About the consistency between Envisat and CryoSat-2 radar freeboard retrieval over Antarctic sea ice

S. Schwegmann[1], E. Rinne[2], R. Ricker[1], S. Hendricks[1], V. Helm[1]

[1] {Alfred Wegener Institute, Helmholtz-Centre for Polar- and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany}

[2] {Finnish Meteorological Institute, Marine Research, Erik Palménin aukio 1,

FI-00560, Helsinki, Finland}

Correspondence to: S. Schwegmann (Sandra.Schwegmann@awi.de)

Abstract

Knowledge about Antarctic sea-ice volume and its changes over the past decades has been sparse due to the lack of systematic sea-ice thickness measurements in this remote area. Recently, first attempts have been made to develop a sea-ice thickness product over the Southern Ocean from space-borne radar altimetry and results look promising. Today, more than 20 years of radar altimeter data are potentially available for such products. However, ~~data come from different sources, and~~ the characteristics of individual radar types~~sensors troughout~~ differ for the available altimeter missions. Hence, it is important and our goal to study the consistency between single sensors in order to develop long and consistent time series~~ over the potentially available measurement period~~. Here, the consistency between freeboard measurements of the Radar Altimeter 2 on-board Envisat and freeboard measurements from the Synthetic-Aperture Interferometric Radar Altimeter on-board CryoSat-2 is tested for their overlap period in 2011. Results indicate that mean and modal values are comparable over the sea-ice growth season (May-Oct) and partly also beyond. In general, Envisat data shows higher freeboards in the ~~seasonal~~ first year ice zone while CryoSat-2 freeboards are higher in the ~~perennial~~ multi-year ice zone and near the coasts. This has consequences for the agreement in individual sectors of the Southern Ocean, where one or the other ice class may dominate. Nevertheless, over the growth season, mean freeboard for the entire (regional separated) Southern Ocean differs generally by not more than 3~~2~~ cm (8~~5~~ cm, with few exceptions~~except for the Amundsen/Bellingshausen Sea~~) between Envisat and

CryoSat-2, and the differences between modal freeboard lie generally within ±10 cm and often even below.

1 Introduction

Over the last three decades, sea-ice extent (SIE) in the Arctic has decreased and submarine ice draft measurements indicate that also sea-ice volume is declining (Rothrock et al., 1999, Rothrock et al., 2008, Lindsay and Schweiger, 2015). In the Antarctic on the contrary, SIE is increasing, but ~~only~~ little is known about the changes in ~~the~~ sea-ice volume. This is due to the lack of systematic sea-ice thickness measurements in the Southern Hemisphere~~ remote area~~. There are only few in situ data sets from upward looking sonars (only Weddell Sea, e.g. Harms et al., 2001, Behrendt et al., 2013), drillings (e.g., Lange and Eicken, 1991, Ozsoy-Cicek et al., 2013, Wadhams et al., 1987, Perovich et al., 2004), electromagnetic methods (Haas, 1998, Weissling et al., 2011, Haas et al., 2008) and airborne altimetry (e.g., Dierking, 1995, Leuschen et al., 2008). Those data are distributed unevenly in location, coverage and time and do not allow for the estimation of seasonal and interannual sea-ice volume changes. Only ship-based visual observations (ASPeCt, Worby et al., 2008) have been used for estimations of the seasonal variability in selected regions. Hence, in order to investigate current mass balance and feedback mechanisms of the entire Antarctic sea-ice zone we need sea-ice thickness retrievals from satellite sensors.

The capability of sea-ice thickness retrieval~~s~~ using satellite radar and laser altimetry data has been demonstrated for Arctic and Antarctic sea ice (Ricker et al., 2014, Laxon et al., 2013, Kurtz et al., 2014, Zwally et al., 2008, Yi et al., 2011). The altimetry sea-ice thickness retrieval algorithm is based on estimations of freeboard, the height of the ice (ice freeboard) or snow surface (total or snow freeboard) above the local sea level. One fundamental requirement for freeboard retrieval is the interpolation~~estimation~~ of sea surface height (SSH) from altimeter range data between leads in the ice cover~~over leads between ice floes~~. The SSH along the satellite ground track forms the reference surface, where the residual of surface elevations over ice gives the freeboard. Sea-ice thickness is then calculated from freeboard using hydrostatic equilibrium equations, requiring estimates of the snow depth and densities of sea ice, snow and water. There are two categories of altimeters currently used for space-borne freeboard measurements: The Geoscience Laser Altimeter System (GLAS) on-board the Ice, Cloud and land Elevation Satellite (ICESat, 2003-2009) measured the distance to the snow/ice surface, hence used~~srevealeds~~ snow freeboard as reference interface. Radar altimeters like the Radar Altimeter 2 (RA2) on-board Envisat (2002-2012) or the Synthetic-Aperture Interferometric Radar Altimeter (SIRAL) on-board CryoSat-2 (CS-2, since 2010) are based on K_u-Band frequencies. Compared to laser altimetry, radar altimeters have the advantage negligible influence ~~of not being influenced~~ by cloud cover. Contrary, the~~, but yield significantly larger~~ surface footprints of radar altimeter is considerably larger than for laser altimeters. A~~I~~n additional complication, especially for sea ice in the~~ the~~ S~~s~~outhern hemisphere, is the location of the main backscattering interface. A~~Surface backscatter a~~t K_u-Band frequencies ~~were~~it is originally assumed that the main part of the echo return power originates from ~~to be dominated by~~ the snow/ice interface for dry and cold conditions.~~,~~ In this case radar altimeter range measurement~~thus~~ generally relate to ~~yielding~~ ice freeboard. However, the generality of this~~is~~ assumption has been recently questioned by several publications (Willatt et al., 2010, Willatt et al., 2011, Ricker et al., 2014, Kurtz et al., 2014, Price et al., 2015, Kwok, 2014).

Over sea ice in the Southern Ocean, Zwally et al. (2008) and Yi et al. (2011) provided a first estimate of snow freeboard and sea-ice thickness distribution and its seasonal evolution in the Weddell Sea using the laser altimeter data from ICESat. They found the highest snow freeboard and the thickest ice in the western Weddell Sea and a clear seasonal cycle of the snow freeboard with the highest values in summer (since all the thin ice is melted away) and lower values in the beginning of winter (due to ~~massive formation of~~ new ice formation). A comparison between field data and ICESat ground track in the Bellingshausen Sea showed a good agreement between both methods (Xie et al., 2011). Recently, Kern and Spreen (2015) estimated finally the potential uncertainty of sea-ice thicknesses derived from ICESat and AMSR-E snow depth, which ranges between 20 % and 80 %. They found that ~~the highest impact~~ ~~comes from the applied SSH detection~~the choice of SSH estimation has the highest sensitivity, but ~~a~~ reasonable alternatives for lead detections~~to that detection~~ do~~es~~ not result in~~show~~ significant~~a huge~~ differences. At the same time as the first ICESat snow freeboard maps were developed by Zwally et al. (2008), Giles et al. (2008) computed freeboard out of radar altimeter data from the European Remote Sensing satellite 2 (ERS-2). In their study they could show that the winter mean freeboard from ERS-2 shows a reasonable distribution and good qualitative agreement with ship based observations. Later, ~~Also~~ Price et al. (2015) found a good agreement with field data using CS-2 radar signals to derive sea-ice freeboard over the fast ice of McMurdo Sound.

Since previous studies show a proof-of-concept of hemisphere-wide sea-ice thickness retrieval using satellite altimeter time series, the next steps would be to merge data sets from different satellite missions to a consistent long-term record of Antarctic sea-ice thickness. With the radar altimeters on the ERS-1, ERS-2, Envisat and CryoSat-2 missions of the European Space Agency, a continuous data set spanning two decades is available. One particular challenge for a merged time series though is the different radar configuration between the pulse-limited altimeters of ERS-1, ERS-2 and Envisat and CS-2, which employs along-track beam-sharpening for a smaller footprint size. As a result, the characteristics of the ~~time-dependent radar backscatter, recorded as~~ radar echo waveform for each single measurement~~,~~ are of inherently different ~~in~~ shape for thefor~~between the~~ two radar altimeter types~~acquisitions~~. Range retrieval from the radar waveform is often based on an empirical evaluation of the leading edge, since the full wave form of a sea-ice target is usually of high complexity. Since existing studies on freeboard or thickness are usually based on a single mission the empirical range retrieval algorithms are not necessarily consistent for different sensor types. Hence, in order to create an inter-sensor time series, we need to test different algorithms on their consistency for different sensors.

Within the ESA Climate Change Initiative (CCI) Sea ice project - Antarctic Sea-ice thickness Option - Envisat and CS-2 freeboard values over the entire Antarctic sea ice cover have been computed for ~~independently from~~ each dataset~~other~~. A freeboard time series created by those sensors has the potential to cover more than 10 years yet, from 2002 until today. More importantly, both data sets have a full year of~~n~~ overlap ~~period~~ in 2011. This overlap is used to assess a potential inter-mission bias and sensor associated uncertainties based on independently produced monthly mean and modal freeboard values from Envisat and CS-2. Differences are discussed with respect to regional and temporal variability and potential causes are identified. We also relate the differences to the occurrence of the diverse ice classes, ~~in which we use the terms “seasonal ice” for predominant occurrence of first~~i.e. first year ice, and~~,~~ ~~perennial~~ multi-year ice ~~for regions with second/multi-year ice~~ and coastal ice for all the ice that occur close to the coasts (deformed drifting ice, first and multi-year ice as well as landfast ice)~~ that occur close to the coasts~~. This effort is the first towards a development of consistent retrieval algorithms for both pulse-limited and beam-sharpened radar altimeters, with the objective to extend the sea-ice thickness time series in the Southern Ocean back to 1991 with ERS-1 and ERS-2.

2 Data and Methods

Antarctic wide freeboard from Envisat and CS-2 data was derived by two different, sensor related processors for the overlap period in 2011. In order to distinguish between open water and sea ice, sea-ice concentration (SIC) is used in both processors. Freeboard was only derived for regions with a SIC above 55%. Monthly mean freeboard was computed from January to December and was gridded onto a 100 km EASE-Grid 2.0 (Brodzik et al., 2012). ~~Some comparisons are also done with a 25 km grid.~~ The individual processors are described in section 2.1 and 2.2, and Table 1 gives an overview of the most important processing parameters.

