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On the improvement of sea ice classification by means of radar polarimetry

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ABSTRACT: Since the early 90s, a number of studies have been published that focus on the utilization of polarimetric synthetic aperture radar (SAR) imagery for sea ice monitoring. The most recent work in this field, carried out by different groups, has been one part of an ESA-initiated study on the use of polarimetry and polarimetric interferometry for applications development in land and ocean monitoring. One of the objectives of the sea ice work has been a critical assessment of the benefits gained by polarimetric SAR in ice type discrimination. To this end, the results of earlier studies have been reviewed, and new data sets as well as new algorithms have been considered. In this paper, an overview of the state-of-the-art is provided.

1 INTRODUCTION

Radar remote sensing of the Earth's surface is independent of cloud cover and daylight. The technique is therefore useful for monitoring the polar regions that are shrouded in clouds and in darkness over long periods of the year. Since March 2002, when the European remote sensing satellite ENVISAT was launched into space by an Ariane-5 rocket, "ASAR", the *A*dvanced *S*ynthetic *A*perture *R*adar, is in orbit around the Earth. ASAR can be operated in a dual-polarized mode. Compared to single-frequency, single-polarization space-borne SAR systems such as ERS-1, ERS-2, Radarsat-1, and JERS-1, the dual-polarization mode gives the opportunity to increase the accuracy of geo- and biophysical parameters that are retrieved from amplitudes and phases of the measured radar signal. Such parameters are, for example, vegetation biomass, soil moisture, and sea ice type distribution. The advantage of using a combination of different frequency bands and different polarizations is known from a number of airborne and ground-based radar measurement campaigns that have been carried out since the 60s. In the near future, quadruple-polarization ("quad-pol") SAR systems will be carried into space: the Japanese PALSAR on ALOS (L-band), the Canadian Radarsat-2 (C-band), the German TerraSAR-X (X-band), and the European TerraSAR-L (L-band).

In 2001, the European Space Agency (ESA) initiated a study that dealt with the application of radar polarimetry and polarimetric interferometry in geo- and biophysical research and monitoring. The results of this "POLSAR/POLINSAR"-study were presented at a workshop at ESRIN held in Frascati/Italy in the beginning of 2003. As part of the study, our group focused on the analysis of polarimetric radar data acquired over ice covered ocean regions. Sea ice influences a number of important processes within the climate system. Among these processes are the radiation balance, the energy exchange between the ocean and the atmosphere, and deep ocean water formation. In order to gain a more detailed understanding of the various interactions and feedback mechanisms between sea ice and its environment, parameters such as extent, concentration, thickness, drift, and deformation need to be monitored over years and decades. Another parameter relevant in this context is the sea ice type distribution. The classification of sea ice by means of a single-frequency single-polarization SAR is often ambiguous. As our contribution to the ESA study, we analyzed publications with emphasis on the utilization of multi-polarization multi-frequency SAR in sea ice classification, and we investigated different data sets from airborne campaigns of the US AIRSAR and the Danish EMISAR system. In this paper, we give an overview of the results of our work.

2 PARAMETERSS AFFECTING CLASSIFICATION

Before we start with a more detailed discussion of the utilization of polarimetric SAR for sea ice classification, a few comments of a more general nature are helpful. In our work we make use of the fact that a certain radar frequency and/or a certain polarization may contain information about a target that is not included in the signals of the other frequency bands and/or polarizations. Besides frequency and polarization of the received signal, the information content of a radar image depends on other factors as well.

Spatial resolution of the image: In order to separate, e. g., smaller patches of open water from sea ice, or to identify single ridge structures on the ice floes, the effective spatial resolution (after averaging over a number of actual resolution cells in order to decrease the contribution of speckle in the SAR image) has to be comparatively high – which is not easily achieved by recent satellite systems for which a typical value is 100 m. Future missions offer a choice of image products with different spatial resolutions and swath widths, whereby the mode of finest resolution (usually coupled with a narrow swath) will be close to values typical for recent airborne data acquisitions (which are about 3-10 m).

