decorrelate to Ku λ in ~4 msec.

Conventional ("LRM", e.g. Jason) altimeters therefore use only incoherent processing. CS2 & S3 "SAR" use coherent T_i = 3.52 ms, unfocused, 300 m along-track resolution.

Along-track correlation of ocean speckle under FF-SAR processing

The ocean is not in focus or coherent in the usual sense; each FF-SAR waveform is a random speckle noise waveform. Moving the focal point along-track yields new waveforms, and the speckle power fluctuations in these 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.

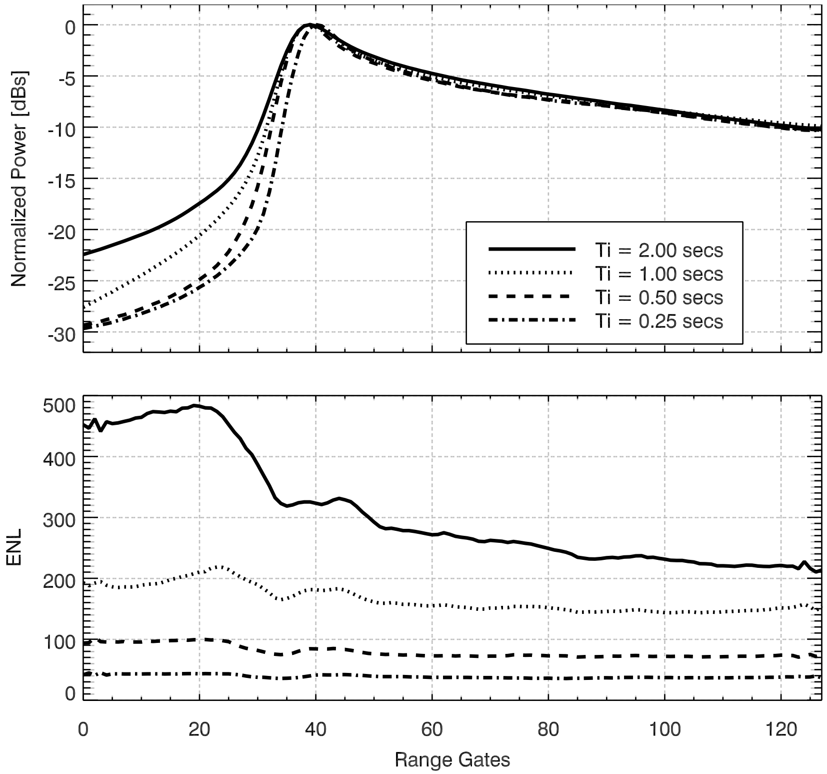




Thus FF-SAR can get statistically independent looks at the ocean every ~0.5 m along track, or ~13,500 per second. [Almost. The lacunar sampling of closed burst mode causes some small degradation in this, by introducing small side lobes in the along-track PTR.]

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).



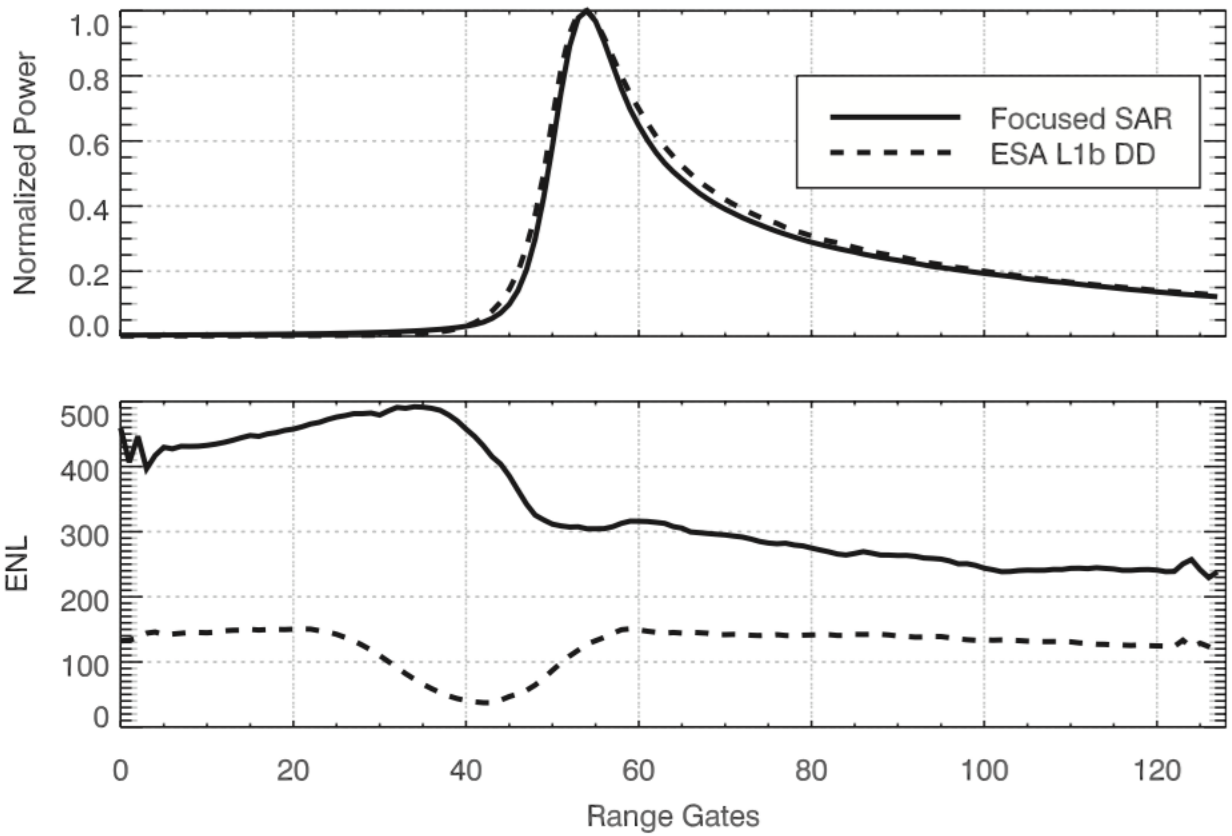
The mean waveform shape depends on the coherent integration time T_i. T_ii = 2 s gives a broad “toe” about 23 dB below peak. Reducing T_i makes the rise steeper and brings the toe down 30 dB below peak.

