Echo to Echo Correlation and Time Alignment in CryoSat FBR SAR data

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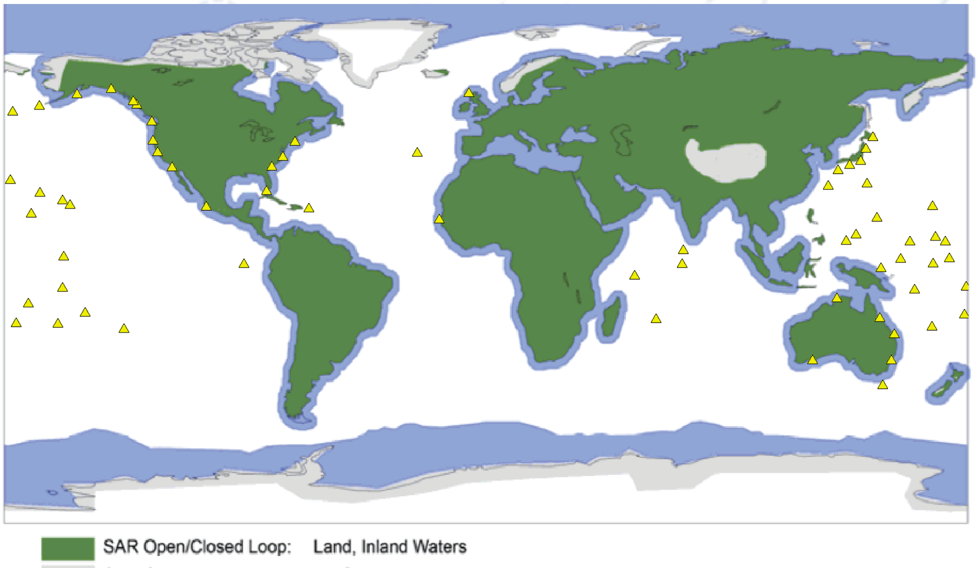
Special thanks to Ron Abileah, my NOAA LSA colleagues, and the CryoSat team, for many helpful discussions.

How is this talk Coastal?



S-3 and J-CS baseline scenarios envision SAR mode (SARM) over coastal zone and conventional (LRM) measurements over open ocean. Since tide gauges are mainly in the coastal mask, we will require inter-calibration of SARM and LRM to bootstrap from coastal gauges to LRM cal.

This talk aims to build a “pseudo-LRM” (P-LRM) or “reduced SARM” in an optimal way, by determining the actual pulse-to-pulse correlation between successive SAR echoes, in order to extract the greatest possible LRM information from raw (FBR) SAR data. This can also test the classical wisdom that LRM with a PRF = 2 kHz decorrelates echo speckle noise, a theoretical result obtained by Walsh [1974, 1982].

Is this talk necessary?

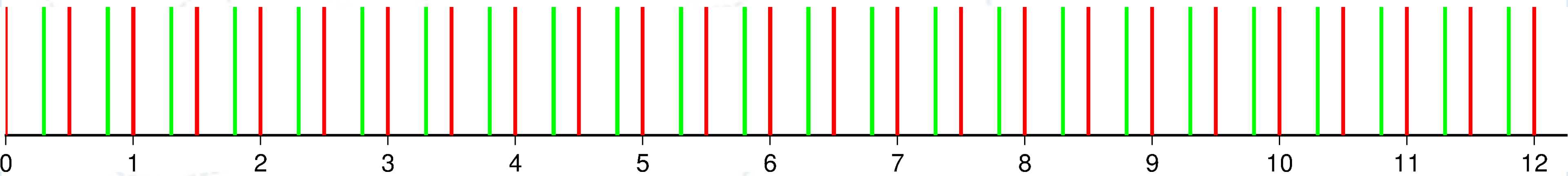
If Sentinel-3 goes to SAR over all ocean, then there is no need to bridge between SARM and LRM in S-3 ocean data.

If Jason-CS has the Interleaved Mode, then it will yield both LRM and SARM. There will be legacy LRM at tide gauges and also obvious inter-calibration between LRM and SARM.

In that case my talk is still interesting, at least to radar design theory, because it tests Walsh's theory for pulse decorrelation.

