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Pulse-to-pulse correlation in CryoSat SAR echoes from ocean surfaces: implications for optimal pseudo-LRM waveform averaging.

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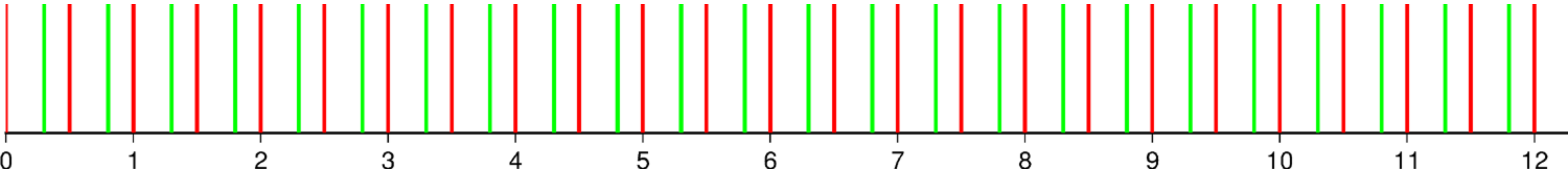
LRM pulse timing



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

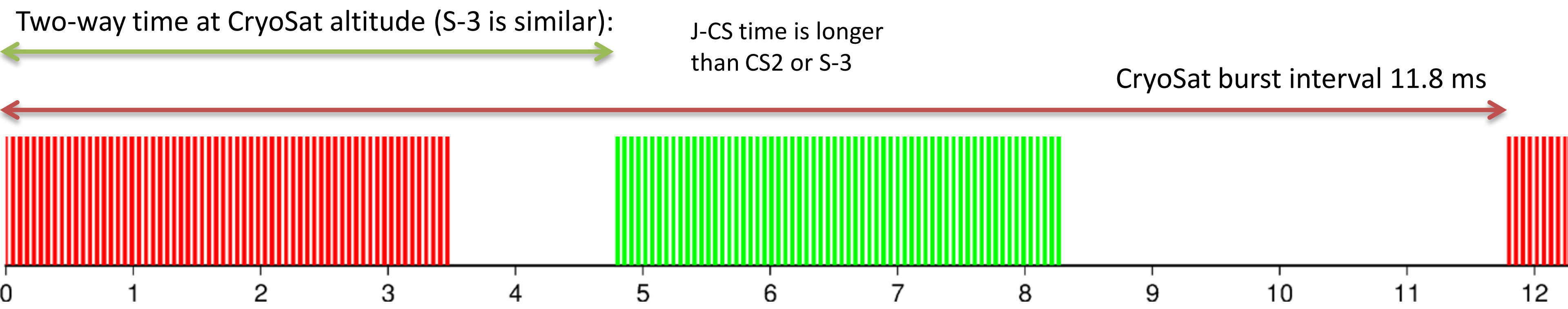
The interval between pulses is long enough that each pulse makes a statistically independent measurement, if the conventional wisdom about pulse decorrelation time [Walsh, 1974; 1982] is correct.

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

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

I say "if Walsh is correct" because, until CryoSat2, we haven't had a data set that could test this theory very well. So that is one aim of this study.

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 0.34 times that of the LRM configuration.

