Development of Fully-Focused SAR Altimetry for Oceanographic Applications

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- Introduction / Context
- OSTST Project Objectives
- Project Developments
  - NOAA LSA SAR-Altimetry Processor
  - SAR Altimetry Processing Optimization
  - Science Application Developments
    - Open Ocean
    - Coastal Zones
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- Conclusions and Future Work

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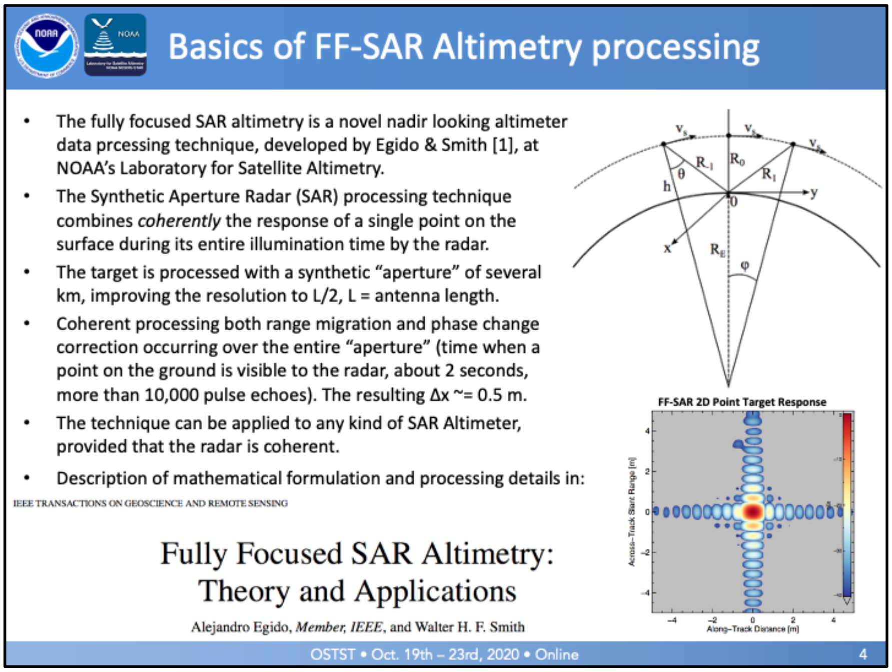
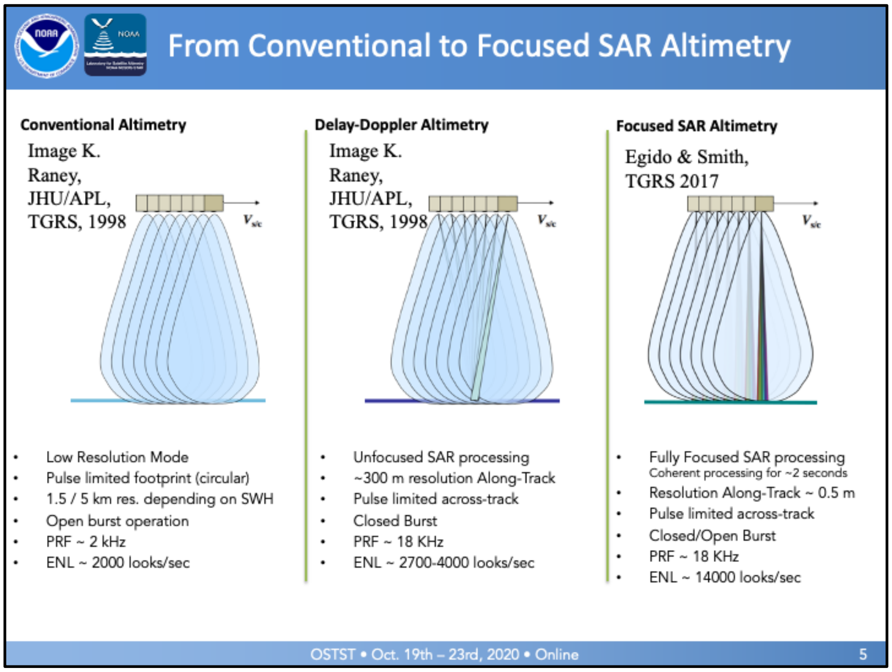


The delay/Doppler (D/D) algorithm implemented for CryoSat-2 and Sentinel-3 data, [Raney, 1998], applies coherent processing to pulses transmitted in bursts. This is the so-called closed-burst operation mode.
The 64 echoes within each burst (equivalent to 3.5 milliseconds of flight) through an along-track FFT, creating Doppler beams of about 300 meters in the along track direction. Doppler beams from subsequents bursts, pointing to the same location on the ground are combined to form the delay/Doppler stack. Those are later multilooked to improve the final speckle noise statistics.
In the case of fully focused synthetic aperture radar (FF-SAR) altimetry [Egido & Smith, 2017] the coherent integration time can be extended, potentially, up to the illumination time of a target on ground, leading to the theoretical limit in the along-track resolution, equal to L/2, where L is the antenna length.

