Sea Ice Altimetry and Classification using Grazing Angle Reflected GNSS Signals Measured by Spire's Nanosatellite Constellation

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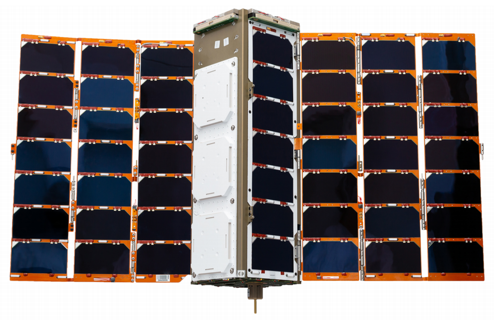
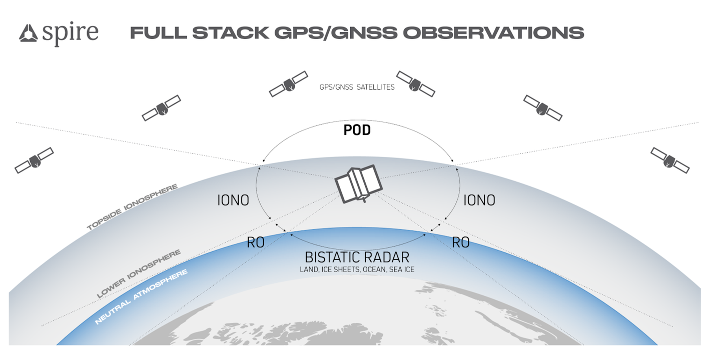
Spire Global, Inc. is a commercial company that currently operates the world's largest earth observation sensing satellite constellation. Each nanosatellite is equipped with a GNSS receiver that was originally designed for radio occultation measurements. More recently, software modifications were made to current RO satellites in-orbit to allow for the additional collection of reflected GNSS measurements (GNSS-R) of the Earth's surface properties.





Grazing Angle GNSS-R

Overview

- At low grazing angle geometries (5 – 30° elevation), reflected GNSS signals are phase coherent over smooth surfaces such as sea ice, which allows for precise altimetric height retrieval
- Sensitivity of reflected GNSS L-band signals to surface roughness also enables studies on sea ice classification and detection

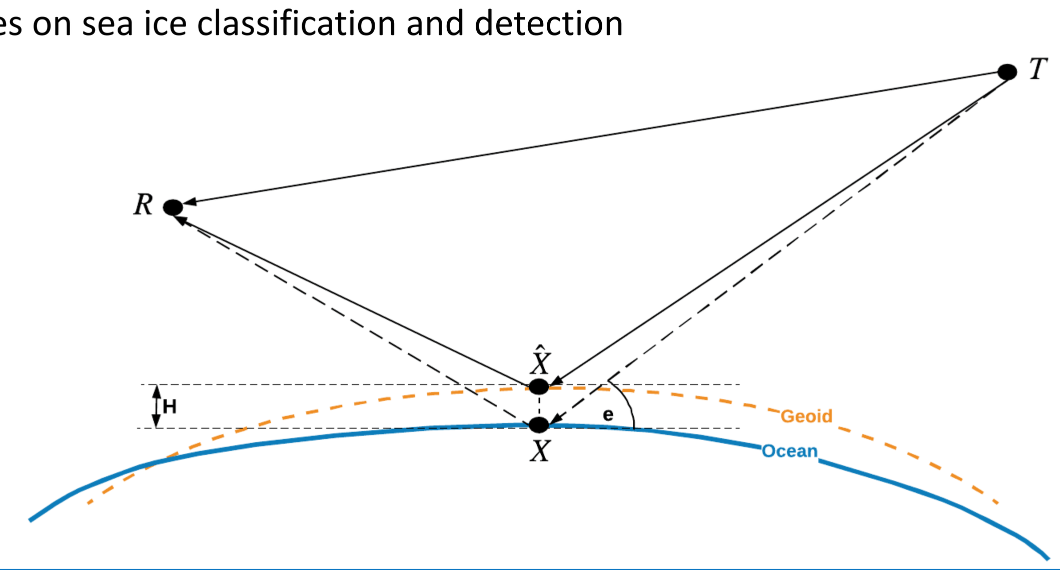


Figure 1: Grazing angle GNSS-R scenario. Phase coherent measurements are used to derive altimetric height residuals from a reference surface such as the Earth geoid.