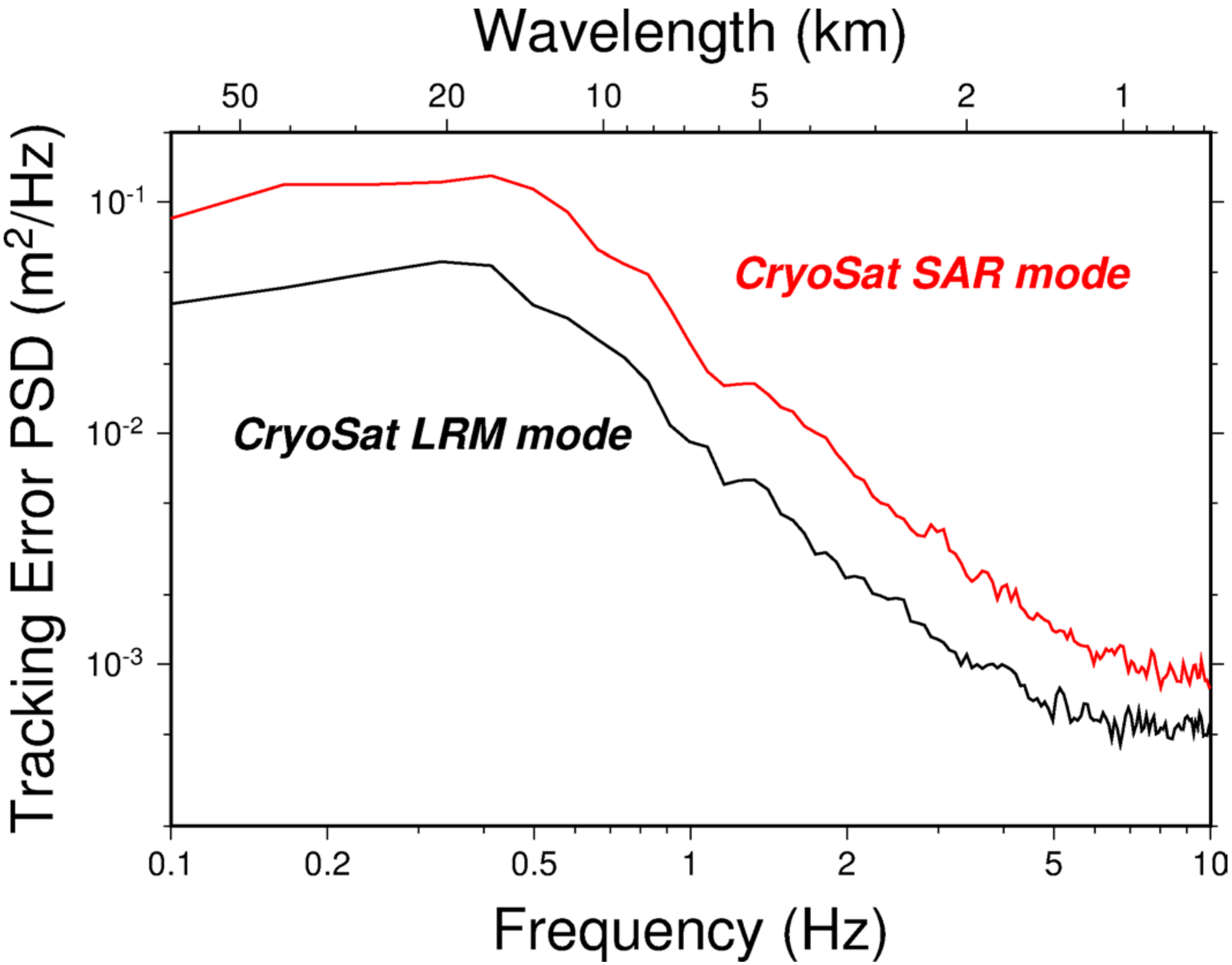
This pulsing scheme cannot be used to make an equivalent LRM measurement. One can make "pseudo-LRM" but the measurement noise should be higher by about a factor of 3 in power, if Walsh is correct.

Why make Pseudo-LRM (P-LRM)? (1)

P-LRM yields a conventional waveform that can be retracked with standard algorithms, providing results to compare with SAR algorithms.

P-LRM, taking only every 9th SAR echo, provides the "tracking echo" that is used by the CS-2 on-board tracker. If Walsh's idea is right, this scheme gives the tracker as much information as possible, and tracking should be noisier in SAR mode than in LRM by a factor of 3 in power. ***Could the on-board tracking be improved?***.