*Note that these **Ifs** will not happen unless there is a strong recommendation from the Coastal Altimetry and OSTST communities.*

LRM pulse timing



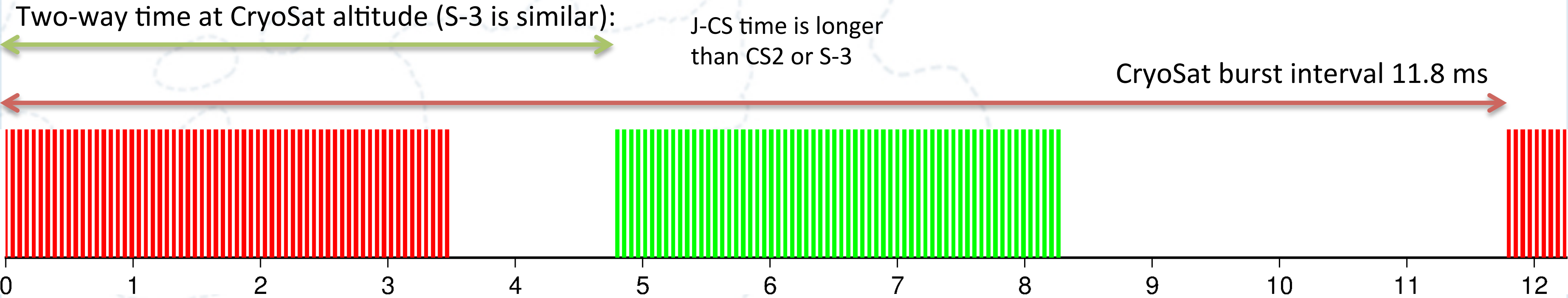
In a conventional LRM instrument, transmit and receive are ***interleaved*** and go on alternately, each at approximately 2 per millisecond (PRF ~= 2 kHz).

The interval between pulses is long enough that each pulse makes a statistically independent measurement, [if Walsh's theory is correct].

Due to the continuously interleaved tx/rx, ***opportunities to make statistically independent measurements are not missed***, [if Walsh is correct].

<u>There are ~2000 statistically independent measurements per second</u>, [if Walsh is correct].

Closed-burst SAR pulse timing

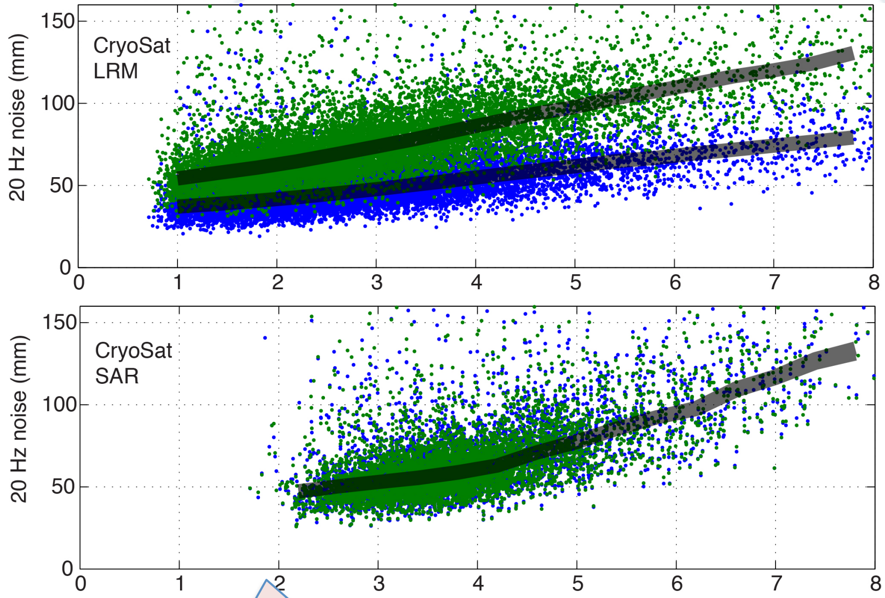


In a closed-burst SAR (CryoSat, S-3, J-CS baseline) transmit and receive are not interleaved and are not continuous. The CryoSat values of N = 64 and PRF = 18 kHz give a burst duration of ~3.5 ms. But the burst-to-burst interval is ~11.8 ms.