2.1 CryoSat-2 freeboard retrieval

The CS-2 freeboard processor has formerly~~originally~~ been used~~developed~~ for ~~applications on~~ Arctic sea ice and has ~~now~~ been adapted for the use of Antarctic sea-ice in this study. We use~~d~~ the geolocated level 1b Synthetic Aperture Radar (SAR) and interferometric SAR (SARIn) waveform~~s~~ products over the Southern Ocean ~~obtained from CS-2~~ (K_u band, 13.575GHz) ~~and~~ provided by ESA (https://earth.esa.int/web/guest/-/how-to-access-cryosat-data-6842). The surface elevations are processed along~~from~~ individual CS-2 orbits~~tracks~~ using the Threshold First-Maximum Retracker Algorithm (TFMRA) described by Helm et al. (2014) and Ricker et al. (2014) in detail.

Specifically, the main scattering horizon is tracked at the waveforms leading edge of the first local maximum ~~of the CS-2 waveform~~ by using a power threshold (see Fig. 1). For the ~~standard~~ processing we define this~~used~~ as threshold of 40% of first maximum power ~~but also tested results using a threshold of 50%~~ to retrieve surface elevations. Geophysical range corrections (e.g. ionospheric, tropospheric and tide corrections) are applied using the values supplied in the level 1b~~L1B~~ data files of ESA. ~~The retrieved freeboard refers to the main scattering horizon of the radar wave.~~ As the exact position of the scattering horizon is unknown we do not apply a correction for the wave propagation speed in the snow layer. Instead we use for our calculation and comparison the freeboard from the uncorrected radar range, termed~~i.e. we obtain the~~ radar freeboard (F_R) in contrast to the physical interfaces~~instead~~ of either ice or snow freeboard:

(1)

L is the retrieved surface elevation, *MSSH* corresponds to the mean sea-surface height product DTU15~~0~~ (ftp.space.dtu.dk/pub/DTU15~~Andersen, 2010~~), which is subtracted from the surface elevations first, in order to remove the main geoid and sea-surface height undulations. The *SSA* is the Sea Surface Anomaly derived from linear interpolation between elevations of detected leads along the orbit track and represents the residuum from the MSSH. The sum of MSSH and SSA thus yields the actual SSH for each orbit. The discrimination between open water (leads) and sea ice is based on the waveform and SAR stack parameters such as the right and left pulse peakiness, beam kurtosis, stack standard deviation as well as an ice concentration threshold. A full description is given in Ricker et al. 2014. such as the ~~so called pulse peakiness (2) of the return signal (Peacock and Laxon, 2004)~~. Leads are cracks in the ice cover and usually have a distinct specular radar echo, while open-ocean and sea-ice surfaces have wider waveforms, resulting from diffuse reflection due to~~of~~ the higher surface roughness (see Fig. 1 for comparison). ~~The pulse peakiness (*PP*) is derived by~~

~~(2)~~

~~N_{WF} is the number of range bins and WF_i describes the echo power at range bin index i.~~ Data points, that cannot be positively identified as echoes from ice, leads or open ocean are discarded due to the possibility of a range bias from off-nadir leads (snagging) (Armitage and Davidson, 2014).

Open-ocean is identified by using SIC data obtained by the Ocean and Sea Ice Satellite Application Facility (OSI SAF) High Latitude Processing Center (Eastwood, 2012) and provided on daily grids with a resolution of 10 km. SIC are interpolated onto the respective CS-2 track in order to define the ice free areas within the CS-2 freeboard processor along those tracks.

Radar freeboard below~~lower than~~ -0.24~~3~~ m and above~~higher than~~ 2.24 m is discarded from the data sets. Indeed, negative sea-ice freeboard is possible in Antarctica, but the CS-2 signal is certainly reflected at the slush-dry snow interface. We therefore assume a valid range for freeboard footprint averages from 0 to 2 meter, but account for speckle range noise (0.24 m) of the CS-2 orbit data, thus also allowing negative freeboard values. ~~However, we allow negative freeboard to accommodate the random uncertainties caused by speckle and~~

~~instrument noise~~. Finally, freeboard values of all CS-2 tracks within a month are compiled and projected onto a 100 km EASE 2.0 grid for further analysis.

2.2 Envisat freeboard retrieval

The input data for the Envisat freeboard processing is the Envisat Sensor Data Record - SGDR (Sensor Geophysical Data Record) product available from ESA (https://earth.esa.int/web/guest/data-access/browse-data-products/-/asset_publisher/y8Qb/content/Envisat-sensor-data-record-1471). For the processing we used the ESA CCI RA2 prototype processor adapted for the Southern Hemisphere. The processing algorithm is described in detail on the Sea Ice CCI Algorithm Theoretical Basis Document (Ridout and Ivanova, 2012) and the prototype system in the Processing System Description (Kern, 2012).

The Envisat processing is similar to the CS-2 processing described in the subsection 2.1. Differences are the ~~L~~lead detection algorithm that is based on a single parameter threshold of the pulse peakiness (PP) defined as (Peacock and Laxon, 2004):

(2)

~~s are distinguished from ice floes and open water by~~ t~~he PP parameter~~. SIC information from the OSI SAF product is then used to differentiate diffuse waveforms from open water and those from ice floes. The waveforms are then retracked to obtain the surface elevation. The surface elevation is then referenced to the DTU15 MSS and the residual of the actual SSH interpolated between lead location is subtracted to obtain radar freeboard. ~~retrieve the target surface elevation and radar freeboard is derived from the lead and floe elevations by interpolating the local sea level elevation measured from leads to ice floe positions and subtracting the former from the latter.~~ As for CS-2, no correction is applied for wave propagation speed in snow so that the derived freeboard refers to the radar freeboard as well.

For Envisat we use different retrackers for leads and floes. For leads we apply the retracker described in Giles et al. (2007). The shape of a specular echo is described by two functions: the first part of the echo is represented by a Gaussian and the second part by an exponentially decaying function. These two functions are linked by a third degree polynomial function. The functions are fitted to the measured waveform using the Levenberg-Marquardt nonlinear least-squares method and one of the variables is the retracking point. For the ice floes we use a standard OCOG (offset centre of gravity) retracker with a 50% threshold.

In the Envisat processing we discard freeboards smaller than -1 m or larger than 2 m. The lower limit for reasonable freeboards is smaller for Envisat than for CS-2 because the noise in Envisat measured elevations is greater. Even if large negative freeboards should not be present the negative tail of the distribution of Envisat measured freeboards extends below -0.3 m and thus we have to use a wider window for reasonable freeboards.

3 Results

The most basic comparison between CS-2 and Envisat freeboard retrieval is to investigate the spatial and temporal distribution of the respective regional and statistical~~computed~~ freeboard distributions. Both data sets show the highest freeboard along the east coast of the Antarctic Peninsula, along the coast of the Bellingshausen/Amundsen Sea and in parts of the Ross Sea, with values of up to 1 m in the CS-2 data set (Fig. 2). These are the regions which remain ice covered during summer and are known to hold the highest freeboard and the thickest sea ice of the Southern Ocean (e.g., Worby et al., 2008, Giles et al., 2008, Yi et al., 2011). However, Envisat freeboard is generally lower in those regions compared to CS-2 freeboard.

~~At particular locations, both products reveal also negative freeboard. CS-2 data show a belt of negative freeboard in the marginal ice zone (MIZ, Fig. 2), while Envisat reveals negative freeboard only sporadically in the inner pack ice zone. In fact, SIE in the CS-2 freeboard product is larger than for Envisat, which produces an inconsistency of the distribution of negative freeboard values in this region.~~

This is also visible in the difference map in Fig. 2, where Envisat freeboard was subtracted from the CS-2 freeboard. Accordingly, red areas indicate that CS-2 has higher freeboard than Envisat, and blue values indicate that Envisat freeboard is higher. During winter months, the Envisat processor yields higher freeboard than CS-2 in large parts of the seasonal first-year sea-ice zone, though in coastal regions and regions with perennial multi-year sea ice CS-2 reveal higher freeboard. In summer, CS-2 freeboard becomes then higher than Envisat freeboard, when all the remaining ice becomes second year ice. In most regions the bias lies within ±0.10 m, in particular between May and December. However, it can increase up to ±0.60 m close to the coasts and in regions with predominantly multi-year ice.

The characteristics of the freeboard distribution, in particular the shape, have been analysed and compared using histograms covering all grid cells of each product (Fig. 3). The distribution of the freeboard is very broad in summer and fall (Jan-Apr). From end of fall until early summer (May-Dec), the distribution shows a steep increase towards a distinct mode at low values and a long but flat tail towards the thicker end. The histograms show a similar shape for most months for both data sets, with Envisat freeboard (blue) slightly shifted to higher values compared to CS-2 data (black). Only during fall (Mar-Apr), the distributions differ strongly.

At the thick end of the distribution, i.e. value above 0.35 m, Envisat freeboard is less strongly represented. On the other hand, negative freeboard occurs more often in Envisat data than in CS-2 as to be expected from the larger noise of along-track Envisat freeboards.

In order to assess a potential inter-mission bias, we calculated Antarctic wide averages of the monthly mean and modal freeboard over the entire sea-ice zone (~~see~~ Tab~~Fig~~. 2~~3~~). For this comparison~~To account for the different SIE~~, only data points occurring in both data sets have been taken into account. CS-2 modal freeboard is lower than mean freeboard in all months, like it was also found for sea ice thickness data from ICESat by Xie et al. (2013); Envisat mean and modal freeboard is generally close to each other with modal values being higher than mean values. M~~For the standard processing (Fig. 3a), m~~ean freeboard shows a seasonal cycle which is comparable for both data products. In summer, mean freeboard is the highest. With the beginning of the freezing season, it shows a slight decrease, ~~and~~ over winter, it ~~is stable~~ increases a bit and towards the summer it shows ~~only~~ a slight decrease again~~in late spring/beginning of summer~~. The modal freeboard of Envisat is the lowest in the beginning and the highest at the end of summer. ummer and the lowest at the beginning of summer. and~~data shows a similar seasonal cycle as mean freeboard with quite constant values over winter.~~ For CS-2, –modal freeboard decreases over summer with a minimum in April and increases over the winter with maximum values between July and October. do not show a seasonal cycle ~~modal freeboard shows in contrast barely any variability in 2011~~ instead.