Collection and Retrieval

- During grazing angle GNSS-R events, signal reflection at two frequencies is observed through the limb-facing antenna and is tracked using an open-loop tracking technique
- Surface altimetric measurements can be inferred by examining the difference between the observed geometric distance of the reflected signal path and the a priori distance based on a reference surface
- Computation of the observed geometric distance requires the estimation and removal of sources contributing to the signal delay
- Direct signal is simultaneously tracked to remove receiver clock errors
- Neutral atmospheric delay is removed using NCEP GFS analysis refractivity values

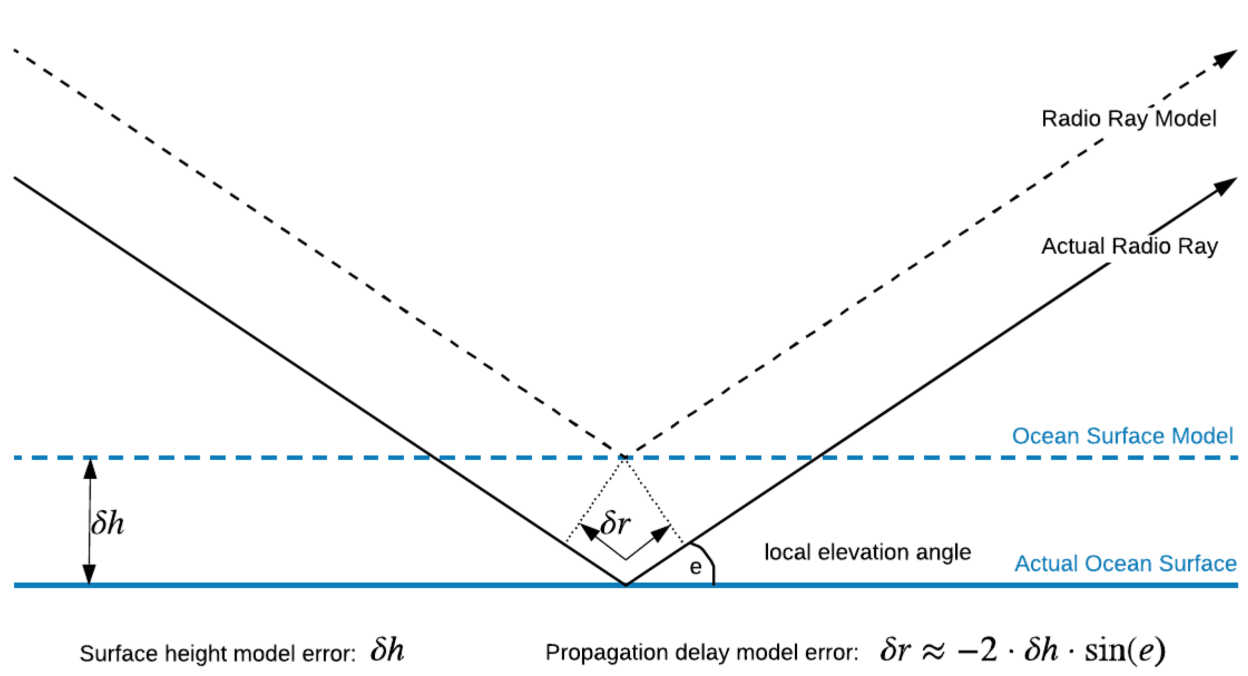


Figure 2: Geometric mapping of reflected ray propagation delay variations to ocean height (altimetry) changes