Environmental conditions: The radar signatures of sea ice, which are determined by the dielectric constant and the surface and volume structure of the ice, vary dependent on the meteorological conditions (temperature, precipitation, wind conditions) and on the region. In particular, melting conditions during late spring, summer, and early fall make the classification of sea ice difficult because of considerable signature changes compared to the winter situation (with temperatures below the freezing point) (Kwok et al., 1992; Onstott and Gogineni, 1985). This has to be taken into account by any classification scheme. Special conditions are encountered at the ice edge, where ocean waves may penetrate into the ice cover and contribute to its deformation and the breakup of larger floes, often causing a wave-like pattern in the radar signature of the ice (e. g. Dierking, 2001, and references cited therein). Open water patches reveal large variations of the radar signatures, depending on wind speed and direction. For example, under calm wind conditions, the water appears very dark in a radar intensity image, whereas it may be as bright as the signature of very rough ice at high wind speeds.

Radar incidence angle**:** In the case of airborne sensors, the incidence angle varies considerably over the swath, but less in the case of satellite sensors. The variation of the radar signatures as a function of the incidence angle can be severe, in particular, if surface scattering is dominating the signal. Usually, this is taken into account by dividing a given image into smaller range intervals with only modest changes of the incidence angle (the "range" direction is perpendicular to the flight track). Results obtained for a certain incidence angle interval may not be valid at other angles.

Dynamics of the ice cover: Sea ice is very dynamic by nature. Wind and ocean currents advect the ice floes. The internal stress in a convergent regime of the ice cover may cause surface deformations, and new ice may form in divergent ice zones. Hence, multi-temporal classification approaches, which require that objects remain fixed at a certain position (though their radar signature might vary as a function of time), cannot be used. Considering additional information about ice advection and changes of meteorological conditions may enhance the classification performance.

3 LITERATURE STUDY: THE EARLY PHASE OF SEA ICE POLARIMETRY

In winter 1988, fully polarimetric SAR data were acquired over sea ice for the first time (Drinkwater et al., 1991). Regions in the Beaufort, Bering and Chukchi Seas were covered, using the airborne NASA AIRSAR system. The AIRSAR was operated at C-, L- and P-band (wavelengths of 5.6, 24, and 68 cm). The "fully" polarimetric information includes, besides the intensities at differently polarized channels, the correlation and phase difference between these channels. The AIRSAR data from 1988 were subsequently used by different researchers. Rignot and Drinkwater (1994) presented an approach to ice type discrimination, which includes a quantitative assessment of the classification accuracy. They identified six ice conditions (multi-year ice and compressed first-year ice, rubble and ridges of first-year ice, rough and smooth first-year ice, and thin ice) and found that at a given frequency band, the fully polarimetric radar mode does not significantly improve the classification accuracy compared to the single-polarization case, whereas the combination of C- and L-band increases the accuracy by 10-20 percent even in single-polarization mode. Lee et al. (1994) focused their work on four ice type classes: first-year ice, multi-year ice, lead ice, and ridges. They reported that difficulties occur in discriminating lead and first-year ice at L-band, and in separating multi-year ice and ridge signatures at C-band. Overall, the L-band revealed the best classification accuracy compared to C-band and P-band. Winebrenner et al. (1995) paid attention to thin lead ice. They found that the L-band co-polarization ratio and phase difference (between the VV- and HH-polarized signals) of thin ice differ significantly from those of thick ice. ("H" and "V" denote horizontal and vertical polarization, respectively; "HV", for example, means that the transmitted signal is horizontally and the received signal vertically polarized).

