Sea Ice Deformation Mapping by Means of SAR

Wolfgang Dierking, Thomas Busche, Carola von Saldern, Jörg Hartmann, Christian Haas, and Christof Lüpkes, Alfred Wegener Institute for Polar and Marine Research, Germany
Irena Hajnsek, Rolf Scheiber, Ralf Horn, and Jens Fischer, German Aerospace Center, Germany
Jørgen Dall, Technical University of Denmark, Denmark

Abstract

Deformation features such as ridges, hummocks, or rafted floes are typical characteristics of sea ice in the Arctic and Antarctic. Mapping these features is of interest not only for marine traffic and offshore operations in polar environments but also for climate research. Synthetic aperture radar (SAR) is regarded a useful tool for sea ice deformation mapping. The capability to quantify the sea ice deformation state with sufficient accuracy depends on frequency, polarization, incidence angle, and spatial resolution of the SAR sensor. Therefore, we utilize data of different airborne and spaceborne SAR systems and of complementary measurement devices such as laser profilers, optical scanners, electromagnetic induction sounders, and meteorological instruments to assess the pros and cons of different SAR configurations and to establish empirical algorithms for retrievals of geophysical parameters such as aerodynamic roughness. The intention of this paper is to give a short overview of our recent activities.

1 Introduction

Ice extent and concentration have been monitored from space since decades. These measurements form a data base that is extremely valuable for climate research and for the assessment of climate variations. In order to determine sea ice mass variations that could have an effect on climate, also spatial and temporal ice thickness variations need to be measured, but this is a difficult task with recent spaceborne sensors. Sea ice deformation, which manifests itself as a more or less rugged topography of the ice surface, is a proxy for the average ice thickness in a given area. Information about locations of heavy deformation is also of large interest for marine navigation.

Since synthetic aperture radar is sensitive to surface roughness on various scales, it is a useful instrument for mapping sea ice deformation. Sea ice covers huge ocean areas, which means that the monitoring devices need a large field of view in order to enable a sufficient coverage in space and time, favouring wide-swath imaging modes of satellite SARs such as ENVISAT ASAR and ALOS PALSAR. A problem of these modes, however, is the loss of details about ice surface characteristics due to the coarse spatial image resolution. In this paper, we discuss our activities related to sea ice deformation and thickness mapping by means of airborne and spaceborne SAR and related field campaigns during which complementary measurement devices are employed. Besides spatial resolution, effects of SAR frequency, polarization, and incidence angle are considered in a number of finished and ongoing studies.

2 Aspects of Sea Ice Research

2.1 Sea Ice and Climate

Vast areas of the ocean's surface are covered by ice. In the Arctic, the ice extent varies between 7 and 14 million km^2 from summer to winter, for the Antarctic, the corresponding numbers are 4 and 20 million km^2, respectively. Sea ice influences a number of parameters and processes that have direct or indirect impact on Earth's climate. Examples are the Earth's radiation balance, the exchange of heat and momentum between the ocean and the atmosphere, and deep ocean water formation. Sea ice responds also to variations of atmospheric and oceanic conditions. Long-term changes of the sea ice cover state are regarded as an indicator to broader climate change such as global warming. In order to gain a more detailed understanding of the various interactions and feedback mechanisms between atmosphere, sea ice, and ocean, the ice needs to be monitored over years and decades. For operational tasks such as ship navigation in Arctic or Antarctic waters, ice maps are required at short time intervals.

The most important parameters characterizing the state of a sea ice cover are: extent; concentration (the fraction of the ocean surface covered by ice in a given area); thickness; drift patterns; occurrence of open water leads and polynyas (as locations of strong heat exchange between the atmosphere and the ocean); and the topography of the ice surface and bottom.

