# Consolidating ICESat-2 Ocean Wave Characteristics with CryoSat-2 during the CRYO2ICE Campaign

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## Introduction

Since July 2020, CryoSat-2 and ICESat-2 has flown in a synchronous orbit configuration, enabling almost same-time observations at significant stretches along the orbit in the northern hemisphere. By utilizing this configuration to observe the changing ocean properties, we get the first look at the performance of satellite altimeters at longer stretches (>30s). We use this data to determine the behavior of the provided data product for the significant wave height (SWH) as well as determining the performance of a novel technique based on the actual ocean surface from the ICESat-2 lidar data. We compare the results with existing altimeter performance studies, and asses the performance of the models in various sea states.

What we determine from this analysis is not only how well the altimeters determine the SWH, as this can already be done using crossover analysis, but we see the performance over at a spatial reach along the groundtracks.

## Method

We use **two different approaches** in estimating the SWH, based on the sea surface variance as well as ocean waves.

**CryoSat-2** As a conventional radar altimeter, the SWH is determined from the empirical relationship between the backscatter and the surface roughness.

**ICESat-2** The standard data product uses the standard deviation as a measure of SWH, while the proposed "histogram model" uses individual surface waves accumulated along-track to determine the SWH. To determine these waves we use a Savitzky-Golay Filter to keep the magnitudes intact from the filtering. From these waves, we determine the mean of the highest one third to establish an SWH. In the further analysis, three models are used, the standard data product (ATL12), the SD model and the histogram mode.

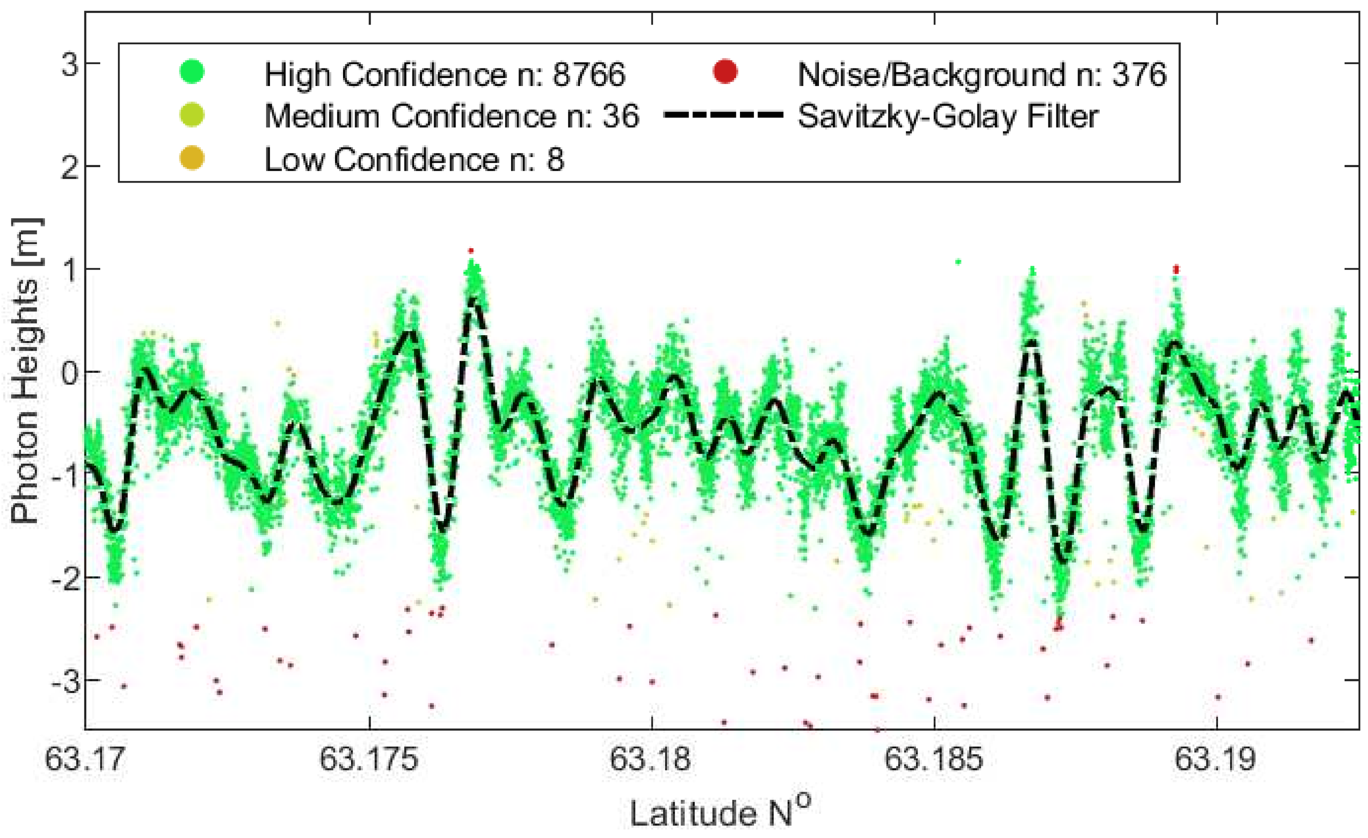
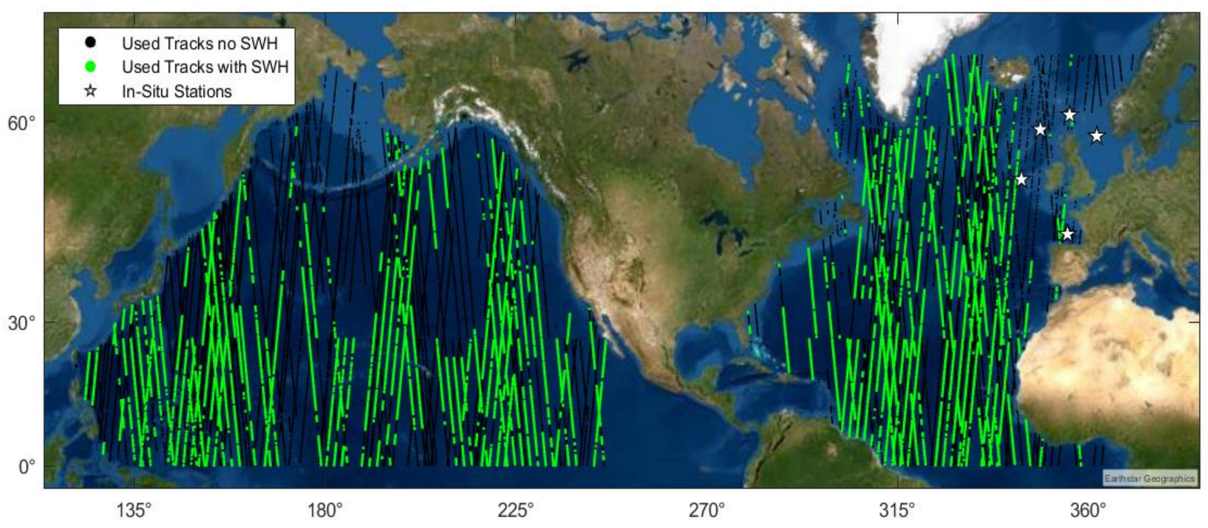



