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# Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data

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**Abstract**

Arctic sea ice is a major element of the Earth's climate system. It acts to regulate regional heat and freshwater budgets and subsequent atmospheric and oceanic circulation across the Arctic and at lower latitudes. Satellites have observed a decline in Arctic sea ice extent for all months since 1979. However, to fully understand how changes in the Arctic sea ice cover impact on our global weather and climate, long-term and accurate observations of its thickness distribution are also required. Such observations were made possible with the launch of the European Space Agency's (ESA's) CryoSat-2 satellite in April 2010, which provides unparalleled coverage of the Arctic Ocean up to 88°N. Here we provide an end-to-end, comprehensive description of the data processing steps employed to estimate Northern Hemisphere sea ice thickness and subsequent volume using CryoSat-2 radar altimeter data and complementary observations. This is a sea ice processor that has been under constant development at the Centre for Polar Observation and Modelling (CPOM) since the early 1990s. We show that there is no significant bias in our satellite sea ice thickness retrievals when compared with independent measurements. We also provide a detailed analysis of the uncertainties associated with our sea ice thickness and volume estimates by considering the independent sources of error in the retrieval. Each month, the main contributors to the uncertainty are snow depth and snow density, which suggests that a crucial next step in Arctic sea ice research is to develop improved estimates of snow loading. In this paper we apply our theory and methods solely to CryoSat-2 data in the Northern Hemisphere. However, they may act as a guide to developing a sea ice processing system for satellite radar altimeter data over the Southern Hemisphere, and from other Polar orbiting missions.


*Keywords:* Cryosphere; Sea ice; Remote sensing; Arctic

## 1. Introduction

Satellite passive microwave observations of Arctic sea ice have recorded a decline in the summer extent of ~40% since 1979 (Cavalieri et al., 1996, updated yearly; Fetterer et al., 2002, updated daily). The decline is coincident with abrupt global and Arctic warming over the last 30 years (Hartmann et al., 2013). It is crucial to observe and understand changes in the Arctic sea ice cover, as it is a major element of the Earth's climate system. Sea ice influences the freshwater (Aagaard and Carmack, 1989; Serreze et al., 2006) and surface heat (Sedlar et al., 2011) budgets of the Arctic, and subsequently the global climate. The melting of sea ice could disrupt the oceanic global thermohaline circulation (Vellinga and Wood, 2002) and atmospheric circulation patterns (Singarayer et al., 2006; Schweiger et al., 2008; Francis and Vavrus, 2012), with knock-on effects for regional weather patterns in Europe, America and much of the northern hemisphere, and potentially the southern hemisphere (Vellinga and Wood, 2002). To fully understand the global impacts of changes in the

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Arctic sea ice cover, long-term and accurate observations of the ice pack as a whole are required. However, it has previously been difficult to quantify trends in sea ice volume because detailed thickness observations have been spatially sparse and temporally sporadic (McLaren, 1989, 1992; Wadhams, 1990).

In April 2010 the European Space Agency's (ESA) CryoSat-2 radar altimeter satellite (Wingham et al., 2006) was launched. CryoSat-2 provides unparalleled coverage of the Arctic Ocean with a region of coverage (ROC) extending to 88°N. In 2013, a study led by scientists at the Centre for Polar Observation and Modelling (CPOM) produced the first estimates of Arctic sea ice thickness and volume from CryoSat-2 (Laxon et al., 2013). The estimates were produced within a fixed central Arctic region that covers an area of $\sim 7.2 \times 10^6$ km$^2$. The region was first defined by scientists at the National Aeronautics and Space Administration (NASA) for use with the NASA ICESat satellite (Kwok et al., 2009), and will herein be referred to as the ICESat domain. The CPOM processor has since been updated to cover all northern hemisphere sea ice, defined as sea ice at latitudes above and including 40°N (Tilling et al., 2015). Since 2013 a number of institutions have published results from their own CryoSat-2 sea ice processing systems, including the National Aeronautics and Space Administration (NASA) Goddard Space Flight Centre (Kurtz et al., 2014), the Alfred Wegener Institute (AWI) (Ricker et al., 2014), NASA Jet Propulsion Laboratory (JPL) (Kwok and Cunningham, 2015), the Finnish Meteorological Institute (FMI) (Rinne and Similä, 2016), and the Ulsan National Institute of Science and Technology (UNIST) (Lee et al., 2016). These all differ slightly in their areal coverage and processing technique. Like CPOM, both NASA teams and AWI provide a publicly available sea ice thickness product. The NASA data are available within the ICESat domain whereas the AWI data cover the area of the Arctic Ocean where values of snow depth and density from a climatology (Warren et al., 1999) are considered realistic. Another key difference is the retrackers applied to CryoSat-2 data for each processor. At CPOM we estimate the elevation of ocean and ice surfaces by applying a Gaussian-exponential retracker to ocean waveforms and a threshold retracker to sea ice waveforms (Section 4.4). NASA Goddard have developed a waveform fitting model, NASA JPL select the first unambiguous peak for all waveforms, and AWI apply a threshold retracker to all waveforms. Other variations include the method used to account for the mean sea surface when estimating instantaneous sea surface height, and to classify sea ice type.