A similar change from summer to winter sea-ice freeboard as has been investigated for the mean freeboard was found by Yi et al. (2011) analysed from ICESat data. Also Worby et al. (2008) found a similar seasonal cycle for sea-ice thicknesses obtained by ship-based observations (ASPeCt), with the highest mean thicknesses during summer and a lot thin sea ice influencing the distribution during fall. The high summer values may be caused by the quick disappearance of large areas with first year ice (FYI) in the seasonal ice zone so that the remaining ~~perennial~~ multi-year ice dominates the freeboard and thickness distribution. In the beginning of the freezing~~e~~ season, large areas are then covered by newly formed first year ice (FYI), which certainly reduces~~affect~~ the mean freeboard ~~to decrease~~ compared to summer values. The slight increase of mean freeboard over the growth season is in accordance with growing ice over winter. However, it may also be that a change in the penetration depth of the signal causes these high freeboard values. During summer, the location of the reflection horizon of the radar wave may be influenced by wet and/or metamorphous snow (e.g., Kwok, 2014, Willatt et al., 2010). This may lead to an apparent increase of the freeboard compared to winter data, when the radar backscatter or absorption inside the snow layer is less pronounced. ~~radar wave potentially penetrates the snow more effectively~~.

There is a positive bias in the mean freeboard ~~nearly~~ all year round (Tab.~~Fig.~~ 2~~3a, light grey line~~), i.e. CS-2 freeboard is on average higher than Envisat freeboard. The highest differences occur during summer, with a maximum of 0.09~~8~~ m and a root mean square error (RMS) of 0.25 m in January~~February~~. During the sea-ice growth season, between May and October, the lowest differences of about 0.01-0.03 m with RMS between 0.12 m and 0.14 m are found. ~~ExceptFrom for May, to September, these differences are not statistically significant on the 95% level.~~ The bias for modal freeboard is instead negative all over the year and does not follow a seasonal cycle. The maximum difference for modal freeboard can be found at the end of spring, in March and April. Over the rest of the year, it remains rather constant with values lower than or equal to 0.1m, considering 5 cm intervals.

~~In order to examine whether these findings are independent from the retracker threshold difference between both processors and also from the grid resolution we modified both and analysed the results. The adaptation of the retracker threshold for CS-2 based waveforms to 50% (Fig. 3b), as it is used for Envisat, results in higher differences for mean and modal freeboard in most months, except for summer. With an increased retracker threshold mean and modal freeboard become lower in the CS-2 data. As mean CS-2 freeboard is close to and modal freeboard mostly even lower than Envisat freeboard in the standard run, differences increase accordingly. The significance of the bias is given in winter months but not for summer months. In summer, the positive bias between CS-2 and Envisat freeboard becomes~~

~~reduced in the perennial~~ multi-year ~~ice zone by the changed retracker threshold. The seasonal cycle of mean and modal CS-2 freeboard does not change.~~

~~An increase of the grid resolution to 25 km (retracker threshold: 40% for CS-2, not shown) results in a similar bias for monthly mean freeboard as in the standard processing. Differences in the modal freeboard are slightly higher, similar to the processing with a retracker threshold of 50%, in particular in the winter months.~~

~~The characteristics of the freeboard distribution, in particular the shape, have also been analysed and compared using histograms covering all grid cells of each product (Fig.~~ 3~~4). The distribution of the freeboard is very broad in summer and fall (Jan-Apr). From end of fall until early summer (May-Dec), the distribution shows a steep increase towards a distinct mode at low values and a long but flat tail towards the thicker end. The histograms show a similar shape for most months for both data sets, with Envisat freeboard (blue) slightly shifted to higher values compared to CS-2 data (black). Only during fall (Mar-Apr), the distributions differ strongly.~~

~~At the thick end of the distribution, i.e. value above 0.35 m, Envisat freeboard is less strongly represented. This issue was already visible in Fig. 2, where we could identify lower freeboard in most of the perennial ice regions. On the other hand, negative freeboard occurs more often in Envisat data than in CS-2. This is in apparent contradiction with Fig. 2, where CS-2 data show large areas covered by negative freeboard. However, these comparisons were only made for regions, where both products have valid values, i.e. large parts of the MIZ in CS-2 data were not taken into consideration in the histograms. Hence, within the pack-ice zone, Envisat data show more often negative freeboard than CS-2 data.~~

~~Figure 5 shows the regional and temporal distribution of the grid-cell based bias in monthly mean freeboard over the entire Southern Ocean. For the calculations, Envisat freeboard was subtracted from the CS-2 freeboard. Accordingly, red areas indicate that CS-2 has higher freeboard than Envisat, and blue values indicate that Envisat freeboard is higher. During winter months, the Envisat processor yields higher freeboard than CS-2 in large parts of the seasonal~~ first-year ~~sea-ice zone, though in coastal regions and regions with perennial~~ multi-year ~~sea ice CS-2 reveal higher freeboard. In late spring, CS-2 freeboard becomes often higher than Envisat freeboard. In most regions the bias lies within ±0.10 m, in particular~~

~~between May and December. However, it can increase up to ±0.60 m close to the coasts and in regions with predominantly perennial~~ multi-year ~~ice.~~

For the individual sectors of the Southern Ocean (following the sector classification in Parkinson and Cavalieri (2012)), the occurrence of ~~perennial~~ multi-year and seasonal ice has a varying impact on mean and modal freeboard (see Tab. 3 for summer and winter values, exemplarily~~see Fig. 6~~). In ~~the Weddell~~ Sea ~~(WS) and~~ the Ross Sea~~s~~ ~~(RS)~~, the bias for the mean radar freeboard is negative from April to August. In the Weddell Sea it is negative in August only. ~~and statistically significant over winter (Apr-Aug for WS and April-Oct for RS)~~. The Ross and Weddell Seas are the regions with the largest SIE, hence, a lot of seasonal ice and free drifting sea ice far away from the coast is apparent in those sectors. Therefore, the total bias becomes partly negative over winter, when the area and therefore the impact of the ~~perennial~~ multi-year ice ~~and the high freeboard close to the coast~~ become less pronounced compared to the total SIE. Over summer, the percentage of those ice classes increases again and therefore, both regions show a positive~~, but partly not significant bias~~ bias, i.e. CS-2 showing on average higher freeboard values than Envisat. In the Indian Ocean sector ~~(IO)~~, the Western Pacific Ocean ~~(WPO)~~ and in the Bellingshausen/Amundsen Sea ~~(ABS)~~, either the ~~perennial~~ multi-year sea ice or the impact of ~~the~~ coastal ice dominates and leads to a year round positive bias in mean freeboard. The combination of both effects, the higher CS-2 freeboard in the ~~perennial~~ multi-year sea-ice zone and near the coast and the lower CS-2 freeboard in the seasonal pack-ice zone, leads to a high positive bias in summer and a nearly balanced (zero) one during winter for data averaged over the entire Antarctic sea-ice zone ~~(see Fig. 3, left)~~. However, the differences in the modal freeboard are for all regions for most months negative, which indicate that most of the ice-covered grid cells have higher values for Envisat data. A positive difference can be found in the Indian Ocean~~O~~ sector (Jan~~-Feb~~), the Western Pacific Ocean sector (Jan-Mar, Dec~~Feb~~), the Ross See (only Feb) and the Amundsen/Bellingshausen Sea (Feb~~-May~~) only in the summer months, when most of the ice is the ~~perennial~~ multi-year and coastal sea ice. Most of the differences for (sectional) modal freeboard are lower than or equal to ±0.1 m (88%), in a lot of months it is even lower than or equal to ±0.05 m (about 58~~7~~%, considering 5 cm intervals).

4 Discussion

The present study investigates the consistency between Envisat and CS-2 radar freeboard developed independently from each other within the ESA CCI Sea ice project. We found a reasonable ~~a good~~ agreement for the regional distribution of freeboard, with thicker radar freeboard in the regions with ~~perennial~~ multi-year ice. However, Envisat freeboard tends to be higher than CS-2 in the ~~seasonal~~ first-year sea-ice zone while CS-2 data are higher compared to Envisat along the coast and in the ~~perennial~~ multi-year sea-ice zone. ~~Though A~~aA simple change in the retracker threshold would~~cannot~~ not solve this issue because such a~~this~~ modification ~~would~~ changes all freeboard values only in one direction. ~~: a higher leading-edge threshold would result in lower freeboard and a lower threshold in higher values. Hence, using e.g. the same retracker thresholds for both products will not improve the consistency between Envisat and CS-2 freeboard.~~ Furthermore, although b~~B~~oth products reveal negative freeboard (Fig. 3),~~.~~ Envisat shows higher fractions of it ~~negative freeboard~~.~~,~~ ~~which~~This might be caused by the coarser spatial resolution, leading to an erroneous sea-surface height interpolation, but also by the difference in noise level and accordingly the cut-off windows for both products~~.~~ In any case, we do not expect, that this negative freeboard is related to flooded sea ice, since the radar signal would not penetrate through the flooded layer.

~~A potential source for inconsistencies between both data sets may be the different SSH product. For Envisat the MSSH is taken directly from the SGDR product (ESA, 2007) file. This instead is derived from the Collecte Localisation Satellite, CLS01 monthly product (Hernandez and Schaeffer, 2000), which is referred to the EM96 geoid. The TFMRA for CS-2 freeboard calculation uses the MSSH product DTU10 (Andersen, 2010), which is a climatology and refers to the WGS84 geoid. Despite this difference, we do not expect a consequence for radar freeboard as the detection of the local SSH by lead detection in both processors should overcome the difference in the mean SSH products. Indeed, leads are expected to be sparse in the western Weddell Sea and along the coasts, because the sea ice is quite compact in those regions. However, w~~

In order to investigate potential causes for the differences in both data sets, we compared the lead fractions within the grid cell of CS-2 and Envisat freeboard (Fig. 4). ~~densities and number of leads (see Fig. 7) for both data sets~~ The goal was to access wheather a difference in the lead fraction between both data sets may lead to different sea surface anomalies (SSA) and thus to~~accordingly to~~ ~~the~~ differences in the respective radar freeboards~~ distribution~~. ~~and~~ The lead fraction is generally much higher for Envisat than for CS-2, but they share a similar regional pattern. ~~However, this does not but there is no distinct pattern that would explain why CS-2 freeboarddata isare higher than Envisat freeboarddata in regions with multi-year ice.~~ We can speculate~~,~~ that the reason for the high Envisat lead fractions is due to its large footprint which therefore has a higher probability for capturing a lead. Hence, the fraction of waveforms~~,~~ that are identified as leads~~,~~ is significantly ~~much~~ higher than for CryoSat-2. It is reasonable to assume that the almost opposite ratios of lead to ice waveform numbers between CS-2 and Envisat cause a selection bias of certain ice types (e.g. preferential sampling of large floes) and thus could explain the observed differences in radar freeboard.