[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_ii = 2 s and drops to around 50 for T_ii = 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. (Alejandro will present the results in more detail.)

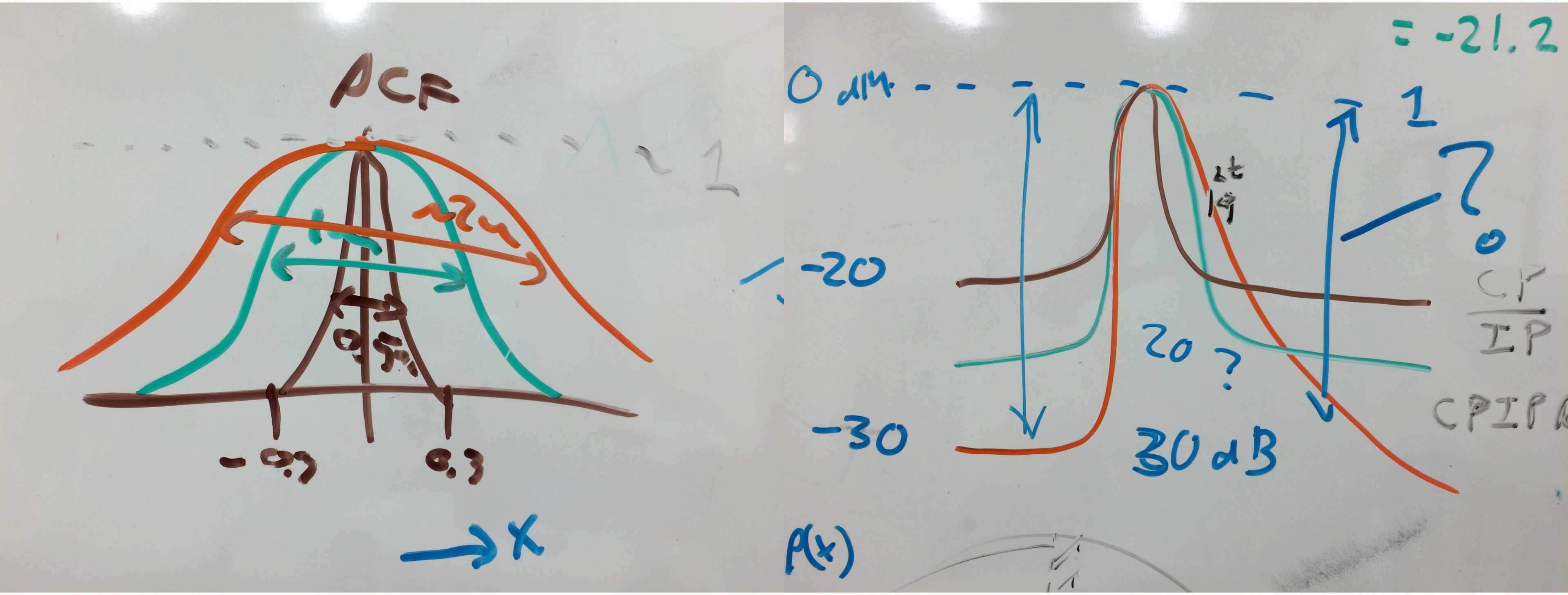
Comparing the ENL per second of altimeter processing methods

- FF-SAR ENL/s = 6000–10000 (300–500@20 Hz)
- CS2/S3 unfocused SAR = 1000–3000 (50–150@20 Hz)
- Conventional (e.g. Jason-3) ENL/s ~1765 ([2060*6/7] Ku pulses/s assumed independent.)

If all techniques give similar SNR, then the higher ENL rate is better.

Jason-3 SNR around 20 dB; FF-SAR around 23 dB, and unfocused SAR appears similar to FF-SAR.

Conclusions



FF-SAR brings Alejandro and me lots of fun discussions (my office white board, above).

It is clearly worthwhile over small targets (leads, rivers, ponds).

It seems a wonderful surprise that it works so well over the open ocean.

Geophysical retrievals from FF-SAR are more precise than those from other methods.

Further research is needed to see if there is an optimum point in T_i and whether FF-SAR over the ocean is really worth all the extra CPU cycles.