Tracker noise levels: LRM vs SAR



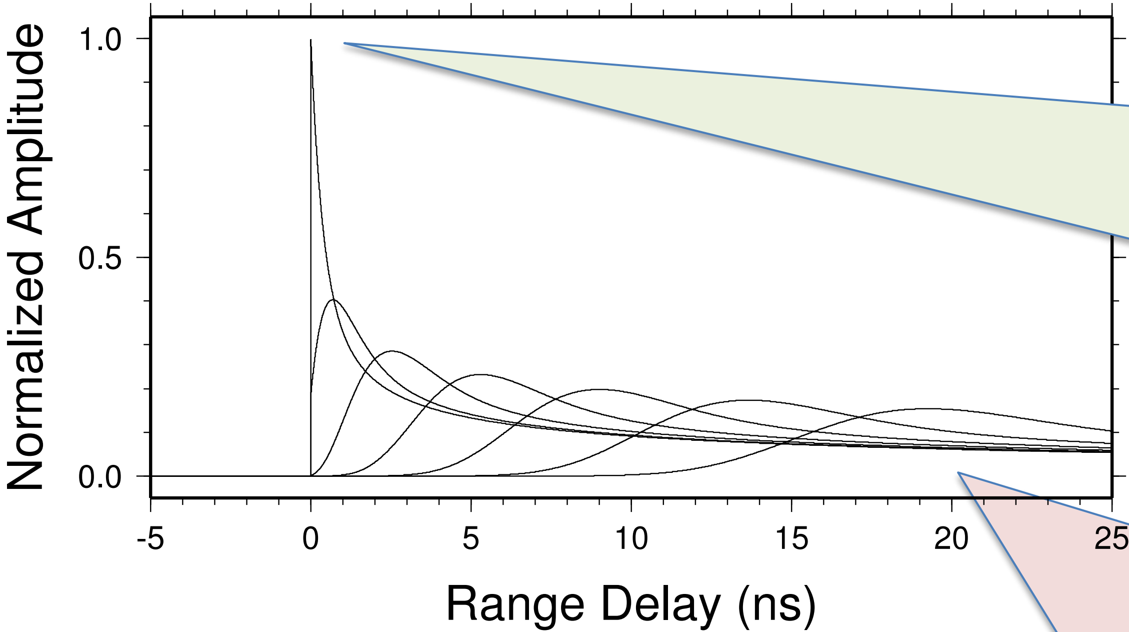
Range gate tracking errors (error in timing the digitizing of the returned radar echoes), expressed as range to the sea surface.

The power (variance, error-squared) is higher by about a factor of in SAR mode relative to LRM mode.

Why make Pseudo-LRM (P-LRM)? (2)

SAR waveforms which have been “multi-looked” in the simple way may not be as sensitive to SWH as P-LRM waveforms. If so, we might get better SWH from P-LRM than from SAR (until we have a better multi-looking algorithm).

SAR Doppler beam impulse responses



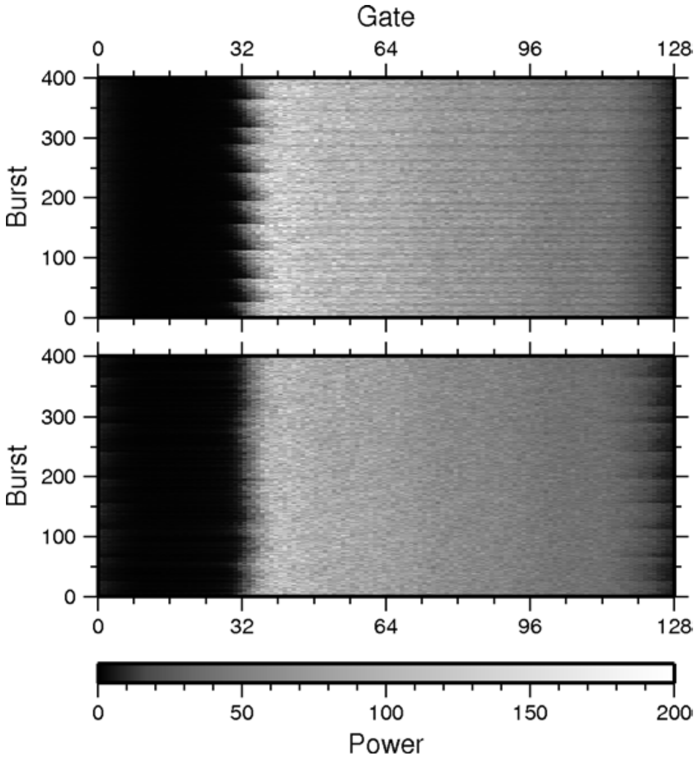
The idea that SAR precision will be 2x better than LRM precision [Jensen & Raney, 1989] derives from the narrow impulse response of the nadir beam.

Multi-looking combines measurements from off-nadir beams. The impulse response broadens quadratically 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; the # of not-too-broad beams will double in going from 18 kHz to 9 kHz PRF.

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 limit is right and reducing 18 kHz PRF to 2 kHz PRF.
- We can do better, using 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.