Less pronounced are the differences in the SSA results of both sensors (Fig. 5). While the SSA shows a consistent low in the central Weddell Sea in both results, a clear offset is visible in the differences of the CS-2 and Envisat SSA estimations. This offset is most likely caused by deviating absolute range values due to different geophysical range corrections. This is supported by the lack of regional patterns in the difference of the two SSA estimations. ~~did not find noticeable lower lead detections in regions where the differences in CS-2 and Envisat freeboard are the highest compared to regions, where the sensor biases are lower. Hence, the correction of the SSH seems not to be hampered by too few leads in the one or other data set. In future, we will nevertheless implement DTU13 consistently in both processors.~~

~~The high radar freeboard in CS-2 data along the coast may be caused by the usage of SARIn data. At the coasts, the satellite mode switches from SAR (over sea ice) to SARIn (over land ice). SARIn has generally a larger noise than the SAR data and this may lead to the higher radar freeboard in that region. However, this counts only for near-coastal grid cells and cannot explain the high radar freeboard in e.g. the western Weddell and the Amundsen/Bellingshausen Seas.~~

Another source for inconsistencies is certainly the difference in the sensor characteristics. The radar altimeter on-board Envisat has a much coarser resolution and lower data coverage than the one on-board CS-2. Due to the Delay/Doppler processing, the CS-2 footprint corresponds to the size of a Doppler cell, which is ~~freeboard measurements are averaged over the footprint of~~ approximately 300x16~~0~~00m (Wingham et al., 2006), while Envisat has~~data have~~ a footprint of 2-10 km (Connor et al., 2009). The CS-2 freeboard captures more features of the sea-ice cover, while, in contrast, the Envisat freeboard is smoother. Moreover the dynamic range of the CS-2 freeboard is higher than for Envisat, which can be assigned to the difference in spatial resolution of both sensors. Accordingly, the CS-2 freeboard captures more features of the sea-ice cover, while, in contrast, the Envisat freeboard is smoother. Moreover the dynamic range of the CS-2 freeboard is higher than for Envisat, which can be assigned to the difference in spatial resolution of both sensors. A study dealing with the impact that different footprint sizes have on mean and modal freeboard in the Arctic (Schwegmann et al., 2014) showed that differences of 0.1-0.2m for modal and 0.005m for mean values can be expected for footprints varying from point measurements, over the ICESat footprint of 70 m to a footprint of 300 m (according to the along-track footprint of CS-2). A similar result was found by Xie et al. (2013), who compared sea ice thicknesses derived from ICESat data on the 70 m ICESat footprint and upscaled to the AMSR-E scale of 12.5 x 12.5 km. Hence, partially,~~a part of~~ the difference between CS-2 and Envisat mean and modal freeboard may simply be caused by the different footprint and resolution of both measurement systems.

Both products reveal negative freeboard (Fig. 3). Envisat shows higher fractions of negative freeboard, which might be caused by the coarser spatial resolution, leading to an erroneous sea-surface height interpolation. In any case, we do not expect, that this negative freeboard is related to flooded sea ice, since the radar signal would not penetrate through the flooded layer.

~~Also the inconsistency in SIE may be caused by the inherent difference in footprint between CS-2 and Envisat. It is likely that during the Envisat processing more data are filtered out in the MIZ because measurements from mixed ice water footprints are discarded during the processing. On the contrary, CS-2 detects more "ice only" waveforms due to the smaller footprint. As a consequence, the MIZs have not the same location in both products. Another impact factor is that in the processing of Envisat, valid ice values depend on the surrounding leads. Only if an ice value is surrounded by leads in both directions, it is valid for the freeboard processing. This criterion is not used for the CS-2 processor.~~

Moreover, ~~another reason for one part of the~~ discrepancies might also be given by ~~may be caused due to~~ the fact ~~it is not well established how well results from different retracking approaches relate to each other in different surface roughness scenarios.~~ ~~that~~ that Envisat uses two individual retrackers for floes and leads. It is not well established how well results from different retracking approaches relate to each other in different surface roughness scenarios. For the Arctic, it was tested whether there is a possible bias in a few marginal ice zones (assuming that the actual ice freeboard of very thin ice is 0), but no bias was found. This could be different in the Antarctic, though~~but~~ it is not likely. The CS-2 processing instead is based on a uniform approach for lead and ice waveforms. This decision is based less on physical considerations but rather evolved from a process where CS-2 radar freeboards were compared to airborne validation data in the Arctic. ~~However, to proof that there is no bias, an in-depth investigation of the waveforms and processor characteristics would be necessary.~~ However, ~~Tt~~the performance analysis of retracker~~s~~ algorithms does require extensive airborne validation data we do not have available in 2011. ~~Such an investigation would also include a closer comparison of waveforms of the seasonal first-year and perennial multi-year ice in order to study the causes for the biases between Envisat and CS-2 freeboard data in more detail.~~

This is also the reason why~~erefore,~~, ~~T~~this does not~~e~~ ~~comparison between CS-2 and Envisat~~~~done in this study does not~~ provide ~~cannot show how~~ information on the accuracy of either ~~te~~ freeboard products~~measurements are and it did not aim to~~ or an answer to the question whether Ku-Band ~~the~~ radar altimeter signals originate ~~come~~ from the snow/ice or snow/air interface, or from somewhere in-between. A study of Price et al. (2015) indicated that the reflection horizon of CS-2 data over Antarctic sea ice, derived with a retracker threshold of 40%, is certainly close to the snow/air interface. ~~An adequate study of this issue is not possible at the moment of writing this paper, as there is barely any validation data published yet.~~ However, Operation IceBridge laser freeboard measurements over Antarctic sea ice as well as laser altimeter data from the RV Polarstern expedition PS81 in winter 2013 and PS89 in summer 2014/2015 are expected to be available in the near future~~soon~~. These datasets will only enable a validation of CS-2 radar freeboard products in the S~~s~~outhern H~~h~~emisphere. We have therefore limited this study to a consistency assessment between the two radar altimeter types well knowing that future improvements due to CS-2 validation efforts have to propagate to the Envisat and ERS1/2 eras. ~~Hence, only in near future a comprehensive evaluation of freeboard data from CS-2 and Envisat with field data becomes possible~~.

~~Nevertheless, we want to give a first estimate how strong discrepancies between both radar freeboards may influence sea-ice volume (SIV) results. Therefore, we estimated SIV for 2011 using Envisat and CS-2 radar freeboard, OSI SAF SIC and snow depth derived from AMSR-E (Frost et al., 2014, Kern et al., 2014) provided by the University of Bremen. We assumed that the main scattering horizon is located at the snow/ice interface, since we have no~~

~~information about the apparent location, but also tested cases where the scattering horizon is located in the snow layer to account for this uncertainty. With this assumption we certainly reveal the upper bound of SIV estimations.~~

~~The Antarctic wide SIV from CS-2 varies from 16554 km^3 at the beginning of winter (May) to 36940 km^3 at the end of winter in September. From Envisat, SIV amounts to 16647 km^3 in May and growths up to 36263 km^3 in September. The difference between both derived SIV is less than 2% over the growth season from May to September (see Fig. 8). This holds also when we change the location of the main scattering horizon to 15 cm below the snow surface. In this case, the difference in winter SIV is slightly above 2% only in September. We can also discover a change in sign in the difference mid of the year. In May and June, Envisat SIV is higher than CS-2 SIV, for the rest of the growths season Envisat SIV is lower. Hence, the impact of the positive bias in the perennial ice zone related to CS-2 dominates the SIV difference.~~

5 Conclusions and Outlook

This study rooted in the ESA CCI Sea Ice project aimed to investigate whether the radar freeboard estimates~~data~~ from CS-2 and Envisat ~~developed independently within the ESA CCI Sea Ice project~~ are consistent so that both time series can be merged without an intermission~~inter-mission~~ freeboard bias. ~~-~~The comparison revealed a reasonable ~~good~~ regional agreement between the pulse-limited (Envisat) and beam-sharpened (CS-2) data. Differences are mostly below 0.1m for modal freeboard and even less for mean freeboard over winter months (May-Oct), although the difference in first year to multi-year regions is much more pronounced in CS-2 than Envisat radar freeboard. ~~there are some inconsistencies that may be improved in future~~. The highest differences occur in regions with ~~perennial~~ multi-year sea ice and along the coasts. In general, the dynamic range of CS-2 freeboard is higher than for Envisat and due to the higher spatial resolution, CryoSat-2 captures more features in the sea ice cover. Also, the fraction of waveforms associated to leads is significantly higher for Envisat then CS-2 leading to a potential preferential sampling of larger ice floes and thus to higher freeboard in the first-year ice. ~~Nevertheless, the impact on the total Antarctic SIV is low: During the sea ice growth season, Antarctic wide SIV does only vary by few percent between Envisat and CS-2, indicating that there is a quite good consistency between both~~

~~sensors. Individual sectors and summer data suffer from higher uncertainties instead, which lead to high discrepancies between the sensor-based freeboard and SIV estimates.~~

In order to improve the consistency between both data sets, an in-depth investigation of the waveform characteristics in both processors is~~are~~ needed, but this effort requires additional data sets on the actual physical snow and ice conditions and such an undertaking is ~~which was~~ out of the scope of this study. For the future, we are ~~however~~ confident that this study by highlighting regions with apparent lack of consistency serves ~~– together with an improved understanding of the waveform characteristics in the pulse-limited and beam-sharpened data -~~ as a basis for further extending the time series of sea-ice freeboard by ERS-1/2 data and compiling a sea-ice thickness time series spanning more than 20 years yet.

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Tables

Table 1: Comparison between characteristics of Envisat and CS-2 and the processors used for freeboard calculations. SSA - Sea Surface Anomaly derived from detected leads, SIC – Sea ice concentration.

	Footprint	Point spacing	SIC product	Automatic lead detection	Sea surface height	Geoid
CS-2	0.3x1.6 km	0.30 km	OSI SAF	Included	DTU15~~0~~ + SSA	WGS84
Envisat	2-10 km	0.36 km	OSI SAF	Included	DTU15~~SGDR~~ + SSA	EGM96

Table 2: Modal and mean freeboard, difference between CS-2 and Envisat and root-mean-square error for Antarctic wide averages.

	Mean (m)		Mode (m)		(m)	(m)	
	CryoSat-2	Envisat	CryoSat-2	Envisat	Difference	RMS	#
January	0.22	0.13	0.15	0.20	0.09	0.25	165
February	0.24	0.16	0.10	0.20	0.08	0.18	141
March	0.28	0.21	0.10	0.25	0.07	0.22	175
April	0.21	0.18	0.05	0.20	0.03	0.17	357
May	0.18	0.17	0.10	0.20	0.01	0.13	723
June	0.18	0.17	0.10	0.20	0.02	0.14	976
July	0.19	0.17	0.15	0.20	0.01	0.12	1181
August	0.20	0.18	0.15	0.20	0.01	0.13	1318
September	0.20	0.19	0.15	0.20	0.01	0.13	1353
October	0.20	0.17	0.15	0.20	0.03	0.14	1290
November	0.18	0.13	0.10	0.20	0.05	0.16	1067
December	0.18	0.10	0.10	0.15	0.08	0.19	672

Table 3: Modal and mean freeboard, difference between CS-2 and Envisat and root-mean-square error for averages in the individual sectors.