2.2 Sea Ice Deformation

Sea ice is deformed by mechanical forces due to wind stress, ocean currents, and blocking effects of land which cause spatial variations of the ice drift velocity. In areas of convergence, rafting and ridging processes increase the ice volume per unit area. In areas of divergence, patches of open water form which are sites of new ice formation in winter. Typical deformation features are rafted floes and blocks, broken ice, pressure ridges, shear zones, hummocks, and rubble fields. Monitoring of sea ice deformation by means of airborne and spaceborne remote sensing is of large interest for several reasons. Intuitively most obvious is that ridges and rubble fields are severe hazards to marine operations and offshore structures. But also a number of research fields related to studies of state and variations of the polar climate require information about sea ice deformation. A parameterization of deformation is needed in numerical models that simulate the dynamics of sea ice in terms of ice export and ridging [1]. The portion of mass contained in ice ridges can be significant relative to the total ice mass (up to 50 percent and even more in some areas) which has to be taken into account when quantifying the mass balance of sea ice [2]. Surface and bottom roughness reflect the development history of an ice area and can be used for ice type classification. The forces acting on the ice due to wind and ocean currents are influenced by the ice surface and bottom topography (including small scales on the order of decimetres and centimetres) and need to be parameterized for use in atmospheric models or in coupled ice-ocean models [3], [4]. Dependent on the spatial scales of the analysis (e. g. modelling studies or development of parameter retrieval algorithms), quantities need to be derived taking into account the properties of individual ridges, of ridge clusters or of large deformed areas and regions.

2.3 Research Strategies for Mapping of Sea Ice Deformation

Scientists at the Alfred Wegener Institute (AWI) and collaborators from the German Aerospace Center (DLR), the Technical University of Denmark (DTU), and partners in EU-projects such as IRIS (Ice Ridging Information for Decision Making in Shipping Operations) focus their investigations on different aspects of deformation mapping:

(a) Different mathematical approaches are used in order to quantify and model ice surface topography/roughness. One goal is to develop an ice roughness classification scheme.

(b) Radar reflections from sea ice and variations of ice surface topography and thickness are measured simultaneously in order to investigate and establish a relationship between radar signatures, on the one hand, and ice deformation, surface roughness, or thickness, on the other hand. To this end, imagery from air- and spaceborne SAR systems (ESAR, EMISAR, Radarsat, ERS-1 and -2 SAR and ENVISAT ASAR) have been analysed together with data from airborne laser altimetry, optical scanners, and meteorological instruments as well as from helicopterborne laser profilers and electromagnetic ice thickness sounders.

(c) Geophysical quantities influenced by sea ice deformation, such as the atmospheric drag coefficient, are acquired simultaneously with radar data in order to investigate the degree of correlation between them.

In the following section, examples for these activities are presented.

3 Examples of Studies on Sea Ice Deformation

3.1 Roughness Characterization

As one part of our investigations we are looking at possibilities to characterize sea ice surface roughness and deformation quantitatively, with the goal to formulate criterions for the classification of ice roughness regimes, under consideration of sea ice type definitions of WMO (World Meteorological Organization), capabilities and limitations of airborne and spaceborne SAR systems, and the needs of numerical models for simulations and forecast of sea ice dynamics. In first studies, statistics of Arctic sea ice surface roughness such as mean and RMS-height (relative to a reference level that closely follows smooth ice surface areas between deformation features), skewness, kurtosis, RMS-slope, and fractal dimension were determined from laser profiles measured at spatial resolutions between 0.3 and 0.4 m. The variations of these parameters were then correlated with changes of the modal ice thickness that was determined from data of electromagnetic induction sounding at a point spacing of 3 to 4 m. The data analysis showed that a number of roughness parameters differed between thinner (up to 1.2 m) and thicker (>1.2 m) ice. Roughness characteristics of thin ice classes (such as young ice, thin and medium first-year ice) could not be separated from one another with a sufficiently high accuracy. Looking at the results of roughness classification algorithms (such as k-nearest neighbour method), we concluded that the relation between modal ice thickness and statistical surface roughness parameters is not sufficiently stable, i. e. the correlation between surface roughness parameters and thickness of the level ice among the deformation features is not high enough. For further details, see [5]. Additional analyses showed that the correlation coefficients between surface roughness and mean ice thickness are low, too. Parameters such as height and spacing between ridges will also be investigated with respect to potential correlations with different ice thickness classes.

3.2 SAR Signatures Versus Ice Deformation and Thickness

Roughness and thickness profiles gathered during field campaigns with RV Polarstern have been linked with Radarsat-1 and ENVISAT ASAR scenes that were acquired over the same areas with only small time differences. One goal was to determine the correlations of ice surface elevation and ice thickness with radar intensity on a point-by-point basis. They turned out to be rather low [6] as was observed also in former studies. Another approach is to use the technique of feature extraction, i. e. separation of deformed and level ice in the SAR signatures and the roughness profiles, and to analyse the correlation of different parameter combinations, e. g. ridge spacing from laser profiler data combined with mean radar intensity. Preliminary results indicate that closer relationships can be established in this manner than without feature extraction.