70% of the opportunity to make measurements is not used.

There are ~680 statistically independent measurements per second, assuming Walsh is correct. This is about 3/10 that of the LRM configuration. Measurement noise is higher than in LRM.

This pulsing scheme cannot be used to make an equivalent LRM measurement.



CryoSat2 LRM, like all LRM altimeters, shows improvement in range noise with two-pass retracking, as opposed to one-pass retracking. [Sandwell & Smith, 2005]

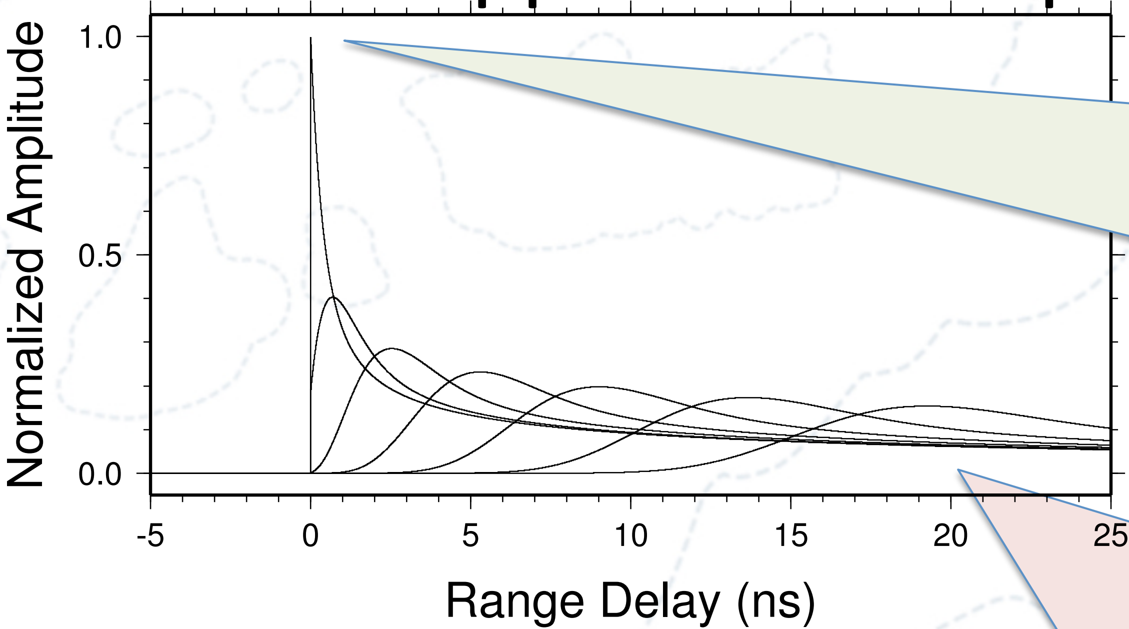
CryoSat2 SARM multi-looked waveforms do not show significant improvement with two-pass retracking [Sandwell et al, 2012]

This is likely due to the double-edged impulse response of the SAR.

Note that SARM rarely gives SWH < 2 m, whereas LRM routinely gives SWH < 1 m.

This is due to multi-looking, which broadens the impulse response, making the SARM unable to resolve low SWH.

SARM Doppler beam impulse responses



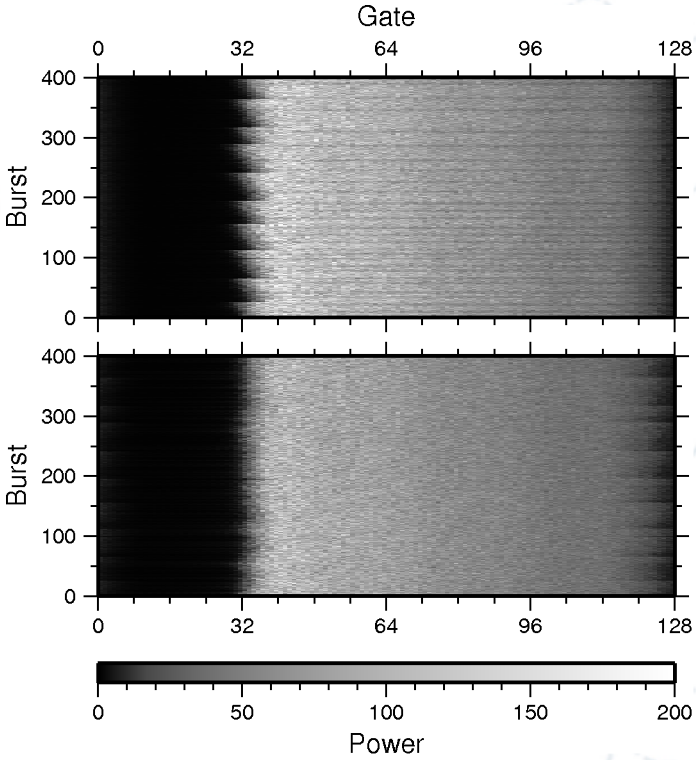
The idea that SAR precision will be 2x better [Jensen & Raney, 1989] derives from the narrow impulse response of the nadir beam.