	Mean (m)		Mode (m)		(m)	(m)	
	CryoSat-2	Envisat	CryoSat-2	Envisat	Difference	RMS	#

Weddell Sea	0.28 0.19	0.23 0.20	0.25 0.15	0.25 0.20	0.04 -0.01	0.17 0.10	107 535
Indian Ocean	0.32 0.14	0.17 0.14	0.05 0.10	0.20 0.20	0.15 0.00	0.23 0.15	16 199
Western Pacific Ocean	0.37 0.26	0.24 0.18	0.30 0.10	0.25 0.20	0.13 0.08	0.32 0.21	12 114
Ross Sea	0.19 0.19	0.11 0.19	0.05 0.20	0.20 0.20	0.08 0.01	0.34 0.11	11 346
Amundsen/ Bellingshausen Sea	0.30 0.28	0.18 0.22	0.10 0.15	0.25 0.20	0.12 0.06	0.27 0.16	29 159

~~Sea-ice volume (SIV) in km^3 calculated from CS-2 and Envisat radar freeboard with AMSR-E snow depth information (Frost et al., 2014, Kern et al., 2014) for three test cases, depending on the location of the radar wave's main scattering horizon: a) location 5 cm below the snow surface, b) location 15 cm below the snow surface, c) location at the ice/snow interface. Data are only listed until September because AMSR-E snow depth information is not available beyond September 2011. Bold numbers show where the difference between CS-2 and Envisat SIV is lower than 2%. Negative values occur when the apparent snow freeboard (radar freeboard + correction for wave propagation speed + assumed snow above main scattering horizon) is lower than the actual snow depth. That means that the assumed location of the main scattering horizon is certainly not realistic in those cases.~~

~~SIV (km^3)~~	~~CS-2 (a)~~	~~Envisat (a)~~	~~CS-2 (b)~~	~~Envisat (b)~~	~~CS-2 (c)~~	~~Envisat (c)~~
~~Jan~~	~~-113.5~~	~~-953.7~~	~~1451.3~~	~~611.1~~	~~5937.1~~	~~5096.9~~
~~Feb~~	~~44.6~~	~~-922.0~~	~~1479.4~~	~~512.7~~	~~5790.1~~	~~4823.4~~
~~Mar~~	~~1829.8~~	~~886.2~~	~~3407.4~~	~~2463.8~~	~~6649.1~~	~~5705.5~~
~~Apr~~	~~3808.8~~	~~2817.0~~	~~6073.5~~	~~5081.7~~	~~9301.4~~	~~8309.6~~
~~May~~	~~**6890.2**~~	~~**6983.8**~~	~~**12642.0**~~	~~**12735.5**~~	~~**16553.6**~~	~~**16647.1**~~
~~Jun~~	~~7899.8~~	~~8191.5~~	~~**16455.9**~~	~~**16747.6**~~	~~**23550.5**~~	~~**23842.2**~~
~~Jul~~	~~7433.3~~	~~7072.1~~	~~**18830.4**~~	~~**18469.2**~~	~~**31860.0**~~	~~**31498.9**~~
~~Aug~~	~~**10930.4**~~	~~**10870.7**~~	~~**23436.1**~~	~~**23376.3**~~	~~**35775.1**~~	~~**35715.4**~~
~~Sep~~	~~12820.3~~	~~12143.6~~	~~25606.2~~	~~24929.4~~	~~**36940.0**~~	~~**36263.2**~~

Figures

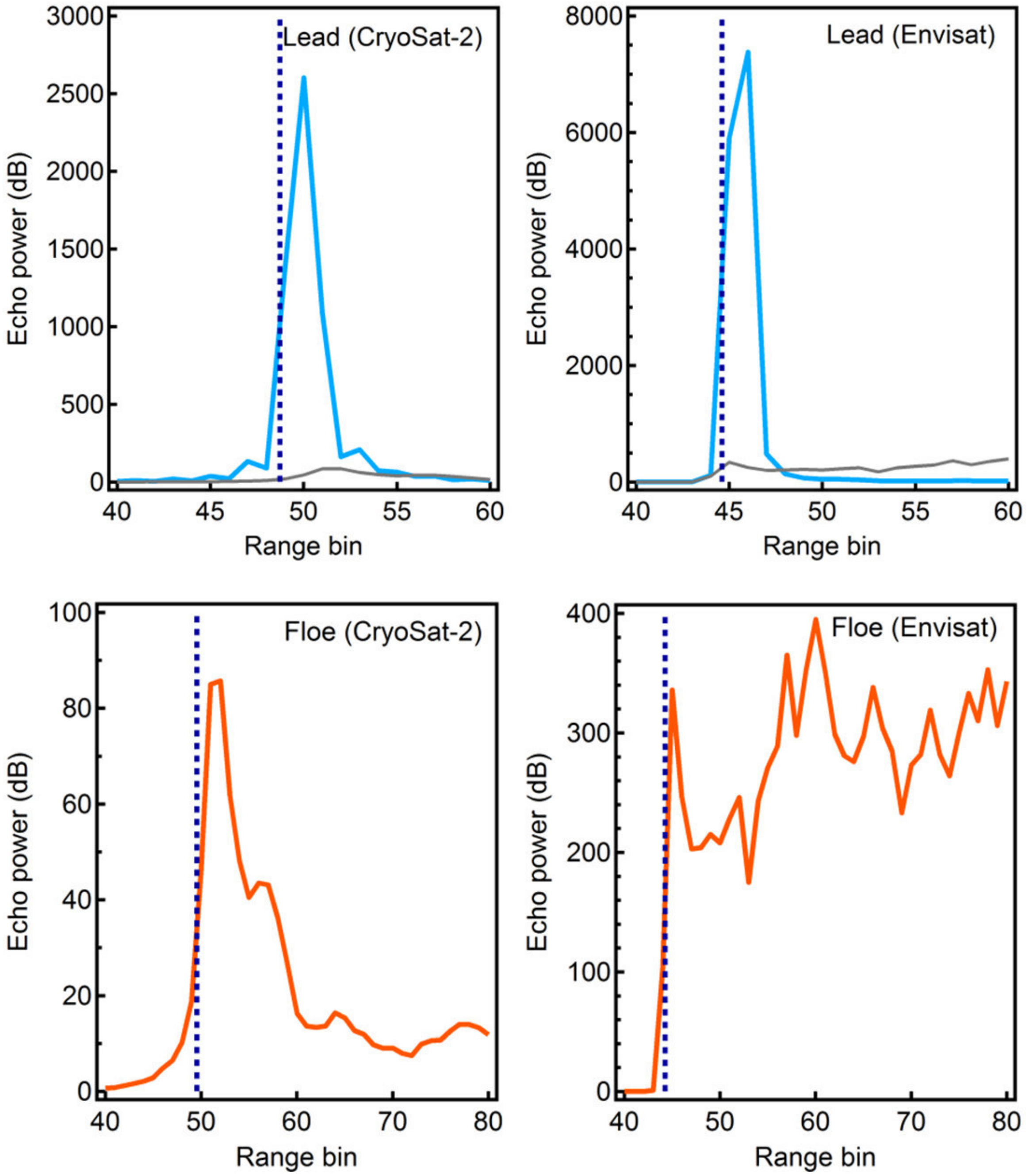


Figure 1: Waveform example for a lead (top) and a floe (bottom) for CS-2 (left) and Envisat (right). Red dashed lines show the retracking point of each waveform. Notice the different scales on the y-axis: Lead detections have a much higher echo power and a steeper leading edge than waveforms originating from ice only detections. To make the different echo powers better visible, the floe waveforms are shown in the upper figures (leads) in grey. Waveforms from CS-2 and Envisat do not originate from the same position but show rather an arbitrary example.

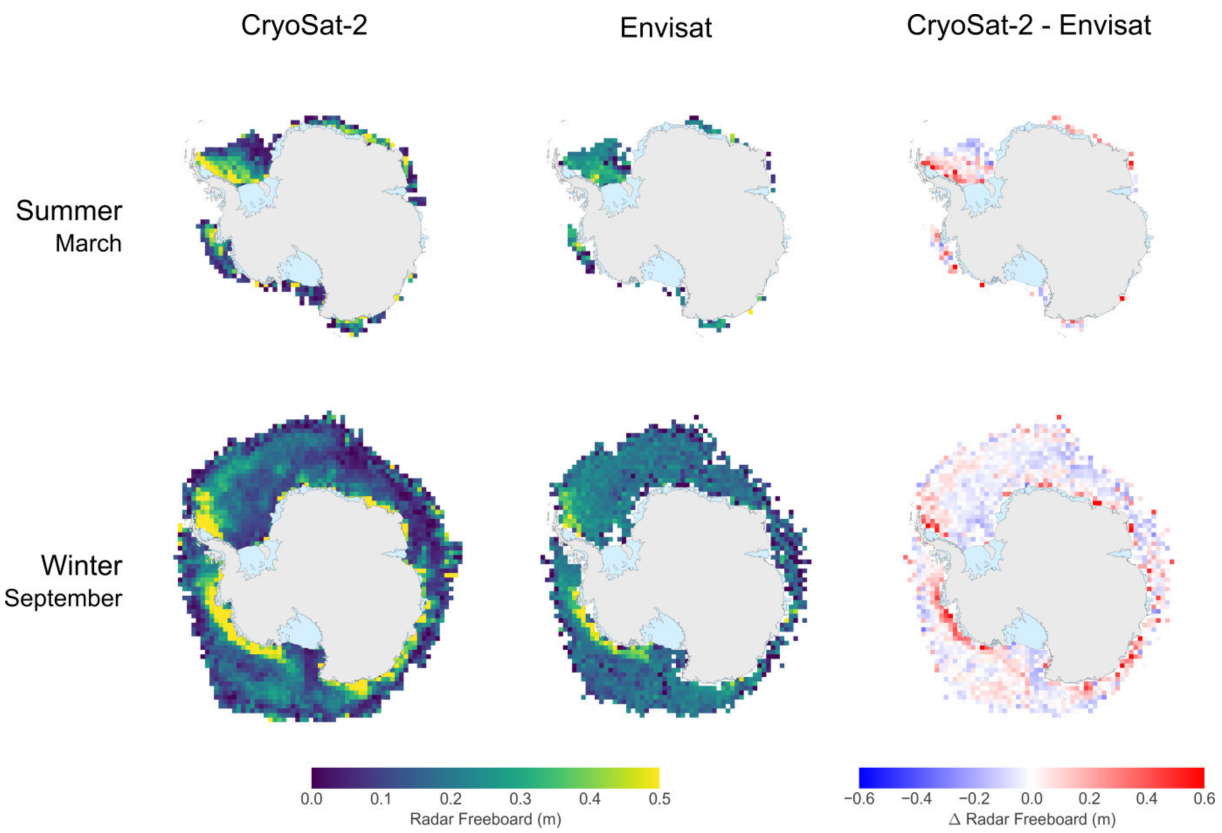


Figure 2: Freeboard maps derived ~~distribution~~ from CS-2 (left~~top~~) and Envisat (center~~bottom~~), and the difference between both products (right) ;~~,~~ shown~~exemplarily~~ for sea-ice minimum in summer (top~~left~~) and maximum in winter (bottom~~right~~). Light blue areas represent the Antarctic ice shelves. ~~regions with negative radar freeboard. Upper left image also includes the definition of the individual sectors after Parkinson and Cavalieri (2012).~~