3.3 Optimal SAR Configuration

From earlier studies of ground-based scatterometer data and air- and spaceborne SAR imagery it can be concluded that longer radar wavelengths are superior for mapping of sea ice deformation. An overview of findings reported in the literature and a comparison of JERS-1 and ERS-1 images is provided in [7]. Major items to be mentioned are:

(a) At L-band, the signature contrast between sea ice deformation features and smooth level ice is larger than at higher radar frequencies.

(b) Because the penetration depth of the radar waves into a medium is larger at lower frequencies, the utilization of L-band data for ice type and surface structure mapping is preferable during the melting period.

(c) If multi-polarization data are available, the overall ice type classification accuracy is higher at L-band than at C-band in case of ice regimes characterized by the occurrence of large-scale deformation features.

Not only frequency, but also polarization, incidence angle, and spatial resolution affect the capability of a sensor to separate level and deformed ice. These aspects were considered in a study using polarimetric C- and L-band imagery from the airborne EMISAR system [8], which gave the opportunity to look at image products of different polarizations. Data were gathered in the Baltic Sea and in the region of Svalbard. The detection of deformed ice in the images was carried out by using a threshold on the radar intensity distribution of level ice. For characterizing the deformation state, areal fraction of deformed ice, average deformation distance, and orientation pattern of elongated deformation features were evaluated. Large differences were found for areal fraction and deformation distance comparing L- and C-band because of the much larger radar intensity contrast between deformed and level ice at L-band. Differences between polarizations at one radar band were smaller but not always negligible. A sequence of images was generated from the original SAR scenes with increasingly coarser spatial resolution (pixel sizes from 5 m to 25 m), keeping the number of looks (about 10) constant. The obtained value for areal fraction and deformation distance increased as the image resolution became coarser, except at C-band where the areal fraction remained constant. The determination of the orientation pattern was less affected by the radar configuration. The pattern was smoother at coarser resolutions but its main characteristics were preserved. We did not find a considerable sensitivity of the intensity contrast to the incidence angle between 30 and 60 deg. Although this investigation provided many useful hints for developing algorithms for sea ice deformation mapping, it was hampered by the lack of usable complementary data, so that only the relative differences between L- and C-band could be analysed.

3.4 SAR Signatures Versus Aerodynamic Roughness

In April 2005, the Svalbard Experiment (SVALEX) took place with the participation of airplanes from DLR (carrying ESAR) and AWI. SAR images were acquired over sea ice in the Barents Sea and in Stjorfjorden, together with atmospheric and ice surface data. Three combined flights were carried out. The AWI-aircraft flew at 30 m altitude (equipment: optical scanner, devices for measuring atmospheric turbulence, ice surface temperature and topography) and the DLR-aircraft operated at 3000 m height (radar modes: L-band polarimetric X-band interferometric, VV-polarization). With a few hours time difference, also ENVISAT ASAR images at wide-swath mode were acquired. One objective is to devise a concept that utilizes parameters retrieved from synthetic aperture radar (SAR) imagery to evaluate aerodynamic roughness and the atmospheric drag coefficient of sea ice. To this end, it is planned to develop further methods for mapping and quantifying sea ice surface structure and deformation (e. g. floe size distribution, ridge spacing) from radar data. At present, SAR and optical images, and laser profiling data are combined and compared (see Fig. 1). Considering typical properties of spaceborne sensors, one important task is to determine at which spatial resolution useful information can be obtained about certain scales of sea ice surface roughness and deformation. A preliminary analysis of the radar and optical imagery showed that the surface of the ice floes was rough so that the radar intensity contrast between deformed and level ice may be lower than in the EMISAR data sets mentioned above. L-band is very sensitive to patterns of rafting in thin ice (< 0.5 m thick) which only have a negligible effect on the average aerodynamic roughness that determines the momentum transfer between atmosphere and ice. This means that an ice type classification of the L-band image should be carried out prior to the retrieval of deformation parameters.