[Raney, 1998] R. K. Raney, "The delay/Doppler radar altimeter," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 36, no. 5, pp. 1578-1588, Sep 1998.

[Egido & Smith, 2017], A. Egido and W. H. F. Smith, "Fully Focused SAR Altimetry: Theory and Applications," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 55, no. 1, pp. 392-406, Jan. 2017.



In this slide we put in perspective three different nadir looking processing techniques: the conventional pulse limited altimeter, the delay/Doppler processing, and the fully-focused SAR altimeter.

The footprint of a fully focused SAR altimeter measurement is an elongated strip on the surface, which is pulse-limited across-track and SAR focused along-track. On a random rough surface like the open ocean, the fully focused altimeter waveforms are a random realizations of speckle noise. These single looks are essentially uncorrelated between each other so they can be incoherently averaged to obtain a multi-looked waveform.

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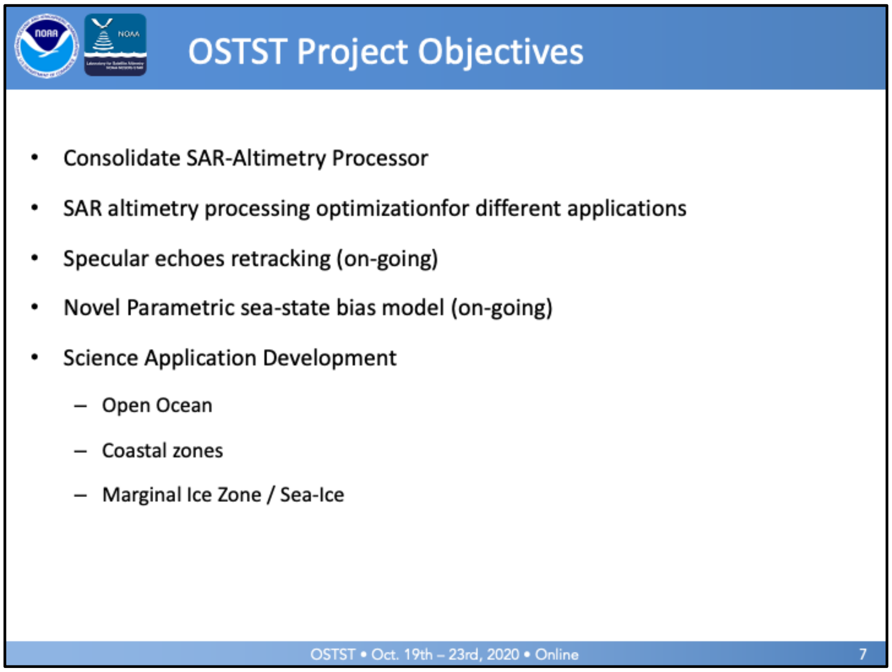

The objective of this project was to develop critical aspects and understanding of the FF-SAR altimetry processing technique, and to develop key applications in key areas, such as the open ocean, coastal zones, and marginal ice zones.

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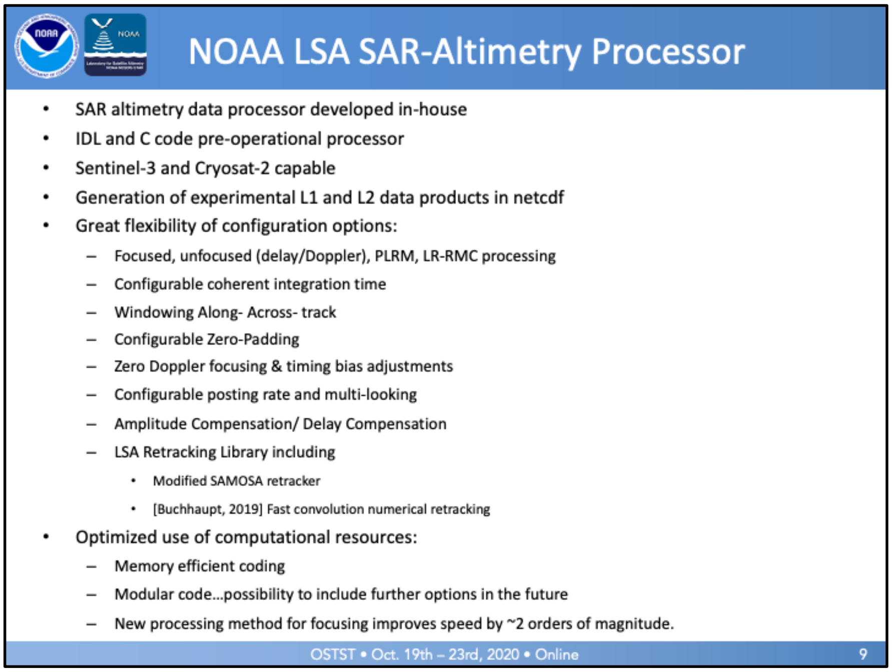

The NOAA LSA SAR-altimetry processor has been fully developed in house.
During this project, the processor was upgraded to a pre-operational level.
The high configuration capability makes this a very valuable tool for the altimetry community as a whole.
It will soon be updated to use Sentinel-6/MF data.