4 LATER STUDIES

Already in the initial phase, major results have been achieved with regard to the usefulness of SAR polarimetry in sea ice classification. For thicker sea ice, the combination of different intensity channels is sufficient, that is, the “fully” polarimetric information is not required (which offers the advantage of a simpler and cheaper technical design of the SAR). L-band data reveal, in general, a better classification performance than C- or P-band, but C-band is superior for the discrimination of certain ice types such as first-year and multi-year level ice. Regarding the discrimination of different thin ice types and open water relative to one another and to thick ice, the study by Winebrenner et al. (1995) indicated a potential need for a fully polarimetric SAR, at least at L-band.

During the 90s, a few more polarimetric SAR measurements were carried out. The Danish EMISAR system was flown over the Greenland and the Baltic Sea in winter 95. The Greenland data set consists of C-band imagery of a mixture of drifting, weathered multi-year ice, with younger ice floes interspersed and thin ice growing in leads between the floes. Using this data set, *Thomsen (2001)* and *Thomsen and co-workers (1998a, b)* showed that the co-polarization phase difference of thin ice was significantly different compared to thicker ice. This was remarkable insofar as the AIRSAR C-band data do not reveal a corresponding signature difference. *Dierking et al. (1997)* and *Dierking and Askne (1998)* investigated the polarimetric signatures of ridged and level ice in the Baltic Sea, whereby they had images at C- and L-band from two consecutive days available. Compared to C-band, they found a better discrimination performance between ridged, deformed and smooth level ice at L-band, and indications that part of the measured L-band signal intensity originated from the underside of the ice cover. In contrast to the Arctic and Antarctic first-year ice, the penetration depth into Baltic Sea ice is larger because of its low salinity. Baltic Sea ice is only first-year, since no ice survives the summer, and its salinity is typically between 0 and 2 ppt (compared to 4-12 ppt for Arctic and Antarctic first-year ice). Further data were acquired in the SIR-C/X-SAR missions in 1994 from the Sea of Ohkotsk, the Labrador Sea, and from the Weddell Sea. Some of the Weddell-Sea data from October 1994 were analysed by *Eriksson et al. (1998)* who used thin first-year ice, brash ice, smooth first-year ice, deformed first-year ice and open water as potentially distinguishable ice categories. They came to the conclusion that a combination of L- and C-band polarimetric quantities give the best classification results, including the co-polarization phase difference at L-band.

In the late 90s, Cloude and co-workers (e. g. Cloude and Pottier, 1996) introduced a new approach to the analysis of fully polarimetric imagery, which makes it possible to decompose the received signal into the contributions of independent scattering mechanisms (direct scattering, double-bounce and/or multiple scattering contributions). This approach requires fully polarimetric data. Scheuchl and co-workers (2001; 2002a, b) applied the technique to the SIR-C data from the Labrador Sea and to the AIRSAR imagery. Compared to the earlier studies that are based on conventional analyses, however, the accuracy of sea ice classification has not been improved.

Usually, each study starts with its own initial separation of different sea ice type as can be recognized from the articles mentioned above. In fact it is a problem to establish definitions of classes which characterize different sea ice types uniquely and are meaningful when applied to radar imagery. The usual approach in SAR image analysis is to define “radar classes” of sea ice which are based on the signature properties of certain ice types and on visually identifiable features (such as leads and ridges). The classification results that are presented are not necessarily of general validity since they are based on particular test sites and sensor parameters. Another major problem of almost all data sets gathered until now is the lack of adequate in-situ data in order to validate the devised ice classification schemes. The usefulness of polarimetry can hence only be tested in a qualitative or semi-quantitative manner, for example, by defining a reference from the combination of all available radar channels, and then comparing single channels or groups of channels to this reference.