Altimetry in the Cryosphere

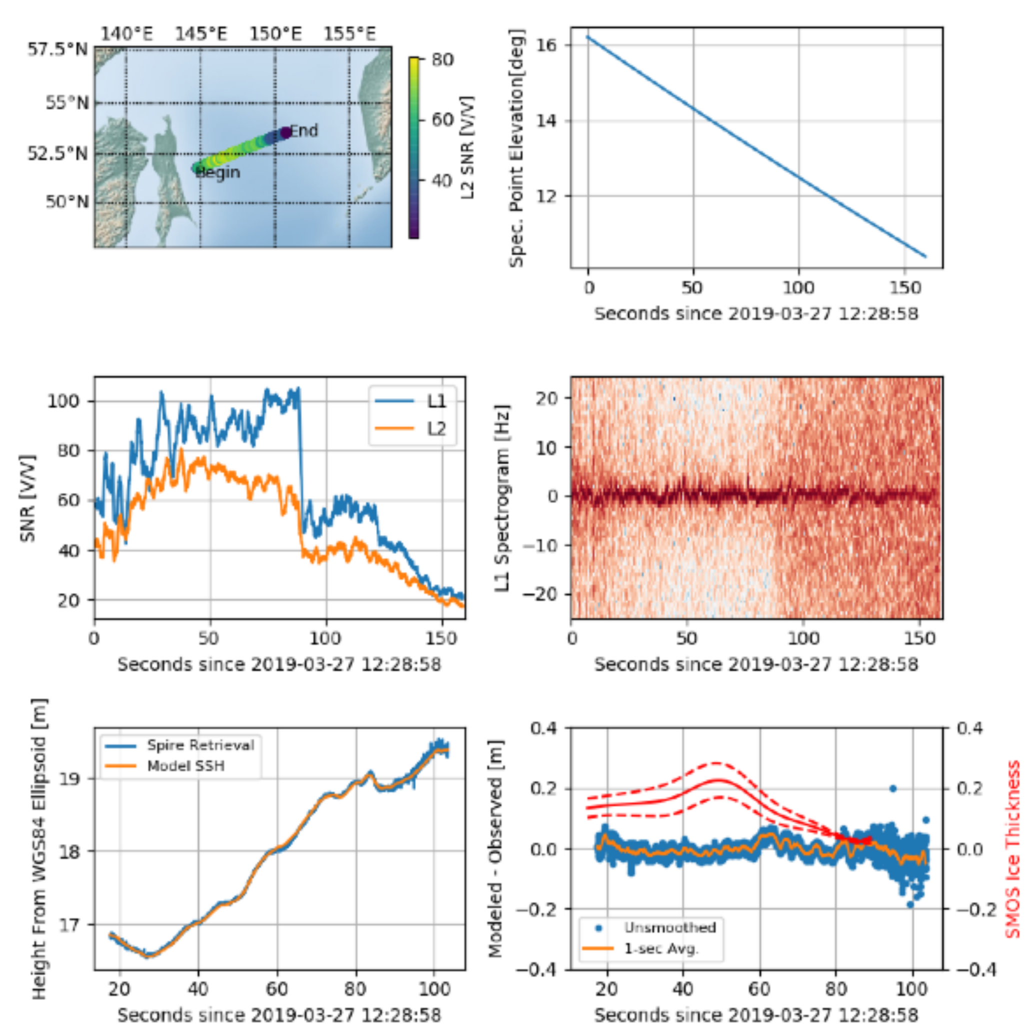


Figure 3: Example of GNSS phase altimetry measurements and retrieval. Figure shows specular point location (top-left), specular point elevation angle (top-right), SNR and spectrogram (middle) and retrieved height estimates and comparison to modeled values (bottom) [*Nguyen et al.*, 2020].