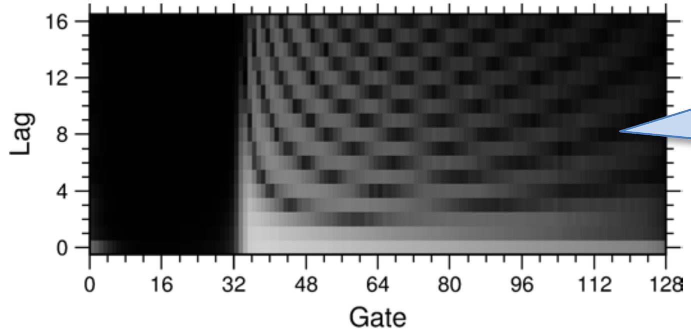
For our NOAA LSA P-LRM I use the orbit height rate to correct the echo alignment timing. For the echo correlation analysis I work in small batches (400 bursts, about 32 km along track) and also use the geoid height as an additional constraint.

Lagged pulse pairs

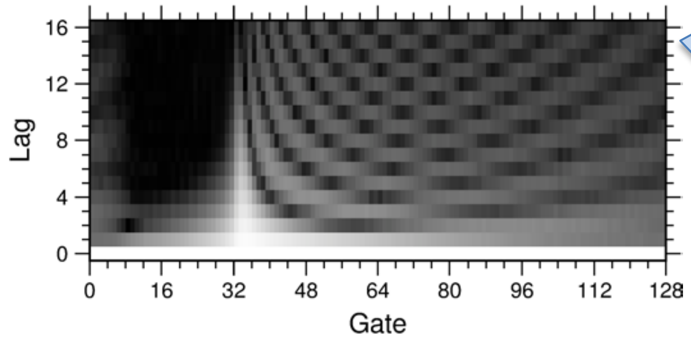
The following analysis shows results obtained from the ensemble average of complex conjugate cross products $C_{k,g} = \langle E_{n,g} E^{*}_{n+k,g} \rangle$ where $E_{n,g}$ is the complex value in echo *n* at range gate *g (after aligning all echoes to a common range time)*, *k* is an echo lag step, 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* (“fast time”), and vertically by lag number, *k* (“slow time”).

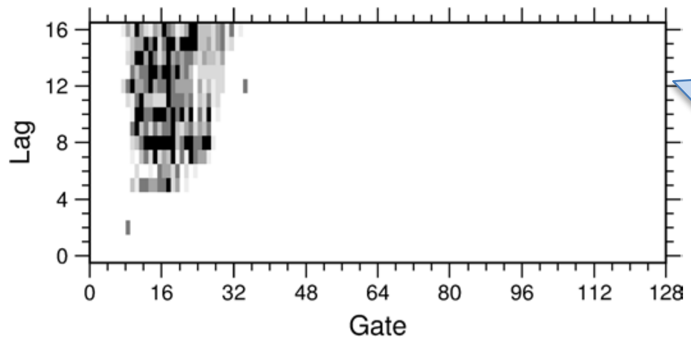
Example: amplitude



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

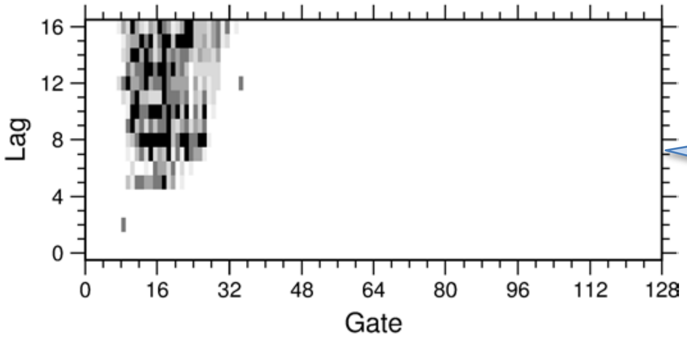


(Biased) Coherence Magnitude,
$\gamma = |C_{k,g}/C_{0,g}|$
Biased: thermal noise only in k=0.