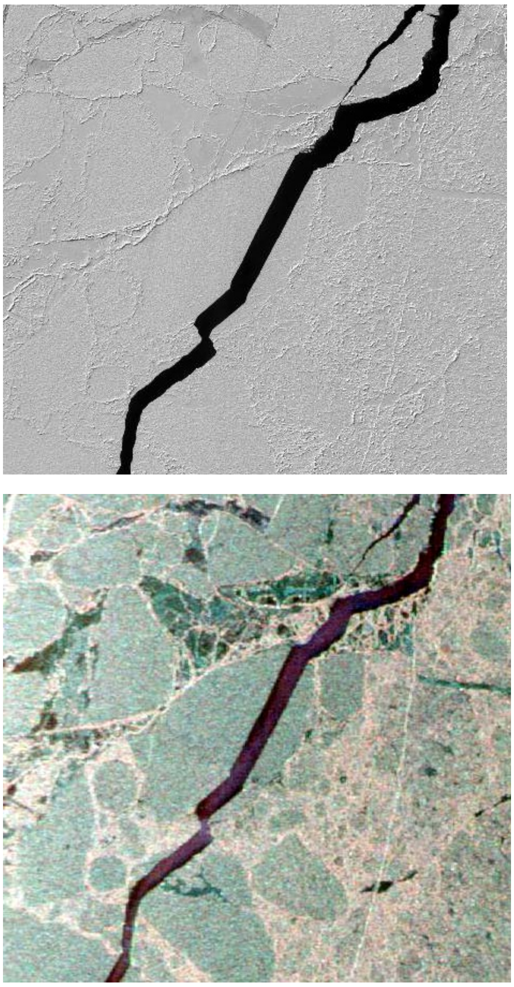

Figure 1 Optical and ESAR image over sea ice in the Barents Sea. SAR image: L-band, R-HV, G-HH, B-VV-polarization. Deformed and rough sea ice and ridges are recognized as bright patches and lineaments, thin ice as dark green areas, and a crack in the ice, releasing the open water surface, as dark feature. The image width (horizontal axis) is approximately 1.5 km.

4 Summary

We presented a short overview of research activities that deal with the utilization of SAR for mapping sea ice deformation and for retrieval of parameters that characterize ice surface topography/roughness. Deformation processes due to wind, ocean currents, and blocking effects of land cause large scale (order of meters) ice surface and bottom undulations. Our research addresses questions such as: (a) Which mathematical methods are most suitable for a quantitative description of ice deformation and of ice surface properties? (b) Which SAR configurations are optimal for mapping and parameter retrieval? (c) Which data processing methods should be used in order to extract direct or indirect information about surface topography, aerodynamic surface roughness, and ice thickness from SAR images with high accuracy? One goal is to assess advantages and limitations of different image products that are generated from data of spaceborne SAR sensors. We consider SAR systems that are in operation (ENVISAT ASAR, Radarsat-1, ALOS PALSAR) or will be launched soon (Radarsat-2, TerraSAR-X).

References

[1] Harder, M., and Lemke, P.: *Modelling the extent of sea ice ridging in the Weddell Sea*, in: The Polar Oceans and Their Role in Shaping the Global Environment, Geophys. Monograph 85, American Geophysical Union, pp. 187-197, 1994

[2] Strass, V. H., and Fahrbach, E.: *Temporal and regional variations of sea ice draft and coverage in the Weddell Sea obtained from upward looking sonars*, in: Antarctic Sea Ice: Physical Processes, Interactions And Variability, Antarctic Research Series, Vol. 74, pp. 123-139, 1998

[3] Steiner, N.: *Introduction of variable drag coefficients into sea ice models*, Annals of Glaciology 33, 2001, pp. 181-186

[4] Garbrecht, T., Lüpkes, C., Hartmann, J., and Wolff, M., *Atmospheric drag coefficients over sea ice – validation of a parameterisation concept*, Tellus 54A, 2002, pp. 205-219

[5] von Saldern, C., Haas, C., and Dierking, W.: *Paramterisation of Arctic sea ice surface roughness for application in ice type classification*, Annals of Glaciology, 2006

[6] Busche, T., von Saldern, C., Haas, C., and Dierking, W., *Comparison of helicopter-borne measurements of sea ice thickness and surface roughness with SAR signatures*, Proc. ESA ENVISAT Symposium, Salzburg, Austria, 2005 (on CD-ROM)

[7] Dierking, W., and Busche, T.: *Sea ice monitoring by L-Band SAR: An assessment based on literature and comparisons of JERS-1 and ERS-1 imagery*, IEEE Trans. Geosci. Remote Sensing, 2006, in print

[8] Dierking, W., and Dall, J.: *The effect of frequency, polarization, and spatial resolution on the quantification of sea ice deformation state using synthetic aperture radar imagery*, Remote Sensing of Environment, submitted, 2006