**Figure 1:** photon backscattering from the ICESat-2 lidar as well as a fitted ocean surface, used for determining the SWH.

## Data

We have used data from August 2020 to August 2021, excluding closed basins and areas close to land (< 50 km). The inter-spatial separation between the two satellites are limited to 50 km, and with a maximum time lag of 3 hours between observations with a mean of 2.3 hours. With these restrictions, we found 136 orbit segments we could use for analysis. We have used five in-situ stations to validate CryoSat-2 SWH observations.

**Figure 2:** CryoSat-2 orbits (black) with all tracks containing data (green). Stars indicate stations used for validating CryoSat-2 SWH observations. This shows the geographic reach of the data used in this project.




## Results

**Ground tracks** The plots seen in figure 3, show the estimated SWH along the ground track of two sections, where we have a long stretch of data – as lidar is obscured by clouds, normally we see shorter sections containing data. We can though see different effects of the altimeters here, as we have segments in both ground tracks, where we have observations from CryoSat-2, but lack observations from ICESat-2. And then we also see gabs from both satellites, where we have islands. In conclusion, we see how the different methods behave, and we will now quantify the performance.

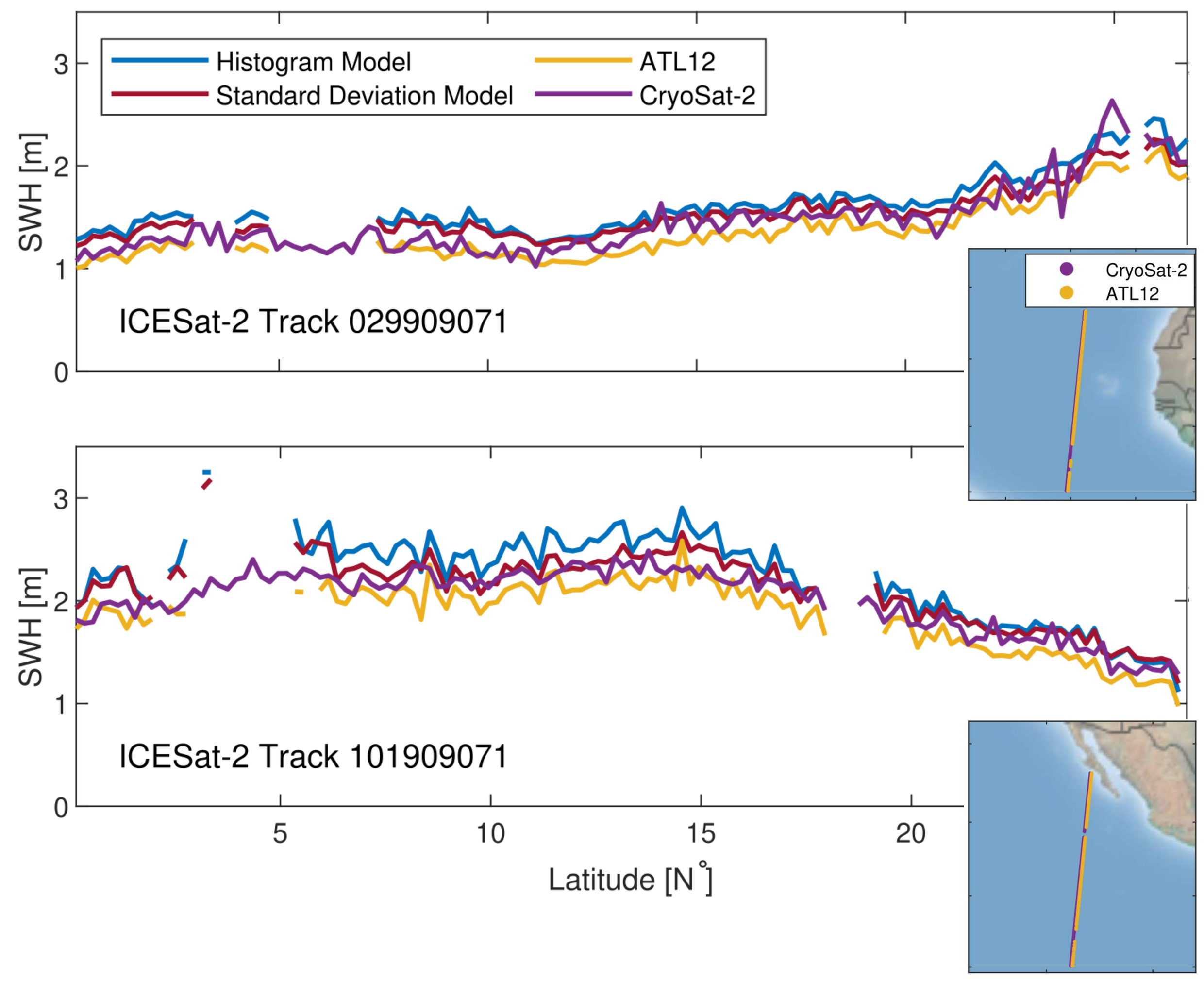



**Figure 3:** Ground tracks of ICESat-2 orbit segments, and the corresponding SWH's for the different models. The segments are from the Atlantic Ocean (top) and the Pacific Ocean (bottom).

**Total comparison** As seen in figure 4, we have collected all observations we have, and computed an average over approximately 20 km, and then used CryoSat-2 as a baseline, to see the deviation and spread of the models using ICESat-2 data. We see here how we have a larger general spread at higher SWH and a larger number of observations close to 0m. Shown in red is the QQ-plot of the residuals.