~~Figure 3: Seasonal cycle of mean (a,c) and modal (b,d) freeboard from CS-2 and Envisat data as well as difference between them (CryoSat-2 - Envisat) for the standard processing (left) and CS-2 processing with retracker threshold of 50% (right). Grey bars show standard deviation of differences. Data have been averaged over the entire Antarctic sea-ice zone covered by at least 55% sea ice, but only where both data products have a valid value.~~

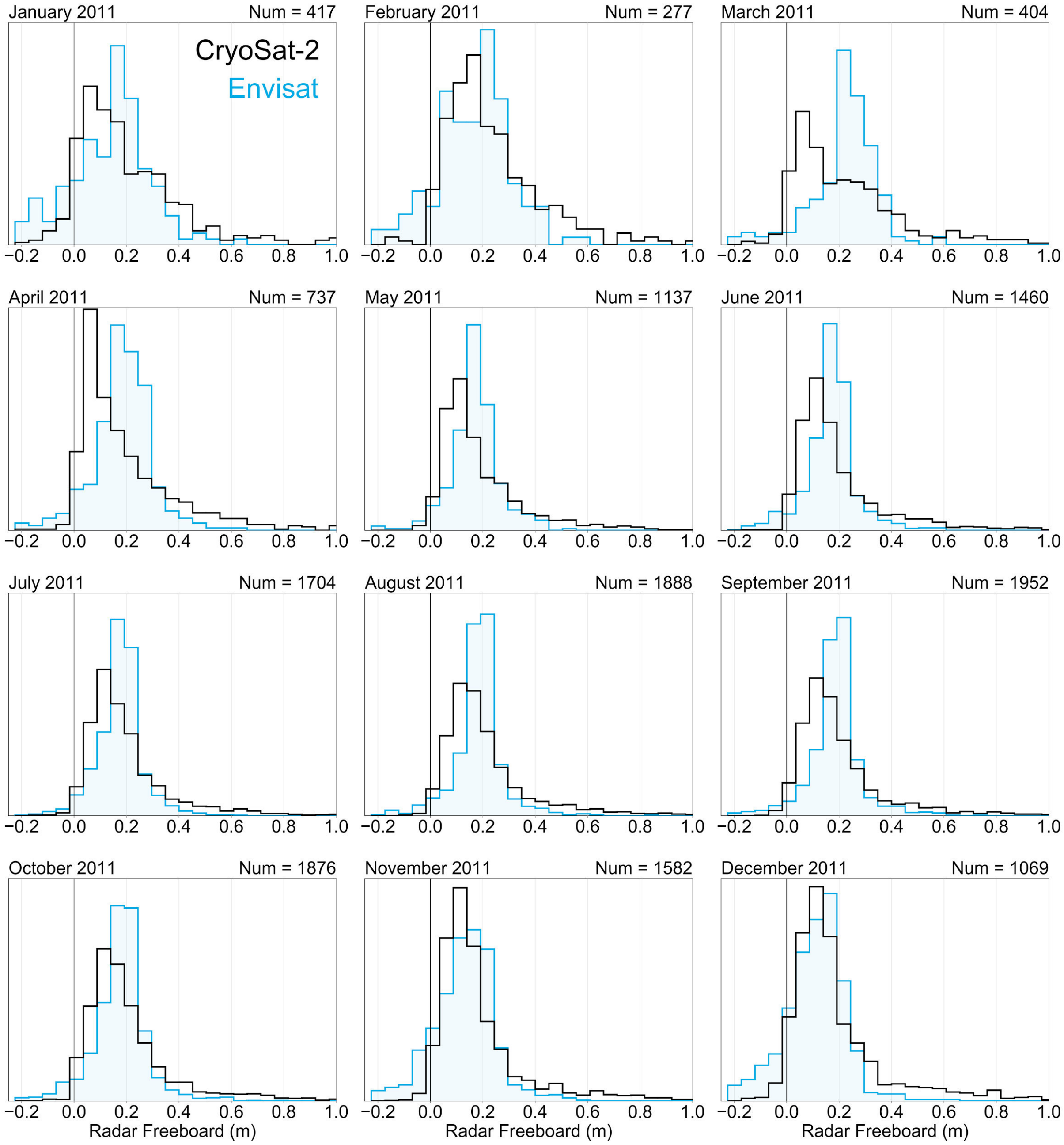
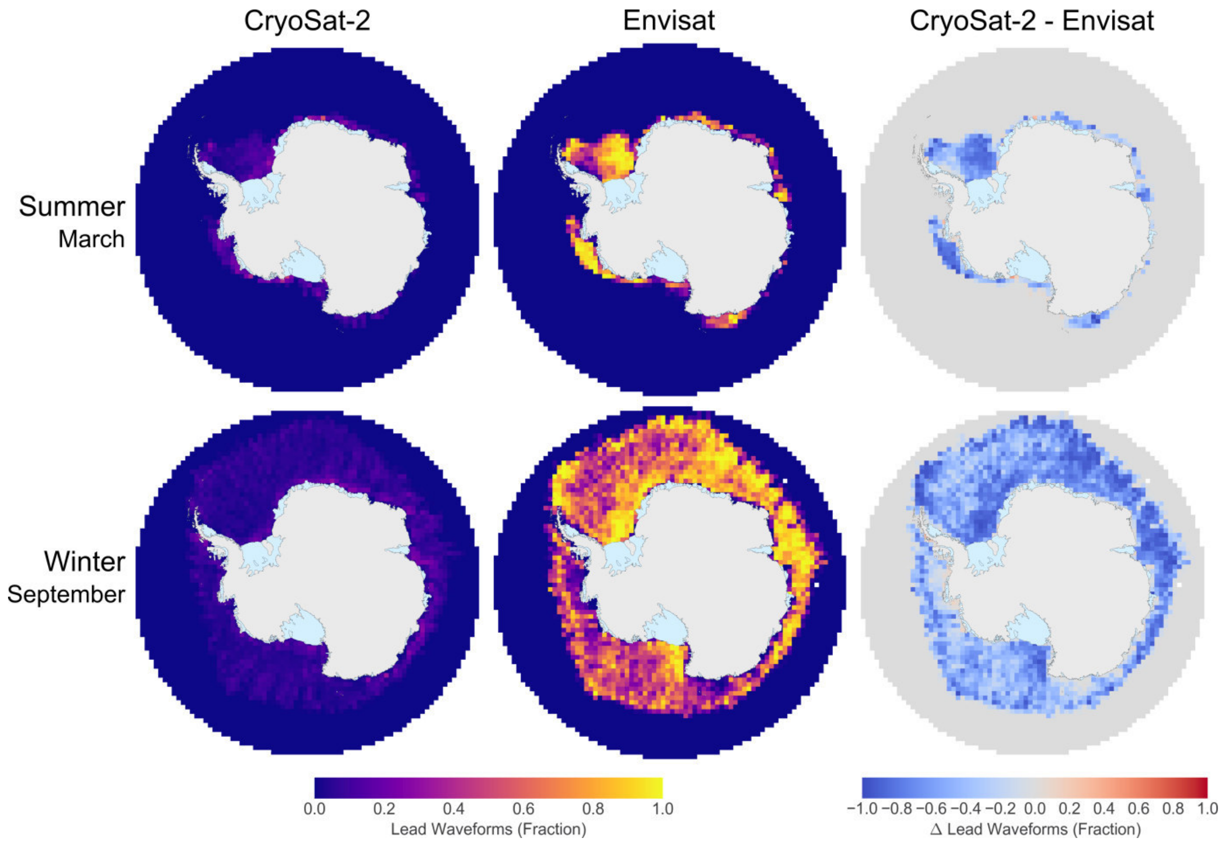


Figure 3: Histograms of freeboard distribution for CS-2 (black) and Envisat (blue) data, exemplarily for March and May (fall), July (winter) and December (summer). Only data occurring in both data sets have been considered. n I the number of compared grid cells.

~~Figure 6: Mean (a-e) and modal (f-j) freeboard averaged for the Weddell Sea (WS), Indian Ocean sector (IO), Western Pacific Ocean (WPO), Ross Sea (RS) and Amundsen/Bellingshausen Seas (ABS). Grey curves show the mean and modal differences between both~~

~~sensors (CryoSat-2 - Envisat) and attached bars show the standard deviation of differences. Only data occurring in both data sets have been considered.~~



~~Figure 7: Number of lead detections per grid cell for CS-2 (left) and Envisat (middle) and the difference CS-2 – Envisat (right). Blue values in the right-hand figure indicate that within a grid cell, for Envisat more waveforms are classified as leads than for CS-2.~~

Figure 4~~7~~: Fraction of waveforms~~,~~ that are identified as leads, for Antarctic summer and winter: CS-2 (left), Envisat (center) and the difference CS-2 - Envisat (right). Blue values in the right-hand figure indicate that within a grid cell, for Envisat more waveforms are classified as leads than for CS-2.