Multi-looking combines measurements from off-nadir beams. The impulse response broadens as the beams move off-nadir, and soon becomes too broad to resolve a low SWH ("toe effect").
This will be less bad with the J-CS Interleaved Mode at 9 kHz as it will be in the J-CS Baseline Scenario at 18 kHz.

Echo-to-echo correlation analysis

- How can we take SAR mode echoes and make the best possible approximation of an LRM measurement, to inter-calibrate them and get unbiased SWH?
- On-board tracker simply uses every 9th echo, assuming Walsh is right and reducing 18 kHz PRF to 2 kHz PRF.
- We can do better, and use all the information in all the echoes, if we can understand how they are correlated.

P-LRM echo alignment



All altimeters, by design, can time the digitizing of received echoes only coarsely. If not corrected, the expected time to nadir jitters by +/- 2 range gates in the waveform.

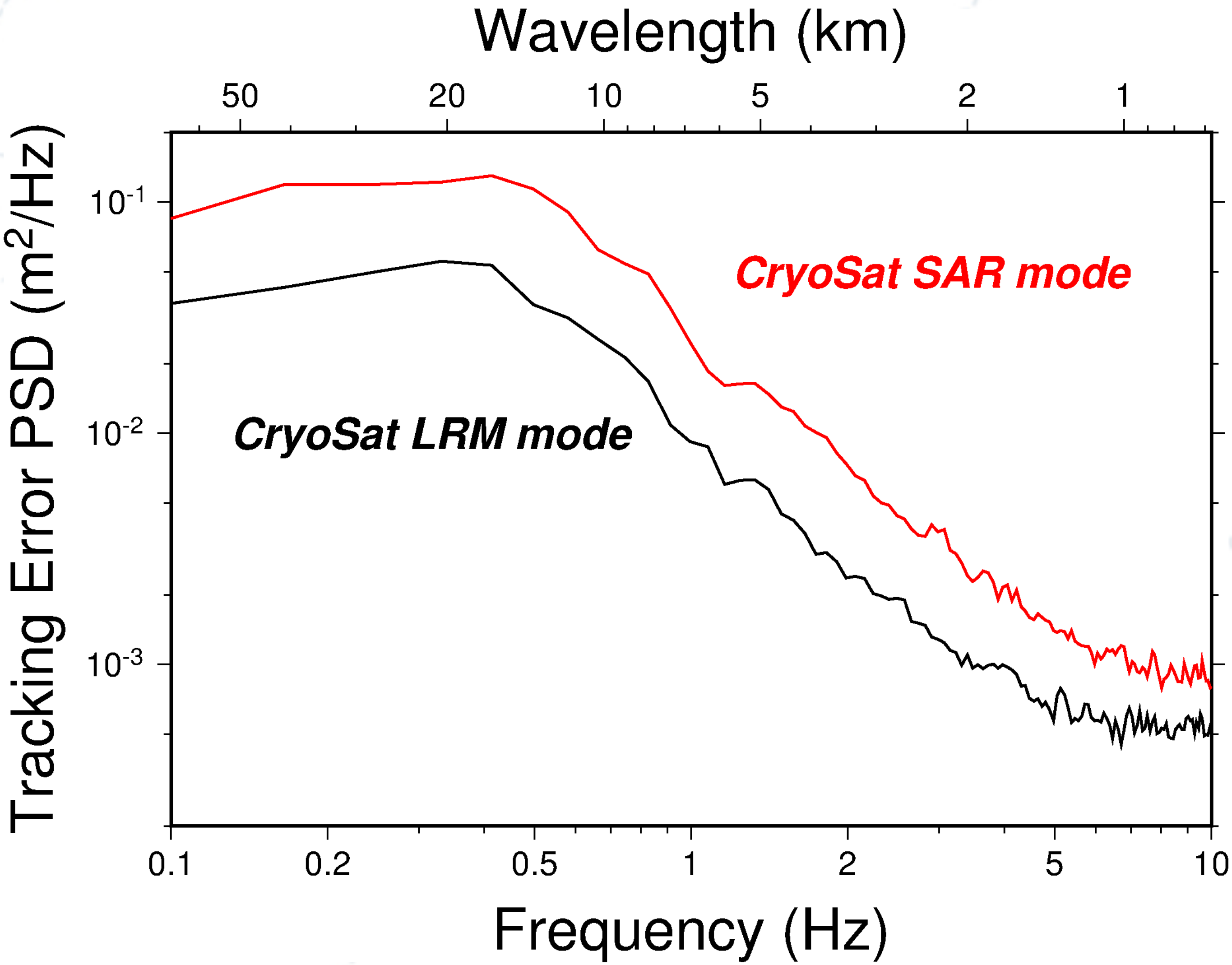
In LRM mode, the instrument applies phase shifts to each echo to align it to a common "track point".