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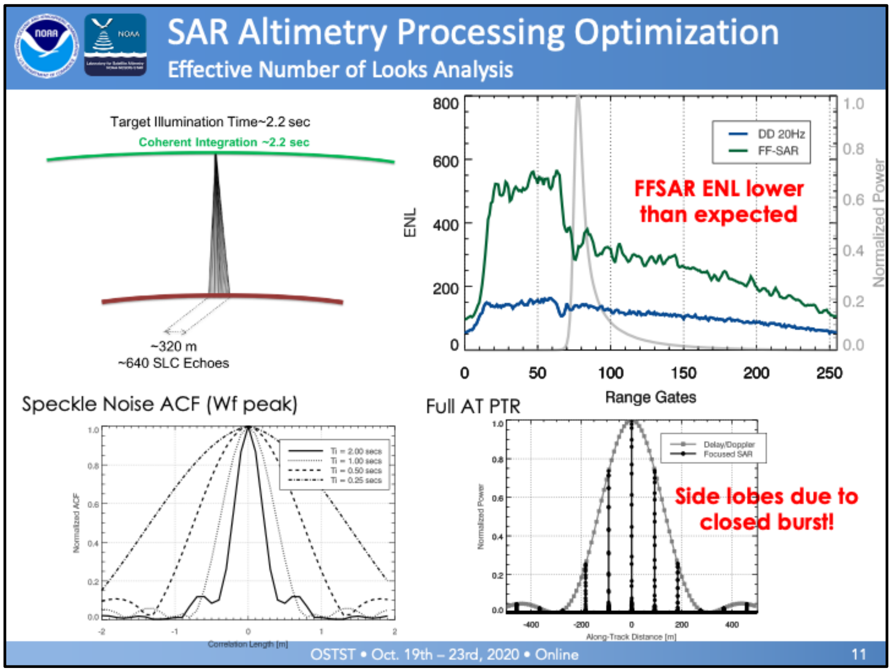
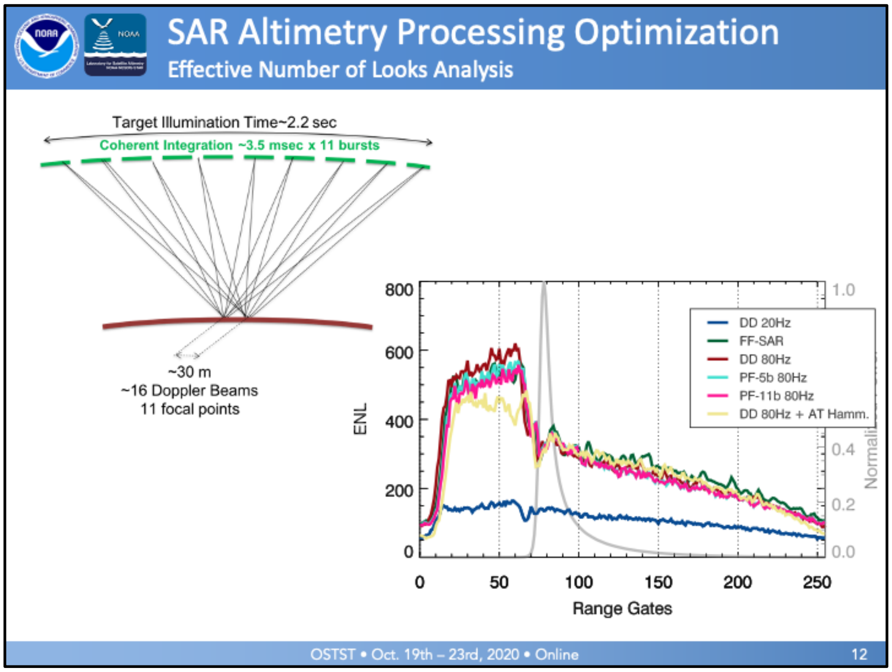


Despite the fact that the FF-SAR 2D point target response shows the expected ~0.5 meter resolution in the along-track and slant-range dimensions, the full along-track PTR shows side-lobes that are due to the lacunar sampling of the Doppler spectra, originated by the closed burst operation.

This limits the performance of FF-SAR for current SAR altimeters. This is observed as the increase in effective number of looks (ENL) from the standard delay/Doppler processing to FF-SAR is lower than expected. The increase is a factor of 2, whereas a factor of about 3 was expected.

This issue is not specific of the FF-SAR processing technique, and could be overcome with an appropriate sampling of the fully available along-track Doppler spectrum. As shown by the autocorrelation function of consecutive FF-SAR waveforms on-ground, the short scale correlation length of individual waveforms is about 0.5 meters, corresponding to the along-track resolution, which suggest an even higher speckle noise reduction if the full Doppler bandwidth was properly sampled.



Using different coherent integration times, such as 5 bursts and 11 bursts for the focusing, but maintaining all bursts for multilooking results in very similar effective number of looks throughout the waveform.