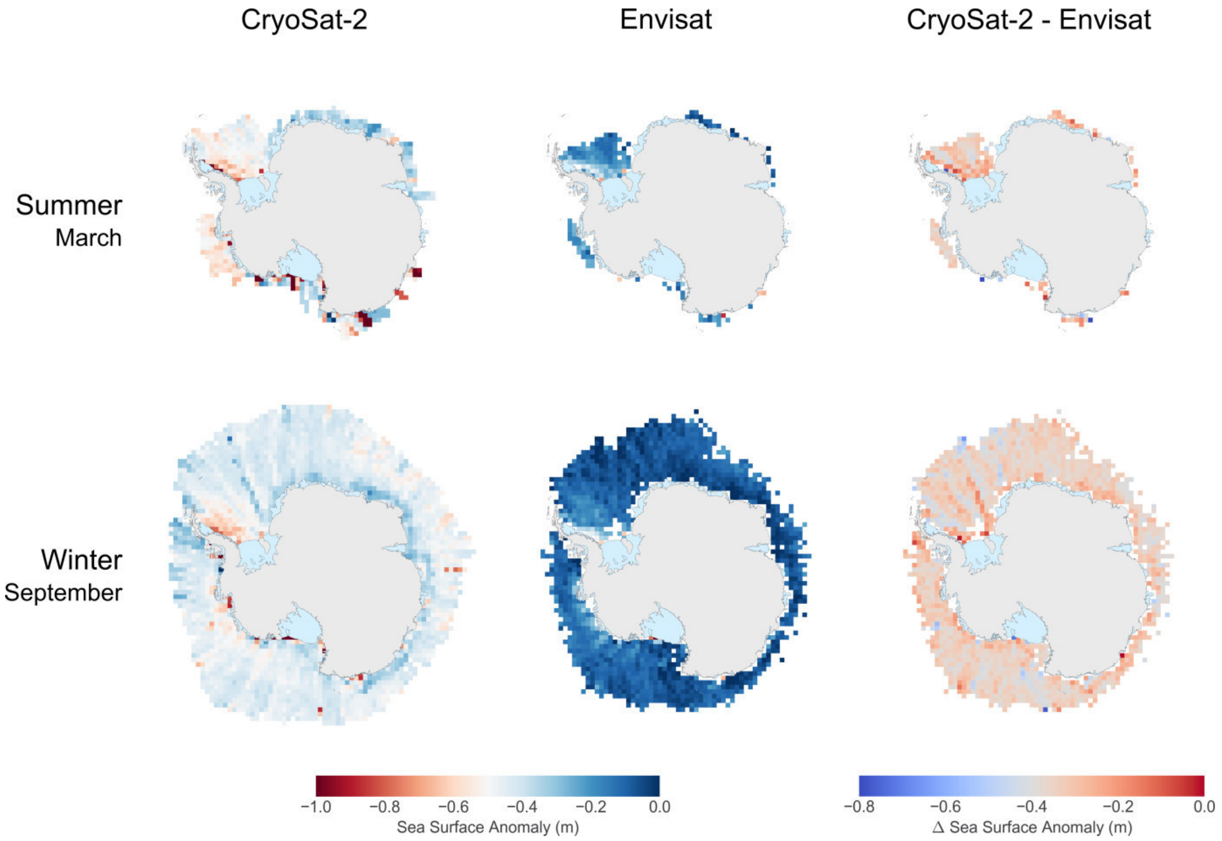


Figure 5~~8~~: Sea surface anomaly for summer (top) and winter (bottom), derived from CryoSat-2 (left) and Envisat (center), and the difference between both products. The difference plot indicates a bias between the CryoSat-2 and the Envisat sea surface height.

~~Figure 8: Sea ice volume (SIV) difference (CS-2 – Envisat) over the sea ice growth season related to the averaged sea ice volume derived from CS-2 and Envisat. Since the location of~~

~~the wave's main scattering horizon is unknown, we tested different cases (location 5 cm and 15 cm below the snow surface and location at ice/snow interface).~~

Interactive comment on “About the consistency between Envisat and CryoSat-2 radar freeboard retrieval over Antarctic sea ice”
by S. Schwegmann et al.

We thank the reviewer for his/her comments. In general we find them positive and we plan to write a revised manuscript for publication in The Cryosphere. Detailed response to the comments can be found below.

Anonymous Referee #1

A comparison of the freeboard retrieval in Antarctic sea ice, between two different space-borne radar altimeter - the Envisat RA2 and Cryosat-2 SIRAL (in SAR and SARIn mode). The author attempt to show that during the overlapping period of 2011, results from the Envisat and CS-2 missions have a reasonable consistency. Thus, it is potentially feasible to construct a consistent time series of sea ice freeboard, thickness, and volume during the satellite radar altimetry and gain the knowledge of the Antarctic sea ice volume in recent two decades. However, as pointed out in the paper, due to different SSH (sea surface height) data used for the two products, I would argue that the current comparison are not valid, although they seem be compatible. Although they offer to use the DTU13 SSH products for both data in the future, I would rather them use DTU13 for this paper to assure a solid publication.

We reprocessed both CS-2 and RA-2 using DTU15 and used that for the final manuscript. We agree that using the same SSH product was an important step towards a consistent study. However, the results did not change significantly. The different SSH products do not account for the bias between both freeboard data sets.

Some general comments:

1. A comparison of the radar elevation and local sea level measured from both sensors would be a good addition to the comparison of the freeboard, at least one can know which one, the elevation from satellites or the local sea level estimation from models, accounts more in the biases/variations between the two datasets.

We have already looked at the mean and local SSH during the data processing and included it in the manuscript now.
While the SSA shows a consistent low in the central Weddell Sea in both results, a clear offset is visible in the differences of the CS-2 and Envisat SSA estimations. This offset is most likely caused by deviating absolute range values due to different geophysical range corrections. This is supported by the lack of regional patterns in the difference of the two SSA estimations.

2. Aside from the comparison with mean and modal value, the root mean squared difference (RMSD) is also a good indicator to interpret the differences/biases between the two missions. And, a table listing the bias and the result of statistical testing in each sector/month would give a better and clear picture of the results.

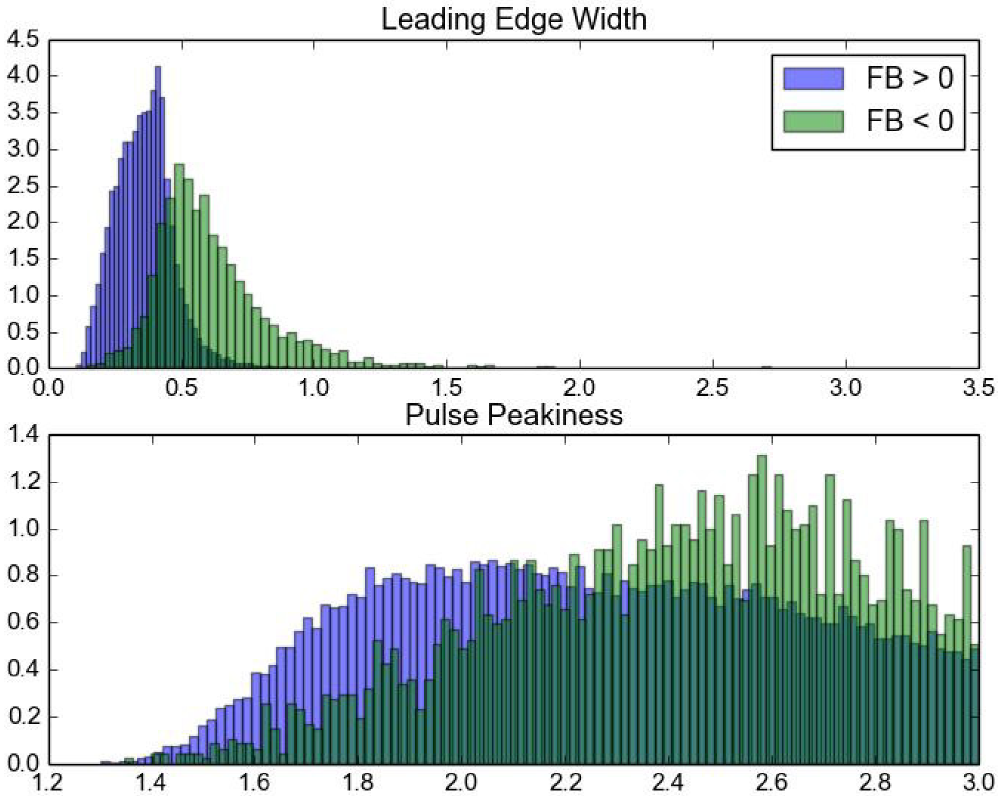
We included a table with monthly mean and modal values, RMS and biases for data averaged over the entire Antarctic. However, we feel that to include all these values for the individual sectors would make the table to crowded and rather confusion than helpful. Therefore we included in a second table only the summer (March) and winter (September) values for the individual sectors.

3. The authors could also consider to introduce some in-situ or airborne altimetry data as a reference to assess that in each month/sector, which sensor would have a better performance.

This would be a good idea, if the purpose of the paper would be to study the accuracy of RA-2 and CS-2 retrievals. However, as clearly stated in the manuscript, our paper is on the consistency of RA-2 and CS-2. We do not assess the performance - only the differences. And thus we do not plan to include external validation data in this study. To keep the scope of this paper manageable, the validation of radar altimetry in the realm of southern seas will have to be left for another paper. As a general comment, this work is ongoing in the Sea Ice CCI Phase 2 round robin exercise and results are to be expected early this year.

4. For the footprints with negative freeboard, does the echo waveform pattern of negative radar freeboard-footprints significantly differ from that with positive radar freeboard?

This is an interesting question and something that demands effort. Once again, to answer this in detail would be a study of its own including a modelling part on the snow pack properties and surface roughness. In order to answer the reviewers comment we quickly looked at the distribution of RA-2 waveform characteristics, namely the Leading edge width and Pulse Peakiness (for definitions see Ridout, A. and Ivanova, N.: Sea Ice Climate Change Initiative Phase 1, Algorithm Theoretical Basis Document (ATBDv0) issue 1.1, ESA Document, Doc Ref: SICCI-ATBDv0-07-12, ESA, available at: http://esa-cci.nersc.no/?q=webfm_send/160). The distributions for the 10 first days of September 2011(admittedly a random timespan) are plotted below:



Looking at the figure, we can say that for RA-2, yes the waveforms of negative and positive freeboards differ. It seems that the leading edge width is larger for negative FB than for positive. This is quite possibly due to the thicker snow cover, contributing to an early rise of the waveform over noise level. The difference in pulse peakiness is more subtle - possibly the PP values < 2 are less common for the negative freeboards than for positive freeboards. This is most likely due to heavily deformed ice (resulting in off-nadir returns and smaller PP) is less likely to have negative freeboard than less deformed.

As the waveforms, at least for RA-2, are different for, we cannot rule out that one of the two different filtering schemes of RA-2 and CS-2, is more prone to filter out good measurements of negative freeboard. This is very unlikely though, but we shall discuss this in the revised manuscript. We believe a more likely candidate for the negative freeboard is the ssh interpolation and the density of leads along track.