5 ANALYSIS OF AIRBORNE SAR DATA

Our approach for the ESA-POLSAR project was to collect typical polarimetric signatures for a number of ice classes as found in the scenes from the AIRSAR campaign 1988 and from the EMISAR flights from 1995 (see Dierking et al., 2003). Because the availability of complementary field data such as aerial photography was limited, we had to select the members of a certain ice class mainly on the basis of their appearance in the radar intensity images (in which the three channels HH, VV and HV/VH were combined in an RGB-format). For each class, the averages of a number of polarimetric parameters were calculated and plotted together with the standard deviations, the minima, and the maxima. Examples are shown in Fig. 1. These graphs give already an impression of the potential separation of the ice classes by means of a certain polarimetric parameter. In a next step, we constructed a hierarchy of decision rules, in which each step was optimal for separating a particular ice type or a group of types from the other ice classes. An example of the graphical presentation of individual steps within the classification hierarchy is provided in Fig. 2. Finally, we ended up with three tables listing a sequence of decision rules, one table for each test site (Beaufort Sea, Greenland Sea, and Baltic Sea). As an example, Tab. 1 contains the sequence for the Beaufort Sea. Although we defined our ice classes differently compared to Rignot and Drinkwater (1994), our findings compare well with their results: Except for the discrimination of thin ice types, the intensity channels are sufficient for a successful classification, and data clusters are better separated at L-band than at C-band (Fig. 2). But more important is the fact that we had to devise different decision rules separately for each test site in order to achieve the respective optimal classification result. This means that the optimal sequence of classification rules and the rules themselves depend on the ice regimes, an experience that is reported also by other researchers (e. g. Bertoia, 1998). A consequence of this result is that we favor the utilization of a hierarchical, knowledge-based classification approach by which also the results of measurements and theoretical modeling can be considered. Decision boundaries at the individual levels in the hierarchy can be determined by means of statistical methods. Such an approach can optimally be adapted to a particular region and season. At the present stage, we achieve classification accuracies of up to 90 percent, which is a reasonably good result.

Table 1. Decision rules for Beaufort Sea ice classification

Ice Class	L-Band	C-Band
MY Ice, Ridges	$\sigma^0_{VV} > -11$ dB and $\sigma^0_{HV} > -21$ dB	$\sigma^0_{VV} > -11$ dB and $\sigma^0_{HV} > 0.73\sigma^0_{VV} - 14.4$ [dB]
FY Ice, Ridges	$\sigma^0_{VV} > -15$ dB and -28 dB $< \sigma^0_{HV} \leq -21$ dB	$\sigma^0_{VV} > -22$ dB and $\sigma^0_{HV} \leq 0.73\sigma^0_{VV} - 17$ [dB] and $\sigma^0_{HV} > -35$ dB
MY Ice, Level	$\sigma^0_{VV} > -18$ dB and $\sigma^0_{HV} \leq -28$ dB	$\sigma^0_{VV} > -11$ dB and $\sigma^0_{HV} \leq 0.73\sigma^0_{VV} - 14.4$ [dB] and $\sigma^0_{HV} > 0.73\sigma^0_{VV} - 17$ [dB]
FY Ice, Level	-27 dB $< \sigma^0_{VV} \leq -18$ dB and $\sigma^0_{HV} \leq -28$ dB	-28 dB $< \sigma^0_{VV} \leq -16$ dB and $\sigma^0_{HV} \leq -35$ dB
Thin Ice, Type “a”	$\sigma^0_{VV} \leq -27$ dB and $\sigma^0_{HV} \leq -28$ dB	$\sigma^0_{VV} \leq -28$ dB and $\sigma^0_{HV} \leq -35$ dB
Thin Ice, Type “b”	-18 dB $< \sigma^0_{VV} \leq -12$ dB and $\phi_{HHVV} > 13$ deg	cannot be discriminated from analyzed polarimetric parameters