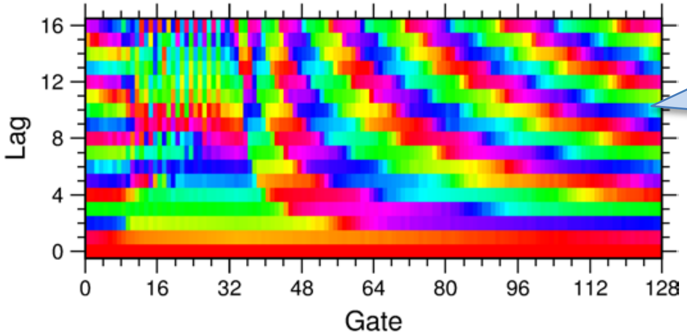


Significance. Reject null hypothesis that true γ = 0.

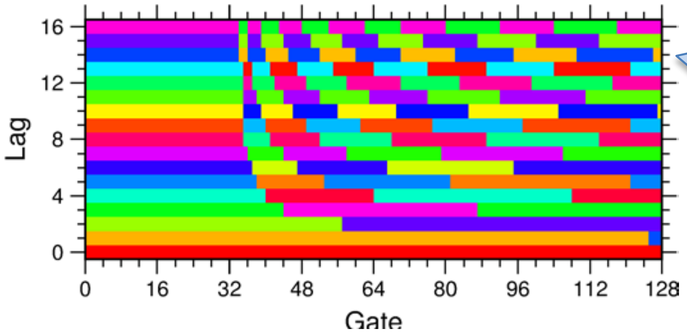
Example: phase



Again, the significance.