I did the same with CryoSat2 FBR SAR.

But I found that the on-board tracking forecast of the time alignment was not accurate enough, because the tracking noise level is higher in SARM than in LRM, due again to the reduced number of independent pulses per unit of time.

For our NOAA LSA P-LRM I use the orbit height rate to correct the echo alignment timing. For the echo correlation analysis I work in small batches (400 bursts, about 32 km along track) and also use the geoid height as an additional constraint.

Tracker noise levels: LRM vs SAR



Range gate tracking errors (error in timing the digitizing of the returned radar echoes), expressed as range to the sea surface.

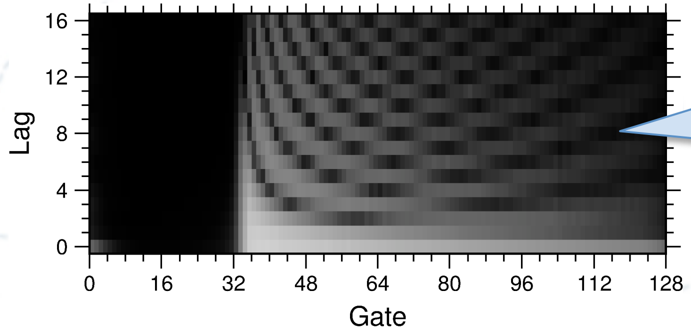
The power (variance, error-squared) is higher by about 10/3 in SAR / LRM mode.

Lagged pulse pairs

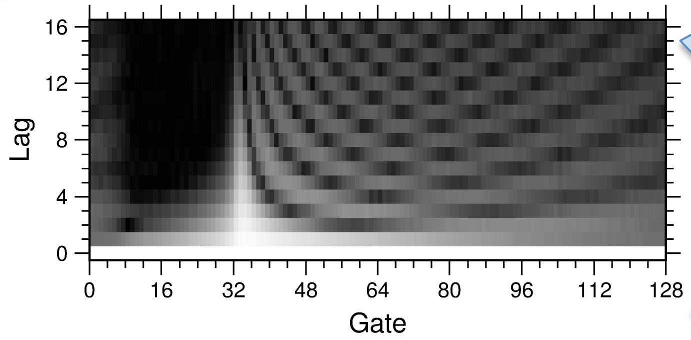
The following analysis shows results obtained from the ensemble average of complex conjugate cross products $C_{k,g} = \langle E_{n,g} E^{*}_{n+k,g} \rangle$ where $E_{n,g}$ is the complex value in echo *n* at range gate *g (after aligning all echoes to a common range time)*, *k* is an echo lag step, and <> is an ensemble average over all pulses, *n*, in 400 consecutive bursts. *(Burst-to-burst amplitude changes due to jitter in AGC were also corrected before ensemble averaging.)*

Results are shown as rectangular arrays, indexed horizontally by range gate number, *g*, and vertically by lag number, *k*.

