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Lead detection using Cryosat-2 delay-doppler processing and Sentinel-1 SAR images

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Abstract

In the Arctic and Antarctic Ocean, where part of the sea surface is seasonally or continuously covered by sea ice, the sea level monitoring from satellite altimetry relies on the localisation of open water areas, especially on the detection of leads: long and narrow fractures in the sea ice, which dominate the radar echoes even if hundreds of meters away from nadir.

The Cryosat-2 altimetry mission is based on the Delay-Doppler processing, in which the averaged waveform is formed by summing up several looks acquired at different look angles and stacked together. This imaging technique and the resulting improved along-track resolution are here exploited to evaluate different lead identification schemes.

In particular, stack and power statistics of Cryosat-2 waveforms are used to classify leads on a subset of 12 tracks in which the altimetry-based classification is compared to a classification based on Sentinel-1A SAR images. For this scope, a dedicated SAR-image automated processing is proposed to avoid the manual classification.

Results show that the adoption of a single new stack parameter (the Stack Peakiness) can perform equally well as the use of multiple stack parameters currently available. Moreover, a multi-waveform analysis of the Stack Peakiness helps to isolate the point where narrow leads cross the tracks at nadir.

For all the tested strategies, the number of altimetry-detected leads that are unidentified by SAR is comparable to the number of detections from both sensors. This could be due to presence of narrow leads, not detected by SAR due to resolution limits, but still dominant in the radar altimeter return due to the high backscatter.

Keywords: Leads detection; Delay-Dopper altimetry; Cryosat-2 stack data; Sentinel-1; SAR image processing

1. Introduction

The measurement of sea level variability in the global ocean is considered among the most important climatic indices. It relies on in situ observations provided by a wide but unevenly distributed set of tide gauges and, since more than 20 years, on measurements collected by the radar altimeters on board of several satellite missions.

The coverage of satellite altimetry over the ocean cannot completely be defined as global, since a large part of the Arctic and Antarctic oceans is excluded. On one side this is due to the limited latitude extent of most of the altimetric missions due to their orbit configuration. On the other side the ocean in the northernmost latitudes is partially covered by sea ice, which reflects the radar signal before it hits the sea surface, preventing the possibility to measure sea level. The estimation in the sea-ice covered regions is limited to the leads, narrow cracks in the sea ice that can be several tens of kms long. Since these ocean patches are very smooth and do not have a developed wave field, the signal

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returned to the satellite is much stronger than the one reflected from the surrounding ice and can dominate the registered waveforms even if the lead is not located at nadir. In particular, Armitage and Davidson (2014) have shown that a lead can be the dominant return in the waveform up to about 1.5 km away from the sub-satellite point (nadir). Such off-nadir returns, if not properly spotted, result in erroneous estimations of the sea level.

Cryosat-2 (CS-2) offers ways for improving the sea level records in these regions. With its orbit configuration, it provides coverage up to 88° in latitude. Thanks to the Delay-Doppler processing of its echoes (when operating in the so-called "SAR mode" over sea ice, not to be confused with SAR imaging from Sentinel-1 used in this study), it stores the signal registered by the satellite looking at the same resolution cell on the ground from different look angles. In particular, the beam-limited along-track footprint size (305 m, Scagliola, 2013) should guarantee a more precise determination of the lead position. Nevertheless, due to the size of the pulse-limited across-track footprint (1.65 km), the distinction of a lead return at nadir from an off-nadir reflection is still challenging. Most of the leads have width of less then a km (Lindsay and Rothrock, 1995; Kwok et al., 2009), while Cryosat-2 has a sampling interval of roughly 300 m (using the 20-Hz rate): in most of the cases, only one range measurement per lead will correspond to the distance at nadir. Being able to correctly identify the nadir echoes of these narrow, but numerous open water openings can increase the amount of sea level measurements and therefore improve the records.

Previous studies on past altimetry missions have used lead-detection algorithms that distinguish leads from sea ice based on the shape of the received signal: Empirical thresholds were assigned in order to classify the waveforms based on the "pulse peakiness" (Peacock and Laxon, 2004). Laxon et al. (2013), Ricker et al. (2014) and Rinne and Similä (2014) have classified CS-2 signals using a combination of different waveform parameters (including the pulse peakiness) available in the European Space Agency (ESA) Baseline C Product files or computable from the waveforms. Recently, Wernecke and Kaleschke (2015) argued that it is possible to obtain an efficient lead classification only based on the absolute value of the maximum waveform power.

Leads can be also determined using thermal infrared sensors (Willmes and Heinemann, 2015), microwave radiometers (Röhrs and Kaleschke, 2012) and SAR images (Ivanova et al., 2016). SAR images have the advantage of being independent from weather conditions, while providing a good resolution (40 m for Sentinel 1A). They can be therefore used for comparison with the altimetry-based lead classification, but the time difference between the acquisition of the two different data sources needs to be taken in consideration, since sea ice moves on average from 4 km/day in winter up to over 9 km/day in summer (as measured by buoys in Rampal et al. (2009)) and leads can quickly refreeze and close (Weeks, 2010).

The objective of this study is to provide a first assessment of the lead-classification methodologies based on the Delay-Doppler processing of Cryosat-2 echoes in comparison to SAR images from Sentinel-1A. Our classification, based on a new parameter computed using the Delay-Doppler processing of CS-2 (in particular from the full stack information) and on a multi-waveform analysis to isolate the nadir return, is compared with the methodologies derived from the recent literature. A SAR-image processing chain is proposed to provide a reference for validation and, for the first time, is used to provide an objective comparison that is not based on a visual recognition of lead-like features.

A description of the dataset and the area of study is provided in Section 2. Section 3 describes the methodology used to analyse the altimetry and SAR dataset and to classify the leads. In Section 4 the results of the comparison are presented and discussed. Section 5 draws the conclusions and the outlook for future research.

2. Dataset

2.1. Cryosat-2 L1B-S data

By exploiting the Doppler frequency and the coherence of consecutive pulses, Delay-Doppler altimeters are able to perform multi-looked acquisitions, i.e. to associate to a resolution cell a certain number of looks (variable depending on the processing settings) acquired at different look angles as the satellite moves over the imaged area (Raney, 1998).

Using processing techniques inherited from the SAR processing, such as Range compression and Range migration correction, all the returns corresponding to the resolution cell (a 20-Hz sampling of the illuminated surface, i.e. one measurement every 300 m roughly) are aligned in a 2D-stack (Figs. 1a and 2a). The Cryosat-2 multilooked radar waveforms, such as the one in Fig. 1c and 2c, are obtained by the incoherent sum of all the echoes in the stack. By summing up the returns in the across-track (Range) dimension (Fig. 1b and 2b), the so-called Range Integrated Power (RIP) waveform, can be generated. It contains information concerning the backscattering properties of the illuminated surface, but it also reveals details of the distribution of the scatterers as the satellite spans different look angles passing over the nadir position (Wingham et al., 2006).

When the satellite moves over a very smooth surface, such as for small lakes or leads (Fig. 1), the signal will be specularly reflected back and the RIP will be peaky. On the opposite, when flying over areas containing scatterers with different orientation, such as for wavy seas or ice, the backscattered power will be more normally distributed (Fig. 2).

L1B products provide statistical parameters that describe the RIP behaviour, but do not provide the full stack, limiting therefore the possibilities of analysis. The ESA Grid Processing on Demand (G-POD) service

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