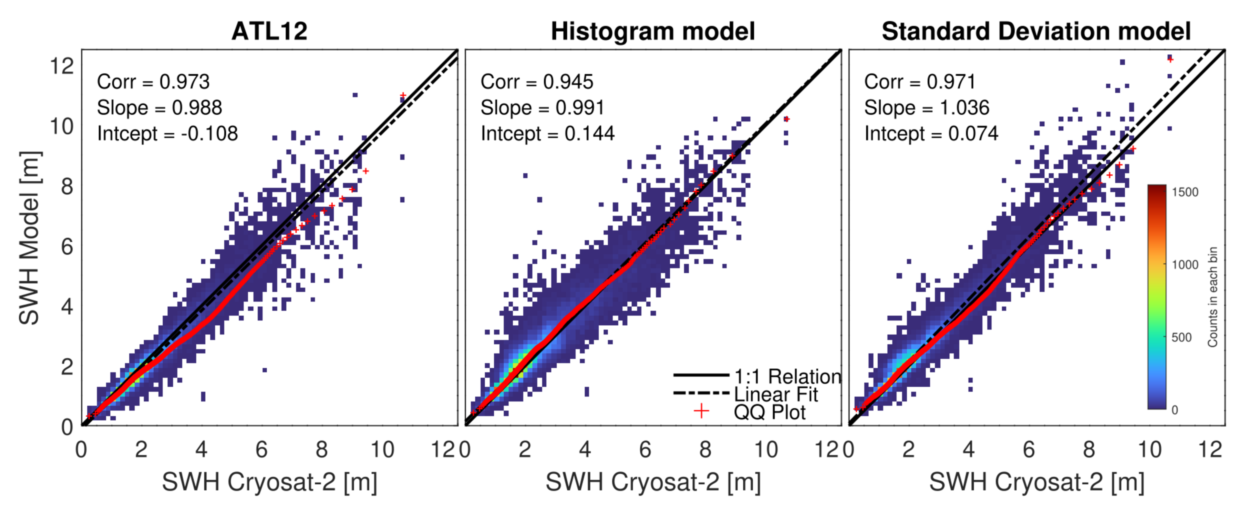



**Figure 4:** Observation of the models plotted against observations from CryoSat-2 as the ground truth. Here sees the correlation and QQ plots.

**Sea-State dependency**
Continuing from the analysis before, we segment the residuals into groups with increasing SWH values. From this we get figure 5, where we see how the mean difference get more volatile at large SWH, while getting a larger RMSE value as well. What we also see though, is the large decrease in the number of observations at high SWH (see > 5 m), and at the observations at lower SWH, the mean difference between the altimeters are quite constant.
As seen, we get a quite large deviation at high SWH (>8m), however we have quite few data from this region.