6 FURTHER RESULTS OF ESA-POLSAR STUDY

In parallel to our work, *Rodrigues et al. (2003)* and *Scheuchl et al. (2003)* also investigated the use of polarimetric SAR data for sea ice classification. Both investigations focused entirely on the classification potential of the SAR parameters resulting from signal decomposition (whereas we included also the more conventional parameters). *Rodrigues et al. (2003)* employed the AIRSAR data set from 1988 and separated the ice conditions into five major classes: multi-year ice, first-year ice, newly formed ice, compressed ice, and ridged ice. They found that ice type discrimination was better at L-band than at C-band. Also *Scheuchl et al. (2003)* made use of the AIRSAR data set, and took over the ice type scheme defined by *Rignot and Drinkwater (1994)*. They had a second data set available that was acquired by the Environment Canada CV-580 airborne SAR at C-band over test sites near Prince Edward Island, Canada, in March 2001. The ice classes for this data set were thin ice, first-year level, - rough, and – ridged ice, whereby first-year level ice at near and far range were taken as two different “classes”, and leads were treated separatly. *Scheuchl et al. (2003)* report that a combination of L-, C- and P-band is of greater use, and that C-band alone has a worse discrimination potential. Both groups mention that the automated classification is sensitive to incidence-angle effects.

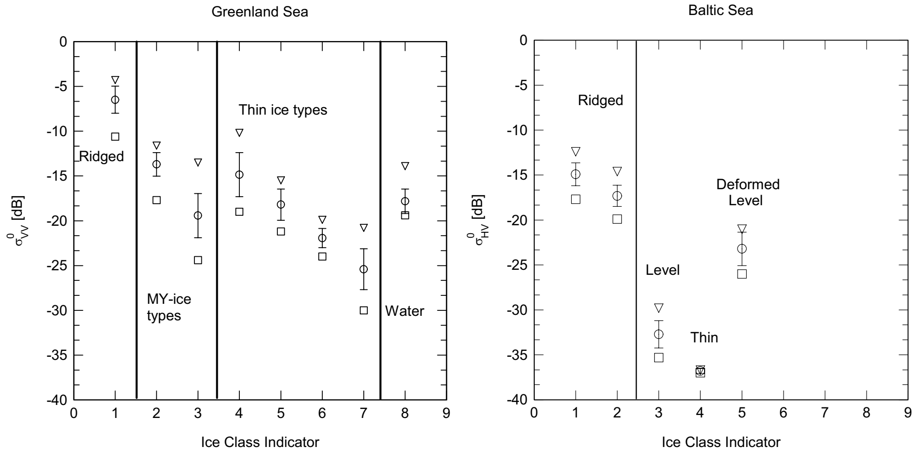

Figure 1. Examples of polarimetric parameters at C-band from the Greenland Sea (left) and at L-band from the Baltic Sea (right). The parameters are the backscattering coefficients at VV- (left) and HV-polarization (right). The mean value is shown as an open circle, the error bar is ±standard deviation, the minimum value is marked by an open rectangle, and the maximum value by an open triangle.