Case Study: Sea of Okhotsk

- Event shows reflected signal is phase coherent and achieves moderate SNR over sea-ice covered regions at the beginning of the track
- Altimetric retrieval estimates show < 5 cm precision when compared to the modeled sea surface height composed of DTU18 mean surface + TPXO ocean tides
- Comparison of the height difference residuals with ice thickness values shows little correlation, implying the signal is likely reflecting off the top of the ice (air/ice or air/snow interface)

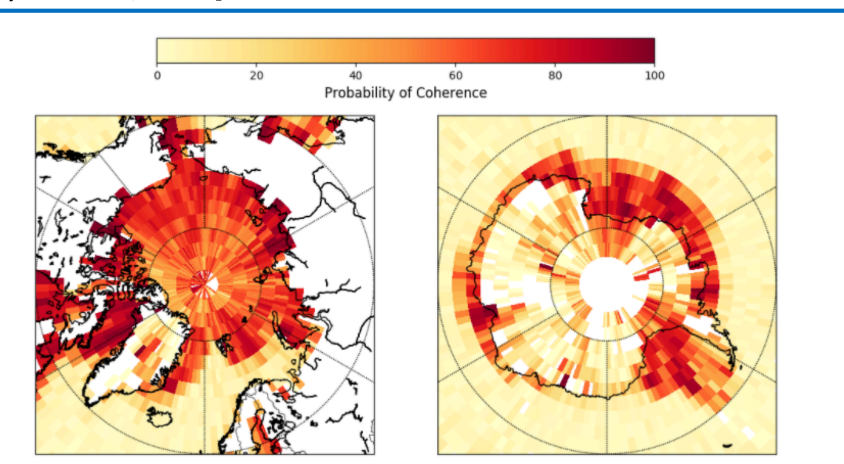


Figure 4: Estimated probability of coherence map for one week (24 Apr – 01 May 2020)

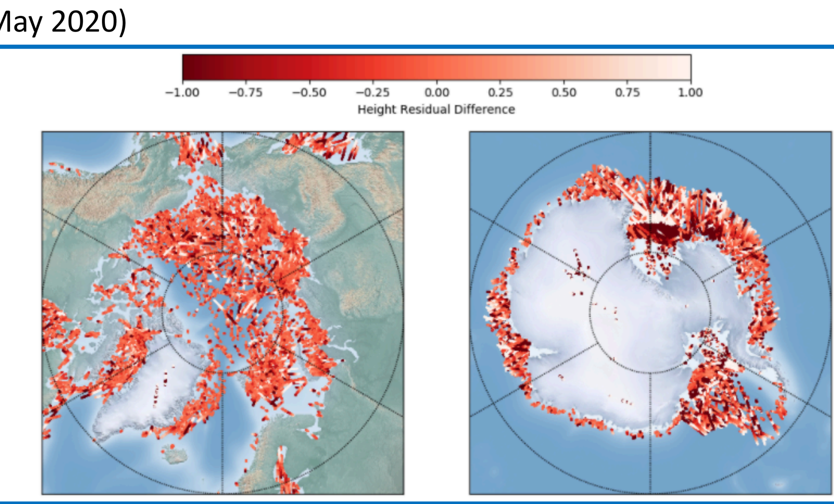


Figure 5: Coverage map of successful Level 2 altimetric height estimates for one week. Larger errors are mainly due to tropospheric delay estimation obtained from a coarse climatological model (Collins, 1999).