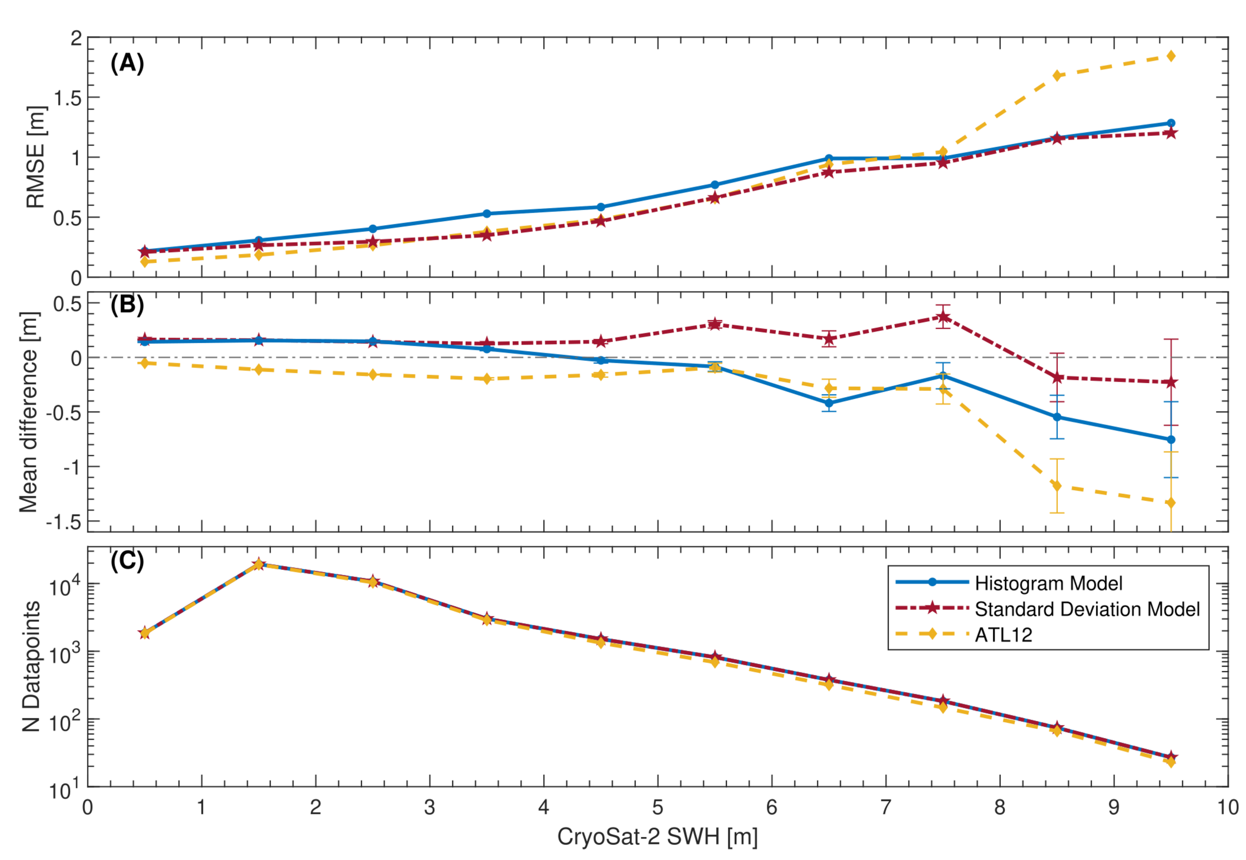



**Figure 5:** Behavior of the three models compared to CryoSat-2. Here sees the RMSE value (top), the mean difference (middle) and the number of observations (logscale, bottom) as a function of SWH

## Conclusion & Outlook

From this study, we have determined the behavior of the SWH observations with three different methods, compared to CryoSat-2. As we see, the performance of the methods has ha strong dependence on the measured SWH, and there is still a need for a proper determination of the behavior at high SWH, due to the low number of observations at these waveheights. The total performance is however able to be determined, and as seen in table 1, we have mean differences below 20 cm for all methods, but with a higher and lower correlation when using the histogram approach, as opposed to the two models using the standard deviation approach. Using more refined filtering techniques and machine learning methods, this could be possible to improve.

| Method | Mean. Diff [m] | RMSE [m] | Corr. | N |
|---|---|---|---|---|
| Histogram Model | 0.14 | 0.42 | 0.95 | 37861 |
| SD Model | 0.17 | 0.33 | 0.97 | 37861 |
| ATL12 | -0.12 | 0.29 | 0.97 | 36763 |

**Table 1:** Table showing the summary statistics of the comparison with the three models using ICESat-2 data, compared with the CryoSat-2 baseline.

In this study we have been restricted to using data from the northern hemisphere, due to the limitations of the orbits. This has also restricted our ability of capturing observations at high SWH as often as would be possible with observations from the Southern Ocean. With the proposed future mission of realigning the orbit of CryoSat-2 to overlap in the southern hemisphere, this comparison would be possible, and would provide valuable data for the comparison at high waveheights.

## References

1) Klotz, B.W.; Neuenschwander, A.; Magruder, L.A. High-resolution ocean wave and wind characteristics determined by the ICESat-2 land surface algorithm. Geophys. Res. Lett. 2020, 47, e2019GL085907.
2) Morison, J.; Hancock, D.; Dickinson, S.; Robbins, J.; Roberts, L.; Kwok, R.; Palm, S.; Smith, B.; Jasinski, M.; Plant, B.; et al. Algorithm Theoretical Basis Document (ATBD) for Ocean Surface Height Version 4.
3) Neumann, T.A.; Brenner, A.; Hancock, D.; Robbins, J.; Saba, J.; Harbeck, K.; Gibbons, A.; Lee, J.; Luthcke, S.B.; Rebold, T.; et al. ATLAS/ICESat-2 L2A Global Geolocated Photon Data, Version 4; NASA National Snow and Ice Data Center Distributed Active Archive Center: Boulder, CO, USA, 2021.
4) Alford, J.; Ewart, M.; Bizon, J.; Easthope, R.; Gourmelen, N.; Parrinello, T.; Bouffard, J.; Michael, C.; Meloni, M. #CRYO2ICE Coincident Data Explorer, Version 1. Available online: http://cryo2ice.org (accessed on 10 August 2021).
5) Nilsson, B.; Andersen, O.B.; Ranndal, H.; Rasmussen, M.L. Consolidating ICESat-2 Ocean Wave Characteristics with CryoSat-2 during the CRYO2ICE Campaign. Remote Sens. 2022, 14, 1300. https://doi.org/10.3390/rs14061300

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