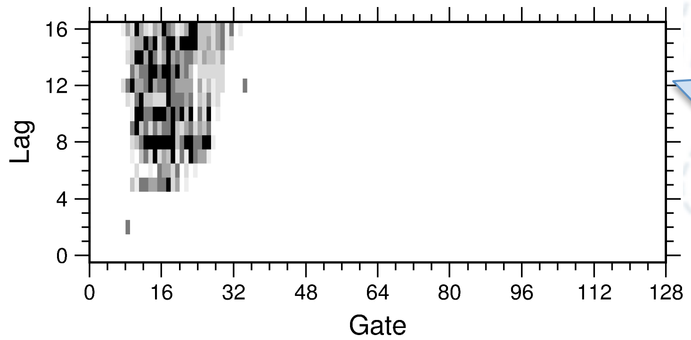
Example: amplitude



Amplitude, $|C_{k,g}|$.
k=0 is Brown model power.

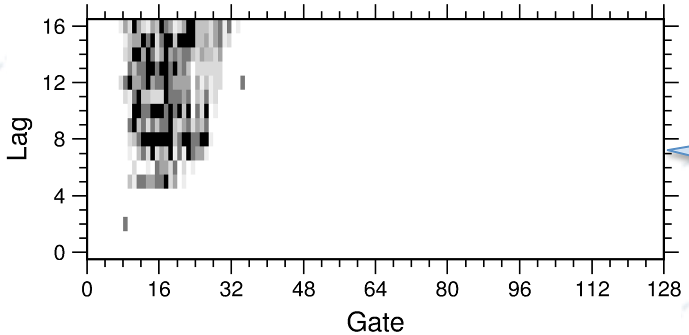


(Biased) Coherence Magnitude,
$\gamma = |C_{k,g}/C_{0,g}|$
Biased: thermal noise only in k=0.

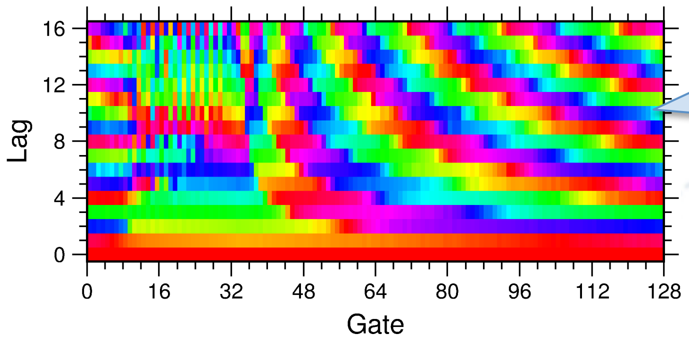


Significance. Reject null hypothesis that true γ = 0.

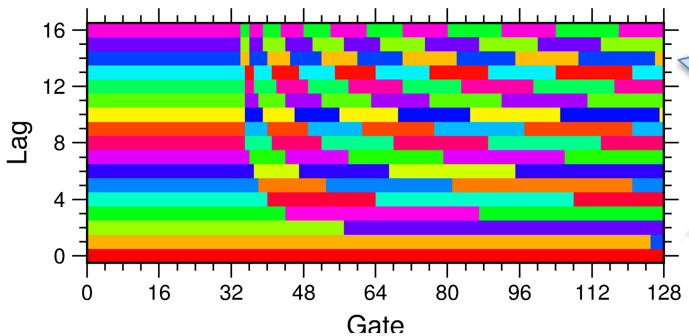
Example: phase



Again, the significance.