Here we provide an end to end, comprehensive description of the data processing steps that we currently employ at CPOM to estimate northern hemisphere sea ice thickness and volume using CryoSat2 radar altimeter data. This is a sea ice processing chain that has been under constant development at CPOM since the early 1990s (Laxon, 1994). Past studies have documented aspects of its evolution (Giles et al., 2008; Laxon et al., 2013, 2003; Peacock and Laxon, 2004; Tilling et al., 2015) and provided a detailed analysis of sources of error and uncertainty in the retrieval of sea ice freeboard from satellite radar altimetry(Tilling et al., 2016; Giles et al., 2007). In this paper we also develop an uncertainty budget for northern hemisphere sea ice thickness and volume, evaluate of our thickness product by comparison with *in situ* and airborne Arctic sea ice measurements, and present an assessment of the changes in sea ice thickness and volume from CryoSat-2.

## 2. The CryoSat-2 satellite

The primary aim of ESA's CryoSat-2 mission is to accurately determine the inter-annual fluctuations and longer-term trends in Earth's continental and marine ice fields (Drinkwater et al., 2004; Wingham et al., 2006). Its primary payload is a Synthetic Aperture Interferometric Radar Altimeter (SIRAL). SIRAL is an altimeter/interferometer system operating in the Ku-band (13.6 GHz). The SIRAL antenna system comprises two nadir looking antenna mounted 1 m apart in the across-track direction (Wingham et al., 2006). It operates in three modes (Fig. 1) – low resolution mode (LRM), synthetic aperture radar (SAR) mode, and SAR interferometric (SARIn) mode – depending on the type of surface that is being observed (ESA/MSSL, 2013).

In LRM a single antenna is used to transmit and receive the radar signal and SIRAL acts as a conventional nadir-pointing, pulse-limited altimeter. This means that the radar footprint size is dependent on the length of the compressed pulse. The typical CryoSat-2 orbital velocity is 7.4 km s$^{-1}$ and the interval between pulses in LRM is approximately 500 μs, which corresponds to a pulse repetition frequency (PRF) of 2 kHz (Wingham et al., 2006). This ensures that returning echoes are uncorrelated. The LRM footprint is the SIRAL pulse-limited footprint (PLF), which is approximately 1.7 km based on an altitude of 730 km (Scagliola, 2013). CryoSat-2 operates in LRM over areas of the continental ice sheets, and the majority of the Earth's ice-free oceans and land (Fig. 1).

When operating in SAR mode, the SIRAL instrument on-board CryoSat-2 uses a single antenna to transmit and receive pulses, but emits a burst of 64 phase-coherent pulses as opposed to a single pulse. By exploiting the slight frequency shifts caused by the Doppler effect, in the forward- and aft-looking parts of the burst, the data processor can separate the burst into narrow beams arranged across-track. The along-track sampling resolution of each beam is approximately 250 m. As with other pulse-limited radar systems, the surface area illuminated by SIRAL continues to grow as an annulus following the time that the PLF is reached. Therefore the PLF is smaller than the full antenna illumination pattern, or antenna-limited footprint. The across-track footprint in SAR mode is simply the antenna-limited footprint, which can reach 15 km depending on satellite altitude (Scagliola, 2013). The beams from

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