Specific Comments

Page6, Line 12: As both the CS-2 SAR and SARIn L1b data used, is there any significant different in retracking and freeboard retrieval between these two modes? Which data is really used for the freeboard retrieval?

The retracking algorithm of CryoSat-2 data does not differ between the SAR and SARin mode. SARin waveforms may have a higher noise level, but this is accounted for in the revised data product. In the original submission higher noise level of SARin data might have resulted in higher freeboard for some cases.

Page 7, Line 21 and Page 9, Line 5: It can be seen that radar freeboard with extreme values (<-0.3m & >2m for CS-2, and <-1m & >2m) are discarded. I hope you can provide some reasoning or citations why these values are selected. What is the reason that the CS-2 did not retrieved much negative freeboard on the inner ice pack? Should it be the result of the higher random error associated with the Envisat freeboard?

The choice of these thresholds is based on our experience of the uncertainty range of the orbit data from the two satellites.

Page 9, the "Results" section: As presented by the manuscript, the Envisat and CS-2 sea ice freeboard are well consistent with each other, as there are only a very low overall bias. However, as the performance of Envisat and CS-2 differs in different time and location, can the authors recommend which one might be better in each of the specified sea sector and/or specified month?

A SAR altimeter of smaller footprint size with less potential for mixing of surface types is definitely preferable over an LRM altimeter. Though at an Envisat like orbit inclination there would be a better coverage for all sea-ice covered areas in the southern hemisphere. The upcoming Sentinel-3 mission will be such a best case for Antarctic sea ice.

Page9, line17-21, negative freeboard is discussed, but it is not shown anywhere in figure 2.

Now we discuss negative freeboard only based on Figure 3, where the occurance is clearly visible.

Page12, line 5-6, why Envisat has more negative freeboard than CS-2?

This is surely due to the different cut-off windows that we used (0.24-2.24 for CS2 and -1 to 2 for Envisat).

Page14 Line 17: The CS-2 freeboard near the Antarctic coast is mostly higher than that of the Envisat in almost all sectors and in all months. The author explained this as the higher error in the SARIn mode. However, it seems this is mostly a bias between the SARIn and Envisat. Also, could this be caused by the higher error or bias in the Envisat when measuring the coastal, fast ice, not by the CS-2 SARIn mode?

At this point we can only speculate about the nature of this observed bias, especially when comparing SAR/SARin (CryoSat-2) and LRM (Envisat) waveforms. It might be true that waveforms of SAR and LRM altimeters show different sensitivities towards certain ice surfaces. One way to verify this would be to extend this analysis to the Arctic, but this is beyond the scope of this study.

Page14, line25-29 about footprint size effect, please also see this paper for the Antarctic. Xie, H., A. Tekeli, S. Ackley, D. Yi, and J. Zwally, 2013. Sea ice thickness estimations from ICESat Altimetry over the Bellingshausen and Amundsen Seas, 2003-2009, Journal of Geophysical Research, doi: 10.1002/jgrc.20179;

The reference has been included: “A similar result was found by Xie et al. (2013), who compared sea ice thicknesses derived from ICESat data on the 70 m ICESat footprint and upscaled to the AMSR-E scale of 12.5 x 12.5 km.”

Page 23: Table 2, I am not sure how the authors handled the situation when snow depth is lower than the pre-set penetration depth (be 5cm or 15cm), this could be the cause of the negative SIV? And, I am not sure if the SIV does include the snow volume.

In case the snow depth is lower than the assumed penetration depth, we assumed full penetration of the main backscatter horizon, which is identical to setting the penetration depth to the snow depth. SIV in our study does not include snow volume. However, we have excluded this part from the manuscript in order to i) not to confuse the reader and ii) to focus on the main topic of the manuscript.

Page 24: Fig.1, what is the measurement/unit of the “Echo power” represented in the plots? It could be DB? Also, the plots could be wide, as the leading edge is extremely steep and it is hard to see if the retracking points are located at the 40% threshold.

The unit is dB. We have included the unit in the figure and made the retracking point better visible by decreasing the x-axis range.

Figure 4, 5, 6. font size of the words are too small to see.

This is true and we used bigger font sizes for our figures now.

Interactive comment on “About the consistency between Envisat and CryoSat-2 radar freeboard retrieval over Antarctic sea ice”
by S. Schwegmann et al.

We thank the reviewer for his/her comments. In general, we find them positive and helpful for identifying points where a more rigorous analysis would be needed. Detailed response to the comments can be found below.

Anonymous Referee #2

This paper discusses the comparability of sea-ice freeboard retrievals from two different satellite sensors as an initial step to eventually establish a long-term (up to 20 years) historical data record of Antarctic sea-ice freeboard – when data from ERS1 and ERS2 can be included. This is a very important step towards a better understanding of Antarctic sea ice and its variability. It is crucial research to be undertaken. I am very pleased to see this issue being addressed, but I have concerns regarding the addition of sea-ice volume estimates into the manuscript. While the quantification of sea-ice thickness (and subsequently volume) is regarded as the holy grail by some researchers in the field, I would suggest to refrain from it here and stick to what the title describes: sea-ice freeboard retrieval. There are too many uncertain variables (snow thickness, and snow, ice and water densities) required for the computation of sea-ice thickness from surface elevation (sea-ice freeboard above a reference surface, ideally local sea level).

The reviewer is correct that too large uncertainties still exist to give a solid volume estimate but our SIV estimates are not meant to be such. We have included them, as stated in the manuscript, to show the impact of discrepancies between the radar freeboards on sea-ice volume (SIV) results. However, we followed the suggestion and excluded this part from the manuscript in order to i) not to confuse the reader and ii) to focus on the main topic of the manuscript.

I would suggest to show the common ground, i.e. the reference surface, from both sensors independently and discuss how well they compare. This will be an important light to shine on the negative freeboard measurements and discussion as well. I would like to suggest a more rigorous statistical analysis of the data at hand (rather than adding more derived variables, see above). Maybe the authors could show quantiles of differences (regional and temporal) in the sea surface height reference data and the freeboard data and possibly derive principle component analysis from that. This would yield a much better handle on when and where the data compare well, and provide the grounds for a discussion of why they compare well (or not).

We included maps showing the difference in SSA for both products and the maps showing the lead fractions and its differences. The lead fraction is generally much higher for Envisat than for CS-2, but they share a similar regional pattern. We can speculate that the reason for the high Envisat lead fractions is due to its large footprint which therefore has a higher probability for capturing a lead. Hence, the fraction of waveforms that are identified as leads is significantly higher than for CryoSat-2. It is reasonable to assume that the almost opposite ratios of lead to ice waveform numbers between CS-2 and Envisat cause a selection bias of certain ice types (e.g. preferential sampling of large floes) and thus could explain the observed differences in radar freeboard.
Less pronounced are the differences in the SSA results of both sensors (Fig. 5). While the SSA shows a consistent low in the central Weddell Sea in both results, a clear offset is visible in the differences of the CS-2 and Envisat SSA estimations. This offset is most likely caused by deviating absolute range values due to different geophysical range corrections. This is supported by the lack of regional patterns in the difference of the two SSA estimations.

While satellite sensors are getting better constantly, the consistency of a long-term data set of sea-ice freeboard from multiple sensors and different missions is of vital importance. It might be worthwhile to consider degrading the more recent (presumably higher resolution, more precise) data set, in order to achieve a compatible data set of which the errors/caveats are well known. What would be needed to produce such a consistent data set?

After receiving the comments of both reviewers, we have decided to reprocess both CryoSat-2 and Envisat time series with a common mean sea surface height product (DTU15). The CryoSat-2 data have been gridded on the same grid projection and resolution as Envisat - that is, the EASE-2 100 km Antarctic grid. For the grid this was already the case for the original manuscript (see P4898, lines 5-7). The 25 km grid we only tested to see if the change of resolution has an effect on the biases (P4903, line 15 onwards).

Specific comments:

- p.4895 l. 25: GLAS on ICESat is not a current altimeter in space (ICESat was decommissioned in Aug. 2010)

We put ICESat in past tense: “The Geoscience Laser Altimeter System (GLAS) on-board the Ice, Cloud and land Elevation Satellite (ICESat) measured the distance to the snow/ice surface, hence **reveals** snow freeboard.” to “The Geoscience Laser Altimeter System (GLAS) on-board the Ice, Cloud and land Elevation Satellite (ICESat) measured the distance to the snow/ice surface, hence **revealed** snow freeboard.”

- p. 4897 l. 23 sqq.: why the introduction the terms ‘seasonal’ and ‘perennial’ sea ice, when ‘first year’ and ‘multi year’ is widely accepted;

Now, we use the terms “first year” and “multi-year” ice instead of seasonal ice and perennial ice.

- p. 4899 l. 23 & p. 4901 l. 1: I would like to see a further justification for the radar freeboard cut-offs for the two sensors. How many values are actually discarded?

The cutoff limits are generous estimates based on our experience with the along-track orbit data.

- Amundsen/Bellingshausen seas should be consistently abbreviated as 'ABS' (Figure 2 top-left and elsewhere)

We excluded the original Figure 2 and do not use any abbreviation any more for the sectors.

p. 4901 l. 18: I am not sure whether I see 'negative freeboard' in the marginal icezone of Fig. 2. There are black areas, but the colour bar does not display negative values, therefore I am assuming it's just a cut off (at 0?);
In the former figure black areas indicated negative values. However, we do not show them as these are not expected to show real negative freeboard but are rather a result of speckle noise range.

- p. 4904 l. 19-20: spell out Weddell Sea and Ross Sea;
We changes it to "In the Weddell Sea and Ross Sea,"

- p. 4905 l. 26 ssq.: what if the same sea surface height retrieval would be used for both altimeter data sets?
We reprocessed the data of both altimeters using the DTU15 sea surface height retrieval consistently. However, results did not change significantly.

- p. 4906 l. 8 ssq.: what month is displayed in Fig.7? Appears to be winter, but how does the lead detection change throughout the months of the inter comparison?
It was September. However, now we show lead fractions for summer and winter, i.e. March and September, to show that the general result, having Envisat lead fraction generally higher than CS-2 lead fraction, is the same in all months. We can speculate that the reason for the high Envisat lead fractions is due to its large footprint which therefore has a higher probability for capturing a lead. Hence, the fraction of waveforms that are identified as leads is significantly higher than for CryoSat-2. It is

reasonable to assume that the almost opposite ratios of lead to ice waveform numbers between CS-2 and Envisat cause a selection bias of certain ice types (e.g. preferential sampling of large floes) and thus could explain the observed differences in radar freeboard.