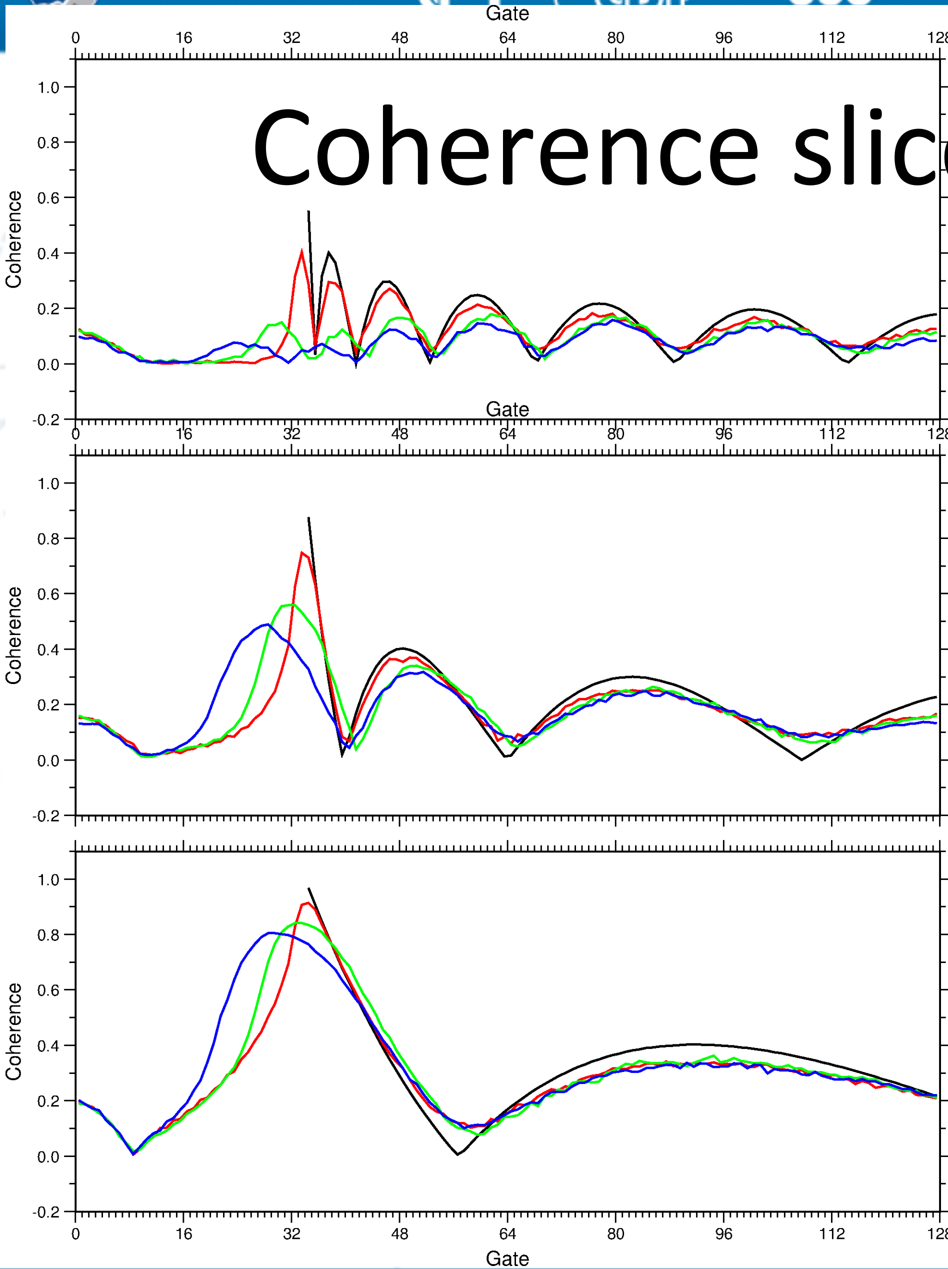


Phase, $\phi = \mathrm{Arg}\,[C_{0,g}]$



I derived a theoretical model that explains the phase as due to antenna velocity.