We concluded that, in closed burst operation mode, as long as all the information is maintained, there is not a significant difference between processing modes, in terms of speckle noise reduction. Therefore, over the open ocean, similar performance in the reduction of measurement noise could potentially be obtained with the delay/Doppler processing and FF-SAR.

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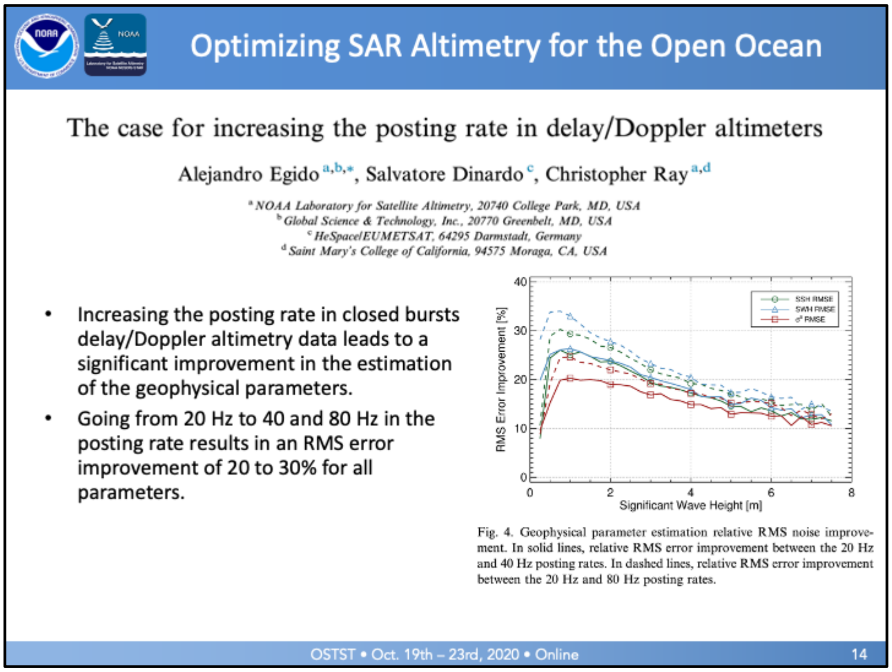
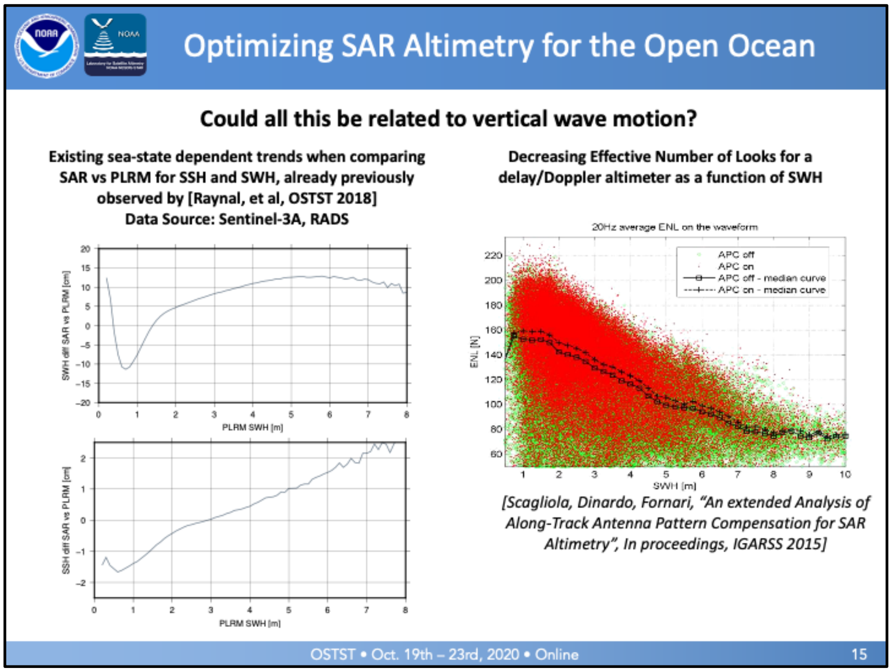


Following that idea, we conducted an investigation in which we determined that the autocorrelation function of adjacent SAR waveforms resulted in a decorrelation length much shorter than the inherent delay/Doppler along-track resolution. Thus, it is justified to increase the posting rate, potentially to ~80 Hz, the burst repetition frequency. By doing so, we obtained significant improvements in the retrieval of geophysical parameters.

This update in the processing requires minimal change in the ground segment, and could become an actionable item for operational agencies.

In 25 years of altimetry special issue:
Alejandro Egido, Salvatore Dinardo, Christopher Ray, “The case for increasing the posting rate in delay/Doppler altimeters”, Advances in Space Research, 2020, https://doi.org/10.1016/j.asr.2020.03.014.



Another aspect of the optimization and validation of our technique over the open ocean was to compare the FF-SAR and delay/Doppler measurements with pseudo-Low Resolution Mode measurements. This is important to compare the new SAR altimeter data to the conventional altimeter geodetic data record.