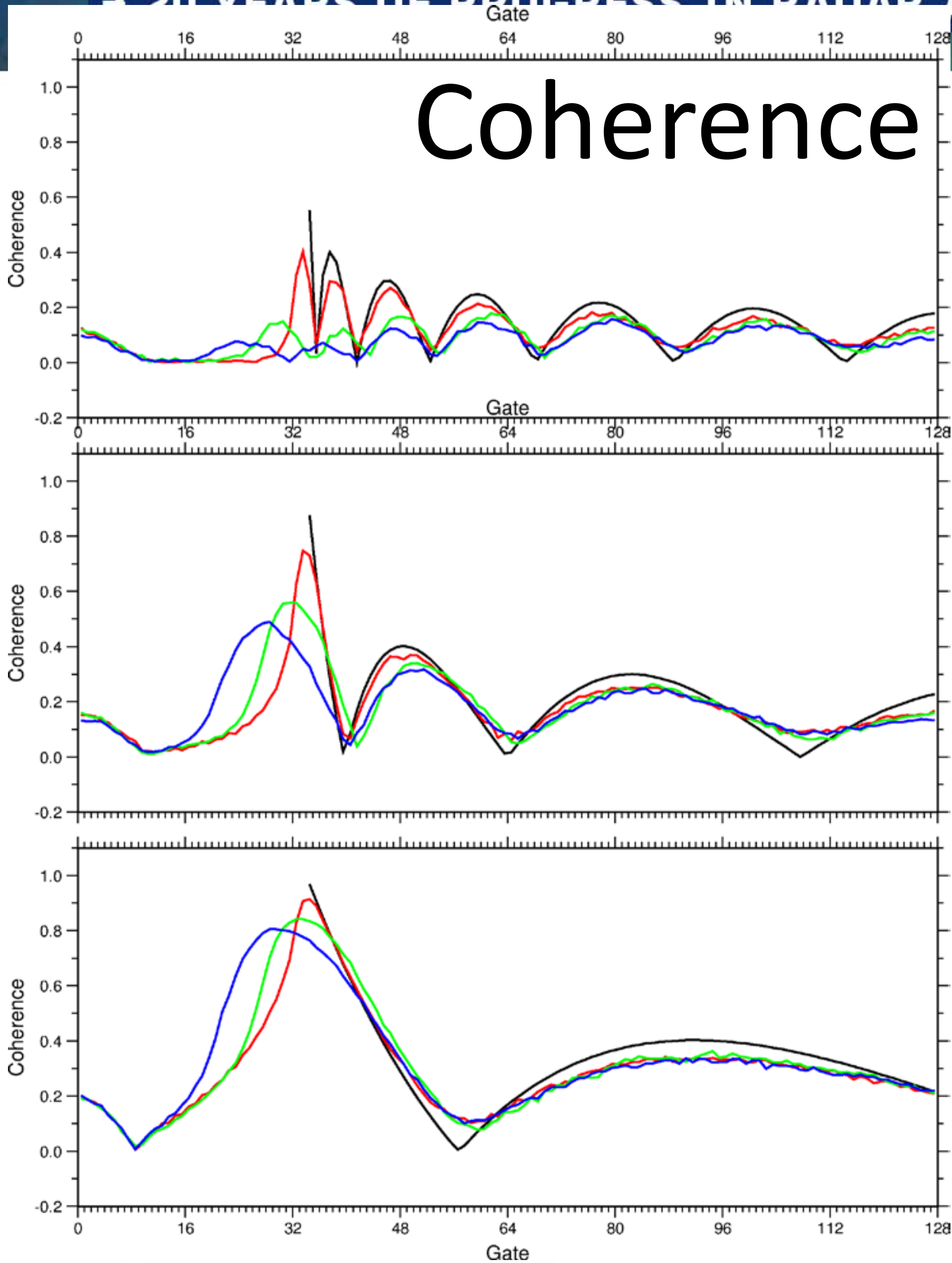


Phase, $\phi = \text{Arg}\,[C_{0,g}]$



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

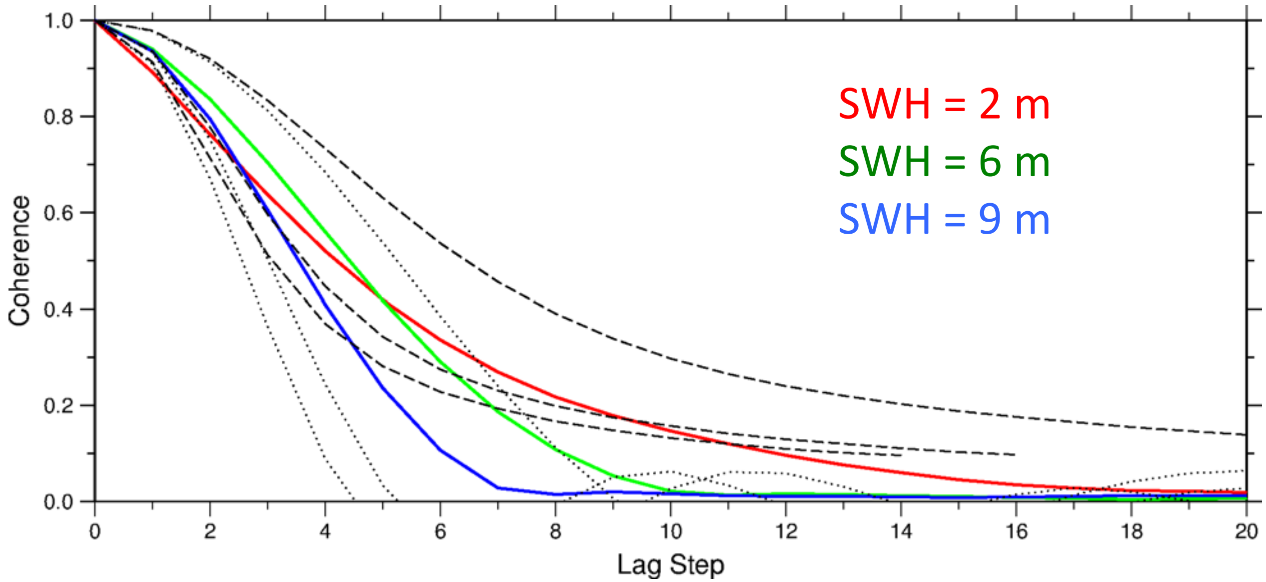
Coherence in fast time



Bottom, middle, top panels are horizontal 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 in slow time 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. (The on-board tracker should use all pulses also.)
- 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 in the LRM mode.

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 challenges that we might prefer to avoid.
- For Jason-CS the "Interleaved Mode" (pulse timing below) can ***simultaneously*** provide both backward-compatible LRM and also a better* ocean SAR than CryoSat heritage, ***over all the ocean***. (*Better because the impulse widening will be less severe at 9 kHz and all Doppler beams will be useable.)
- For Sentinel-3 there may be an option to use SAR everywhere over the ocean. This will allow tide gauge calibration of the whole ocean, avoiding problems at mode switch points. However, it might mean that SWH estimates will be biased high when true SWH is low. Remko's talk shows we can mitigate this with our P-LRM.