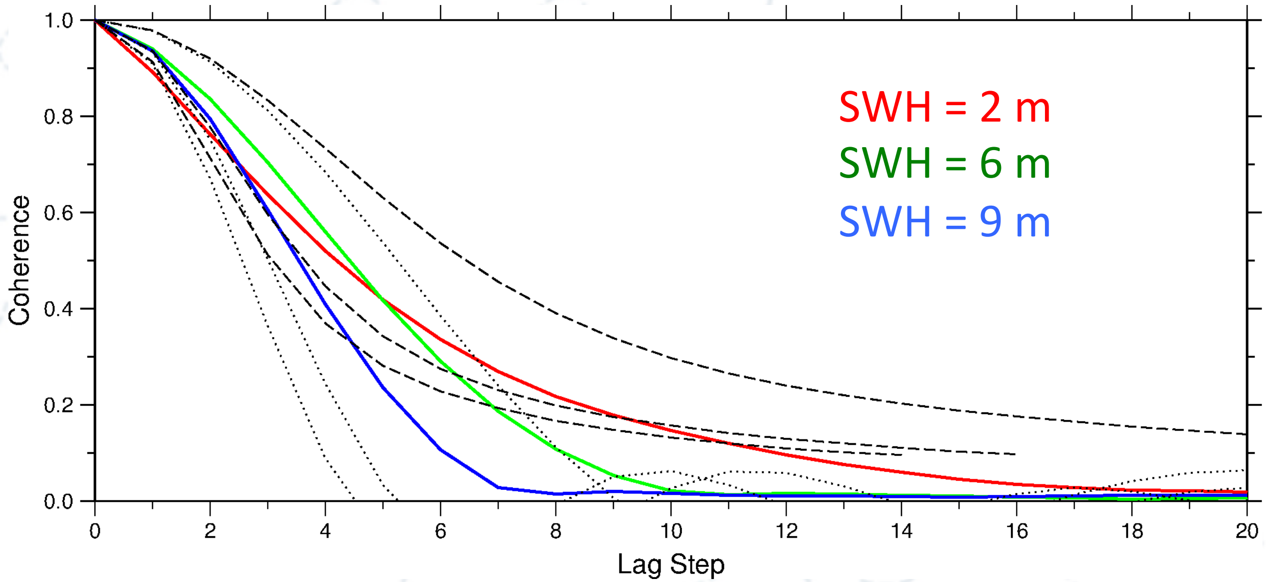
Coherence sliced horizontally



Bottom, middle, top panels are slices through coherence magnitude at lags of 2, 4, 8 steps, respectively. Colors red, green, blue show data from areas with SWH = 2, 6, 9 m, respectively.

My simple theory (black) is, like the data, independent of wave height. It is derived assuming the probability of radar scattering is the same at all azimuths with respect to the flight direction. Its amplitude (at left) depends on the horizontal motion of the antenna, while its phase (previous slide) is due to the vertical motion of the antenna.

Coherence sliced vertically at track gate



Thin dotted lines show Walsh's theory for each SWH example. Walsh assumed uniform scattering intensity over a circular footprint with a sharp edge.
If I assume a Gaussian pulse causes a diffuse edge, I get the fatter dashed lines.
Both Walsh and I are assuming everything else is perfect (no heterogeneity in the surface, no instrument imperfections, perfect alignment of echoes to the track point, etc.) Reality is more complicated. Results at lag = 9 agree with Ron Abileah's RAIES results. Lag = 9 corresponds to CryoSat's SAR tracking echo.

Conclusions on pulse correlation

- Pulse decorrelation is not as simple as Walsh suggested; there is no sharp drop to a zero crossing.
- An optimally weighted pseudo-LRM from SAR should use all pulses, not merely every 9th one.
- Our (not yet optimal) P-LRM results are in Remko Scharroo's talk. We use all 64; results look good.
- There is value in doing LRM with a PRF higher than 2 kHz. Even at 9 kHz (J-CS Interleaved) there will be some improved performance.

Broader Implications

- SAR is new and wonderful but also complex. The inter-calibration between SAR and LRM is not yet established and doesn't appear simple to understand.
- For this reason it is my opinion that switching between the two modes, with each necessarily exclusive of the other (i.e., the baseline scenario for Sentinel-3 and Jason-CS) may present undesirable challenges.
- For Jason-CS the "Interleaved Mode" (pulse timing below) can provide both legacy LRM and also a better ocean SAR than CryoSat heritage, both simultaneously. This seems like the best of both worlds to me.
- For Sentinel-3 there may be an option to bite the bullet, take a leap of faith, and use SAR everywhere over the ocean. This will allow tide gauge calibration of the whole ocean, and avoid problems at mode switch points. However, if it means that SWH estimates will be too high when true SWH is low, this may be an unwanted side effect.