As other authors, we observed that there are sea-state dependent biases in the determination of both SSH and SWH. Another effect that has been previously observed was the reduction on the effective number of looks with sea-state, something that is not observed in LRM mode.

We posed the question whether all this could be linked to vertical wave motion.

Numerical Simulations

delay/Doppler map computation

$$\mathrm{DDM}(\tau, f) = \frac{\lambda^2}{(4\pi)^3} \int_A \frac{G^2(\vec{\rho})\sigma^0(\vec{\rho})\chi^2(\delta\tau, \delta f)}{R^4(\vec{\rho})} d\vec{\rho}$$

- G: Antenna Gain
- σ^0: Radar Backscattering
- χ: Woodward-Ambiguity Function (WAF)
- R: Distance to point on surface

$$\chi(\delta\tau, \delta f) \approx \mathrm{sinc}\,[B\,\delta\tau]\,\mathrm{sinc}\,[T_i\,\delta f]$$

- B: Chirp signal bandwidth
- T_i: Coherent integration time (burst duration for delay/Doppler)

For altimeter geometry σ^0 and R can be considered to be mostly constant over the antenna footprint, and therefore:

$$\mathrm{DDM}(\tau, f) \approx K \int_A G^2(\vec{\rho})\chi^2(\delta\tau, \delta f) d\vec{\rho}$$

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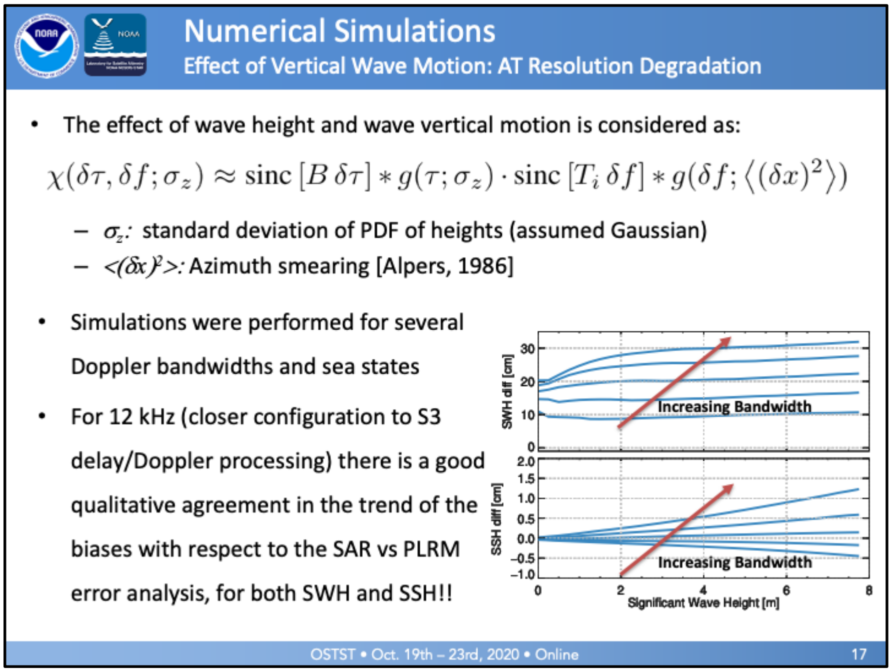
In order to investigate this issue, we performed numerical simulations of the delay/Doppler waveform.



We introduced the effect of the vertical wave motion as a degradation of the along-track resolution, as proposed in [Alpers, 1986].
The azimuth degradation is considered as a convolution of the original along-track PTR with a Gaussian, whose variance depends on the vertical velocity through the significant wave height.
We performed several numerical simulations of SAR waveform returns for different sea-states and Doppler bandwidths.
We then retracked those waveforms without considering the vertical wave motion effect to see if we could reproduce the biases observed in the S3A data.
For a 12 kHz bandwidth, comparable to S3, the results we obtained from the numerical simulations qualitatively agree with the results from S3A data.
We are now working on introducing the vertical wave motion effect in our SAR waveform model to estimate it in the retracking process.