Global Statistics

- Relative altimetric retrieval (bias from model mean sea surface is removed for each event) is currently applied to all Spire grazing angle GNSS-R events in near-real-time
- Successful altimetric retrieval depends on the phase coherence of the reflected signal, which is highest over new sea ice regions
- Potential areas of improvement in the retrieval include **a)** more robust phase unwrapping, **b)** more accurate neutral atmospheric delay estimation, and **c)** resolving measurement biases

Data Access and Conclusions

- Spire's RO satellites are also tasked with continuously collecting grazing angle GNSS-R measurements for cryospheric study
- Phase coherent measurements can be used to derive altimetric measurements over sea ice < 10 cm precision
- GNSS-R phase noise is sensitive to surface roughness and thus, can be utilized for detecting sea ice extent and type
- Spire Level 1 and 2 grazing GNSS-R, altimetric and sea ice classification products are currently produced in near-real time
- Level 1 products are available for researchers through the NASA Commercial Smallsat Data Acquisition (CSDA) Program. Level 2 products are currently under evaluation and are expected to be available soon.

Sea Ice Detection and Classification

Retrieval

- To assess the coherence of the samples, the statistics of the residual phase change over 1-second windows is calculated
- High (low) standard deviation represents low (high) phase coherence

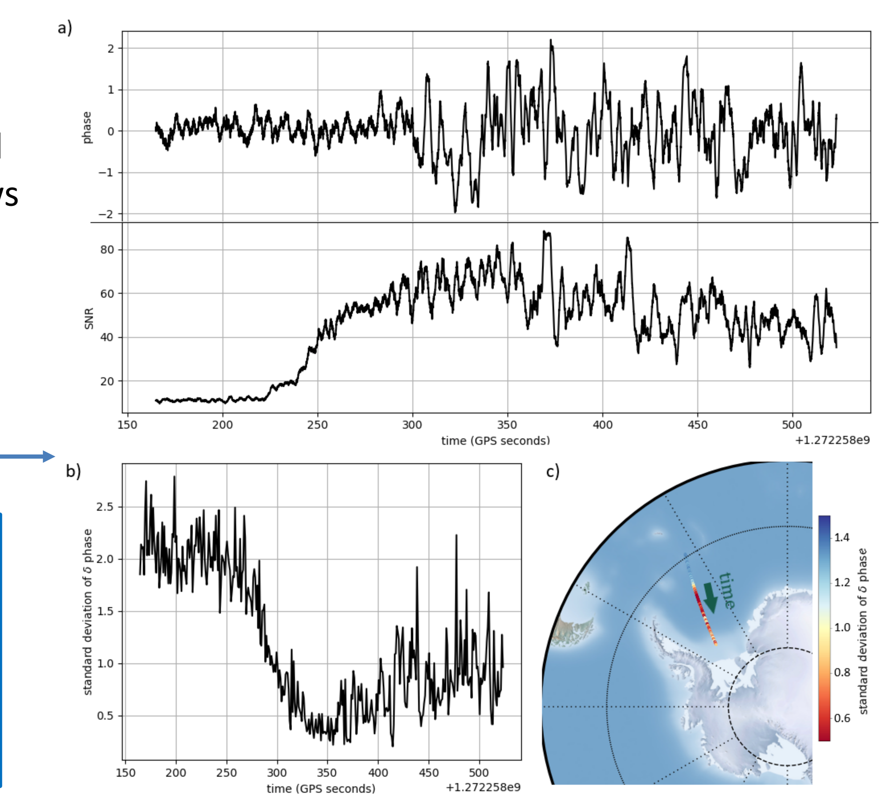
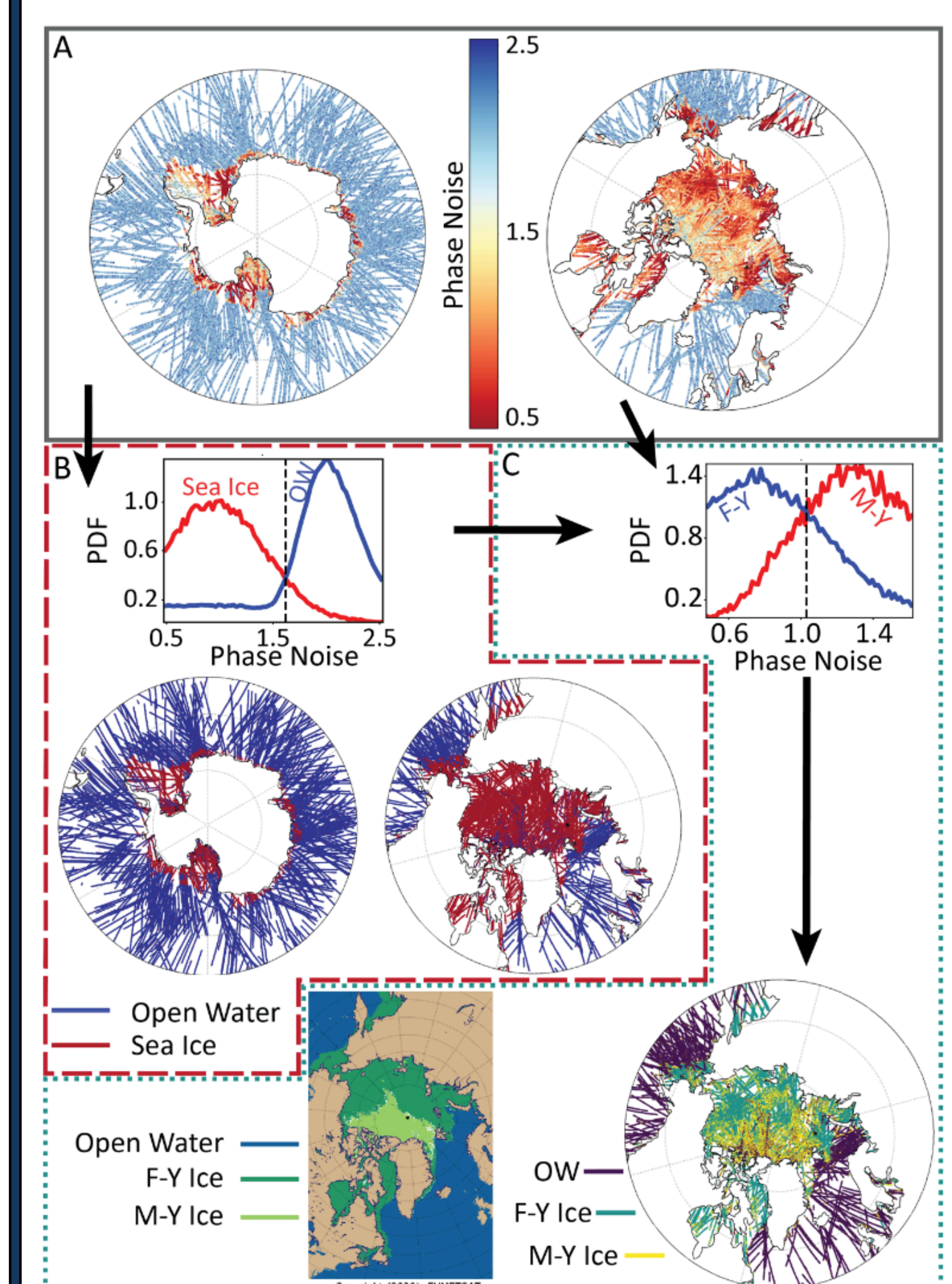


Figure 6: Example of residual phase and SNR during a grazing angle GNSS-R event and how that converts to the coherence metric. The sharp decrease in phase noise represents the transition from open ocean to sea ice.