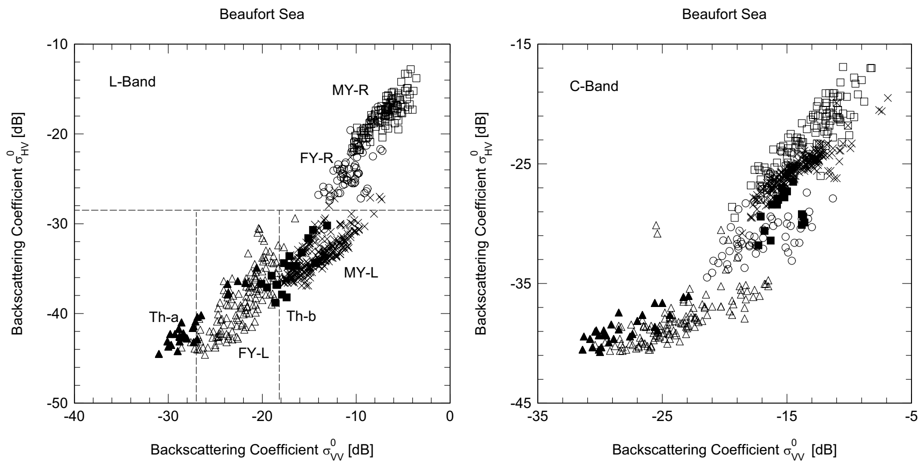

Figure 2. Ice type clusters at L- and C-band for the data set from the Beaufort Sea. The data marks indicate the following ice classes: multi-year level ice (MY-L) – closed circles, multi-year ridges (MY-R) - open squares, first-year level ice (FY-L) – open triangles, first-year ridges (FY-R) – open circles, thin ice type “a” (Th-a) - closed triangles, thin ice type “b” (Th-b) – x.

7 DISCUSSION

Concerning the application of SAR polarimetry for sea ice mapping, three points deserve attention: (1) Many authors find that L-band gives a better overall classification accuracy than C-band, emphasizing the need for L-band SAR missions in space complementing the C-band systems. (2) All authors agree that the goal of a robust, fully automated sea ice classification scheme by means of polarimetric SAR is not yet achieved. One problem is the already mentioned lack of extensive, independent data sets, by which the results of polarimetric classification schemes can be validated. Hence, further airborne and ground-based campaigns are necessary during which different types of sensors are combined. (3) General rules are required concerning the optimal separation of ice classes in radar imagery. By means of radar, it is not possible to identify each ice type as defined in the WMO (World Meteorology Organization) classification scheme that is mainly based on the visual appearance of the ice. In particular, at a coarser spatial resolution of the radar imagery, details relevant for identifying certain "WMO" ice types are lost. However, the radar offers complementary information about surface conditions and volume structure of the ice that cannot be obtained by means of visual observations and aerial photography.

For operational use, sea ice classification schemes have been developed for single-polarization, single-frequency SAR (e. g. *Bertoia et al., 1998*, and *Kwok et al., 1992*) and are still being improved to mimic the reasoning process of human operators experienced in utilizing conventional SAR images from ERS-1, ERS-2, and Radarsat-1 (e. g. *Bertoia et al., 1999*). It is important to note that for operational use, a wide swath (about 500 kilometers) is required in many cases. This, however, is a problem with a fully polarimetric SAR mode. The future satellite SAR missions (Radarsat-2, PALSAR, TerraSAR-X and –L) operate with swath widths of about 20 to 70 km in the quad-pol mode. Therefore, the results of *Rignot and Drinkwater (1994)* and of our group *(Dierking et al., 2003)* need to be emphasized: namely that the phase difference and correlation between the different channels may improve the type discrimination only in special (but nevertheless important) situations (see below). This means that for a lot of sea ice classification tasks, two satellites operating in dual-polarization mode and at longer (L-band) and shorter (C-, X-band) wavelengths, following each other closely in orbit, may be of a larger benefit for operational sea ice type mapping than a single-frequency polarimetric SAR.

For thin ice up to 20-40 cm, the phase difference between the HH- and VV-polarized channels is promising for thickness estimation and for classification, requiring a fully polarimetric mode. In particular for studies of the local and regional climate, monitoring and mapping of thin ice areas is important. Salt and heat fluxes depend on the ice thickness. Thin ice features such as polynyas and leads reflect the regional variability of these fluxes. However, it is still under discussion which scattering mechanisms are dominant in the case of thin ice, what radar frequency is optimal for mapping, and what model should be used for the retrieval of ice thickness from polarimetric data.

8 SUMMARY

We presented an overview of studies dealing with the application of radar polarimetry for sea ice classification. All research groups agree that the first step for a major improvement of operational sea ice mapping is achieved by combining different frequency bands rather than different polarizations. For certain applications, however, fully polarimetric radar data are needed. On the one hand, it seems to be possible that full polarimetry can be used to retrieve the thickness of thin ice, or at least to increase the discrimination performance between thin ice types and open water. On the other hand, polarimetry is helpful to improve our understanding of the interaction between the radar waves and the inhomogeneous medium ice.

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