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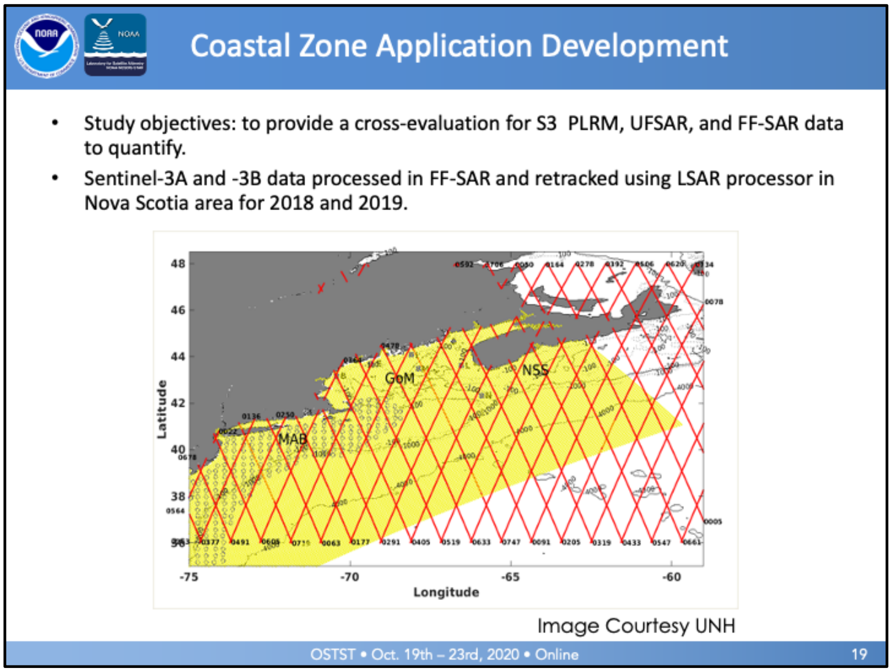
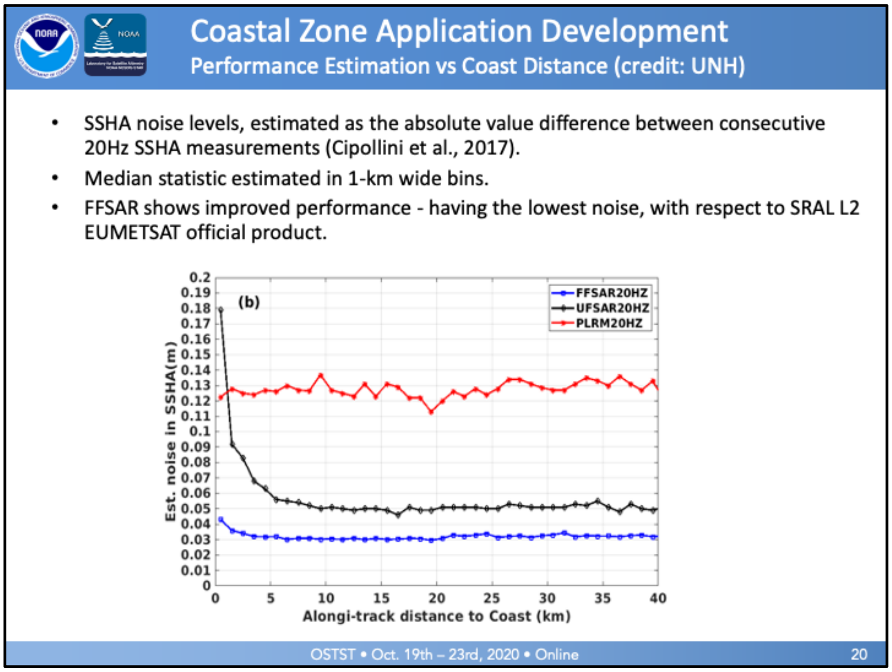
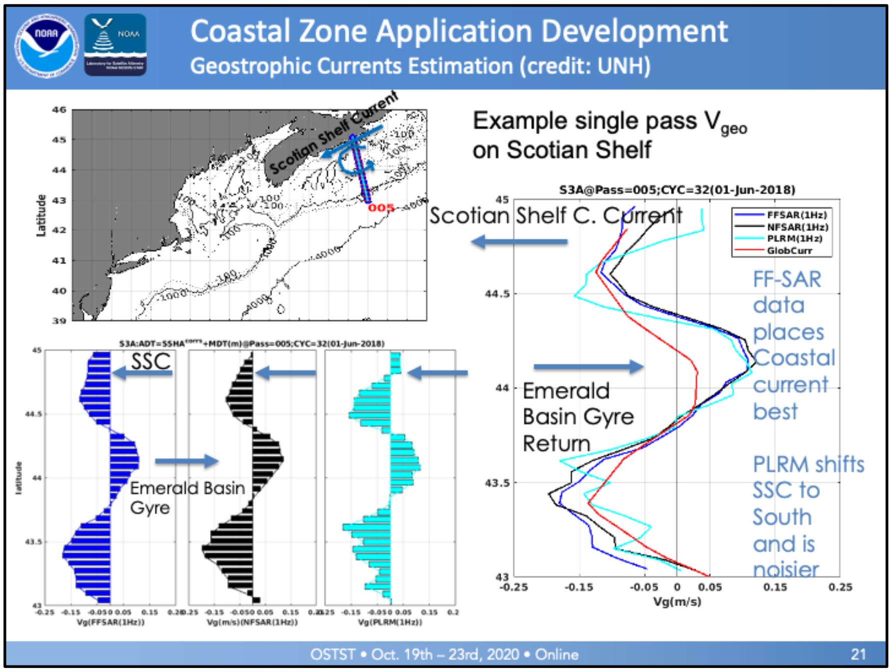


We tested the benefits of using FF-SAR for coastal zones in the Nova Scotia area. For this we processed two full years of Sentinel-3A data and Sentinel-3B in 2018 and 2019.