Results and Validation

- The phase noise of the signal also yields information on the roughness of the surface at the scale of L-band wavelengths
- Open water appears as higher phase noise than ice, and older (rougher) appears as higher phase noise than younger (smoother) ice
- Results for the March through May 2020 dataset show 95% agreement with operational ice edge products

Figure 7: Process of sea ice detection and classification. Box A shows input data of the phase noise over two weeks (2nd March – 15th March 2020) in both the Antarctic (left) and Arctic (right). Box B shows the identification of sea ice and open water (OW) using a training dataset from OSI SAF. Box C (dotted outline) shows the progression of this ice detection to ice type classification in the same manner using an ice type training dataset from OSISAF (shown bottom left for comparison)

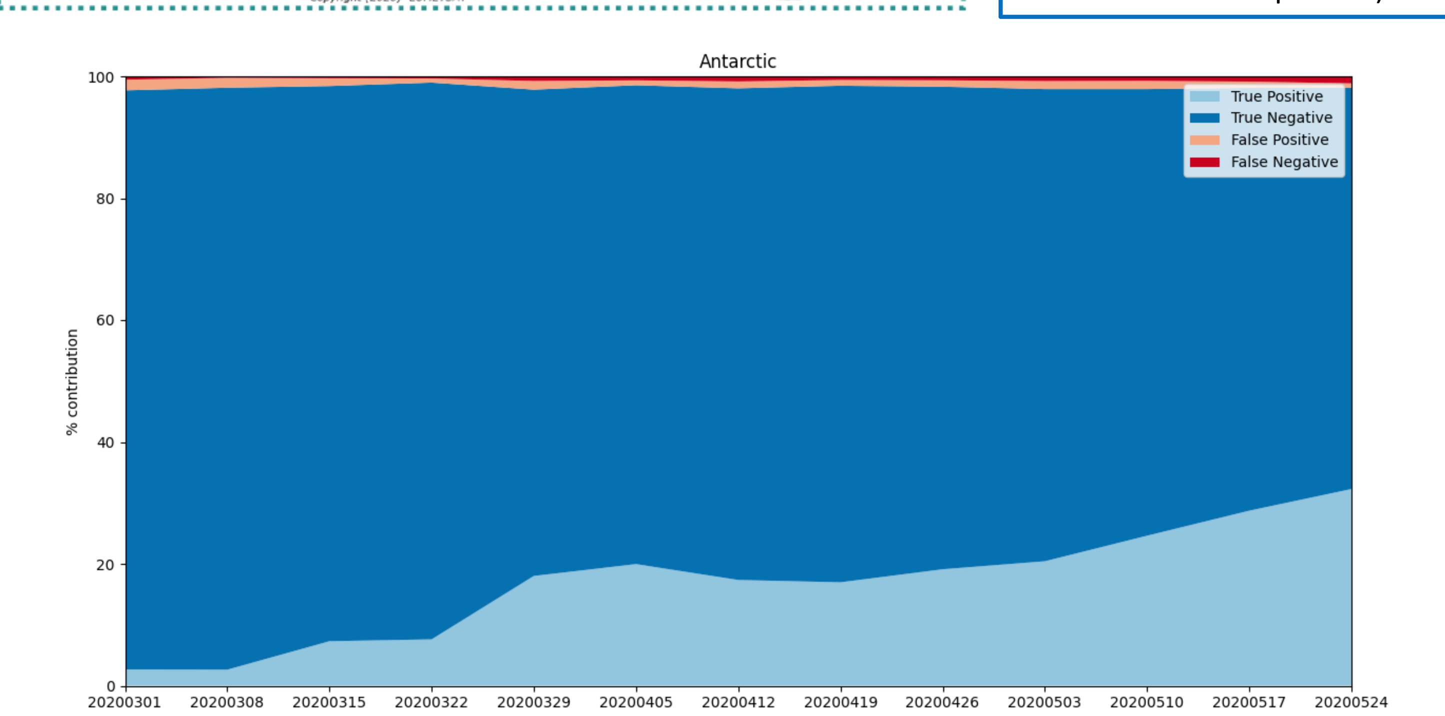


Figure 8: Area plot show weekly proportion of samples correctly (blue) and falsely (red) assigned for the Antarctic region during the March through May 2020 period. Light colors represent positive ice detection and darker negative ice detection.