The results show that the FF-SAR has superior performance than delay/Doppler (UF-SAR in this slide), specially at distances closer to the coast.



We are now using these data to estimate geostrophic currents in the region. The extended temporal dataset should allow us to investigate the seasonality of these currents.

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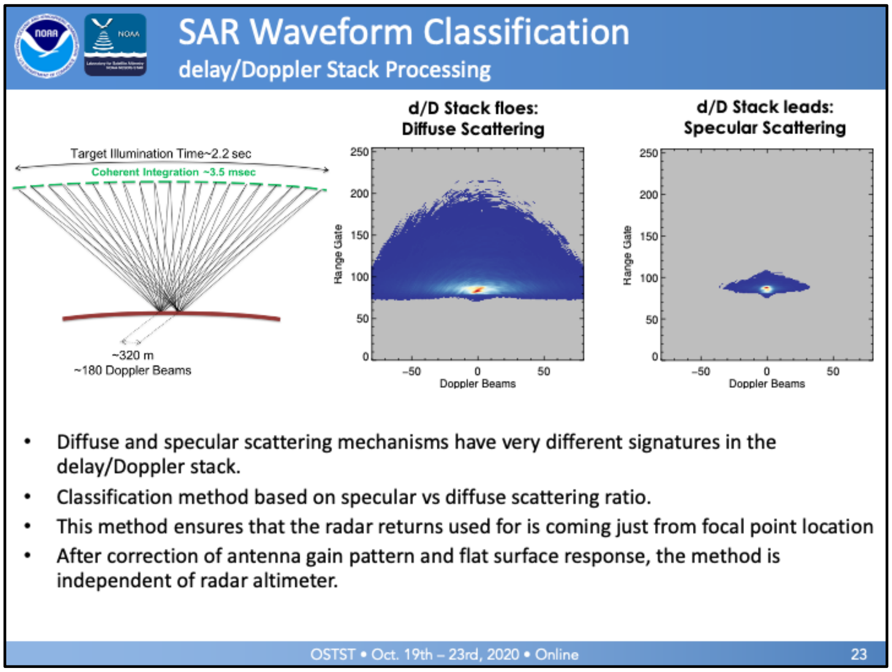
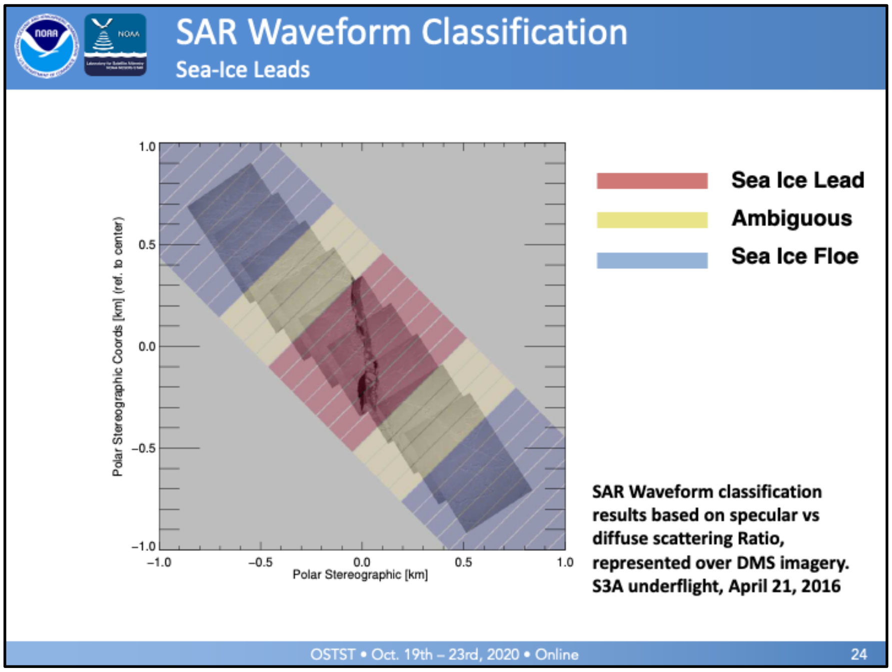


For the development of sea-ice application component we are now working on the development of a physical based retracker for sea-ice, and specifically specular echoes.

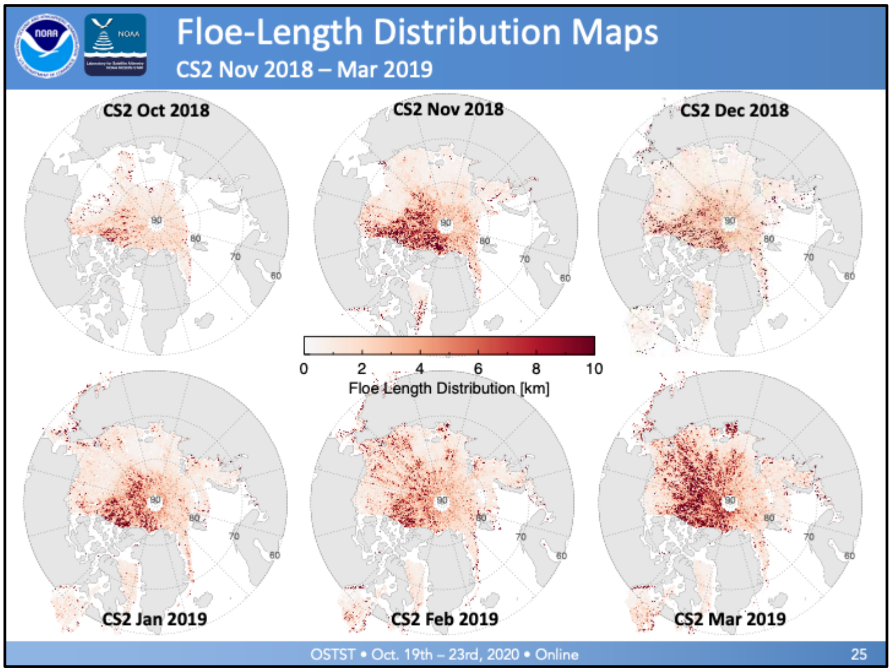
The first step in this process is to develop a classification method to discriminate SAR altimetry waveforms from leads or floes.

We have developed a new classification method based on the specular vs. diffuse scattering ratio, that we obtain from the delay/Doppler stack, with the idea that highly specular returns coming from leads have the energy concentrated on the central Doppler beams, whereas diffuse echoes from floes have the energy distributed across the stack.



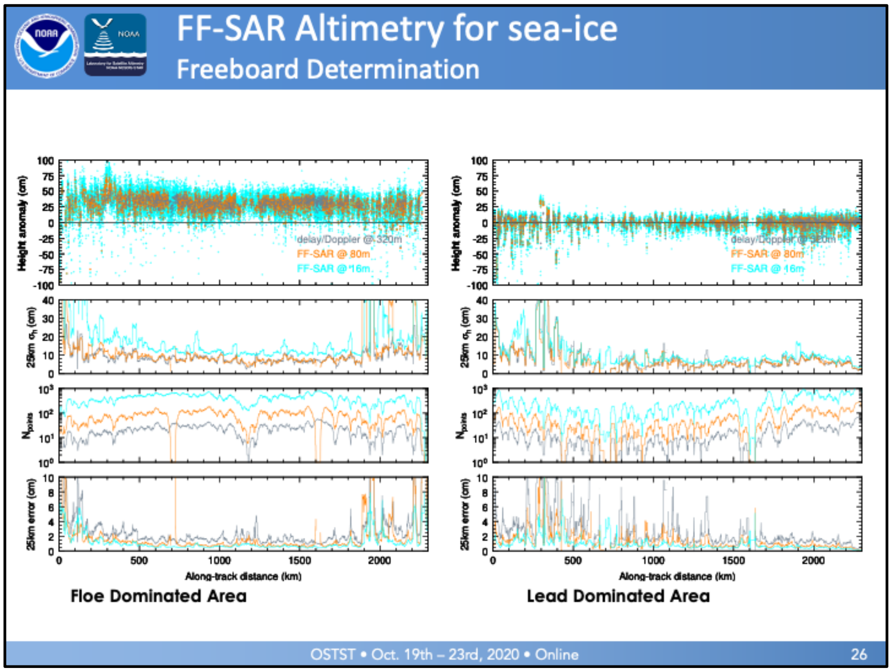
We have tested this classification method using NASA Ice-bridge underflights for both CS2 and S3.

In this slide we're showing images of the Data Mapping System camera, overlaid with the classified S3A footprint, showing extremely good agreement between the position of leads and ice-floes based on this classification method. Mixed or ambiguous returns are also classified, and those will be excluded from later analysis.



Based on this classification method we have developed sea-ice floe length maps for a full Arctic season.

This high resolution Arctic data will be made available shortly through public ftp.



We have also tried the performance of FF-SAR in the determination of sea-ice freeboard.

For that, we have considered the processing of CryoSat-2 SAR mode echoes in full FF-SAR resolution, and we have then applied different multilooking lengths, to test the performance of those. The sea-ice waveforms were then classified with a retracked based on JPL's sea-ice retracker.

We determined that by using shorter multilooking lenghts, due to the higher number of measurements, it was possible to reduce the measurement error of heights measurements over both floes and leads at scales of 10 to 25 kms.

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Conclusions and Future Work

- During this project we have developed critical aspects of SAR altimetry and investigated the application of FF-SAR processing to key science application areas.
- We have developed a SAR altimetry L1 and L2 pre-operational processor with a full range of configuration capabilities and state of the art processing methods.
- We have investigated the application of FF-SAR in the open ocean, coastal areas and marginal ice zones, with very promising results.
- During this last year of the project we will finalize the development a the parametric sea-state bias model and the implementation of a physical retrack for sea-ice applications.
- Work for future projects entails a complete investigation on the effects of vertical wave motion on SAR altimetry and the reconciliation of the conventional low resolution mode altimetry data record with the novel SAR altimetry data record.