
Presented by Zhang Xi, Wolfgang Dierking
I. Introduction

- The region surrounding the Bohai Sea is an important strategic economical circle.
- Sea ice seriously impacts ports, shipping, fishers, and marine operations around the Bohai Sea.
- Sea ice monitoring is an important task.

Study area
Objectives

- Develop methods for extracting sea ice parameters
  - Multi-Sensor data: optical/radar/IR...
  - Sea ice parameters: types, concentration, thickness, drift, ...

- Hazard risk assessment
  - Methods of calculating sea-ice-hazard risk
  - Study the spatial distribution characteristics and occurrence probability of sea-ice-hazard risk in the Bohai Sea

- Cooperation
  - Application and comparison of developed algorithms for different sea ice area, Bohai Sea, Arctic, Baltic Sea, ...
  - Training young scientists
Project partners

**European**
- Dr. Wolfgang Dierking (PI) — Alfred Wegener Institute for Polar and Marine Research, Germany.
- Dr. Markku Similä and Dr. Marko Mäkynen — Finnish Meteorological Institute, Finland

**Chinese**
- Dr. Zhang Xi (PI), Dr. Meng Junmin, and Dr. Ji Yonggang — the First Institute of Oceanography, SOA
- Dr. Guo Hao — Dalian Maritime University
- Dr. Wang Zhiyong — Shandong University of Science and Technology
II. Progress and results

Key parameters monitoring

1. Sea ice classification
2. Sea ice thickness retrieval
3. Sea ice drift tracking

Hazard risk assessment

4. Calculating hazard risk
5. Spatial distribution
1. Sea ice classification

\[ Y = f(X_1, X_2, \ldots, X_n) \]

**Ice Types**
- Open water
- New ice
- Grey ice
- Grey-white ice
- First-year ice

**Classifiers**
- MLC
- KNN
- SVM
- ANN
- Fuzzy logic

**Features**
- Spectral
- Backscattering
- Polarimetric
- Semantic

Key problem: Which features can well separate the ice types?
SAR features (backscattering and polarimetric)

- Select training samples from 23-scene SAR data (15 ASAR, 8 Radarsat-2), and 80,000 pixels are used as the training samples.
- Using the Bayes maximum likelihood classifier to analyze which features have high classification accuracy.
- 2,000 classification tests to be performed.

<table>
<thead>
<tr>
<th>Backscattering Coefficients</th>
<th>HH</th>
<th>HV or VH</th>
<th>VV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarized ratio</td>
<td>HV/HH</td>
<td>VH/VV</td>
<td>VV/HH</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polarization coherence</th>
<th>$\rho_{VH-HH}$</th>
<th>$\rho_{VV-HH}$</th>
<th>$\rho_{VV-VH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H/A/$\alpha$ decomposition</td>
<td>entropy</td>
<td>anisotropy</td>
<td>alpha</td>
</tr>
</tbody>
</table>
- **Backscattering: HH and VV**
- **Polarimetric: H and λ**

Classification accuracy

Classification accuracy
Optical features (VIR and hyperspectral)

- **VIR (MODIS, GaoFen-1):**

  **MODIS:**
  
<table>
<thead>
<tr>
<th>Feature</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud</td>
<td>(CH5+CH6)/CH4&lt;0.8</td>
</tr>
<tr>
<td>Land-water</td>
<td>1.0&lt;CH1/CH2&lt;3.8</td>
</tr>
<tr>
<td>Ice-water</td>
<td>1.0&lt;CH1/CH2&lt;1.8</td>
</tr>
<tr>
<td>Ice</td>
<td>Ch1 &gt; 0.08, and T31 &lt; 272k</td>
</tr>
</tbody>
</table>

  **Gaofen-1:**
  
<table>
<thead>
<tr>
<th>Feature</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud</td>
<td>0.6&lt;Blue&lt;0.8, and 0.6&lt;Green&lt;0.8</td>
</tr>
<tr>
<td>Open Water</td>
<td>4.0&lt;B2I&lt;5.5, and 0.20&lt;B_R&lt;0.24</td>
</tr>
<tr>
<td>Thin Ice</td>
<td>0.05&lt;Red&lt;0.1, and 0.52&lt;B_I&lt;0.59</td>
</tr>
<tr>
<td>Grey Ice</td>
<td>0.28&lt;Red&lt;0.35, and 0.35&lt;B_I&lt;0.4</td>
</tr>
<tr>
<td>Grey-white Ice</td>
<td>0.19&lt;Red&lt;0.25, and 0.45&lt;B_I&lt;0.5</td>
</tr>
</tbody>
</table>

- **Hyperspectral (MERISE):**

  \[
  \begin{align*}
  \frac{CH_{13}}{CH_{10}} & > 0.68 \quad \text{land and cloud} \\
  \frac{CH_{2}}{CH_{1}} & \leq 0.68 \quad \text{sea water and ice} \\
  \frac{CH_{2}}{CH_{1}} & < 0.95 \quad \text{water} \\
  \frac{CH_{1}}{CH_{1}} & > 0.95 \quad \text{ice}
  \end{align*}
  \]
Method

- SAR\VIR\Hyperspectral
- Segmentation
- Feature Extraction
- Semantic descriptors
  - Shape:
    - Grey ice more rounded
    - New ice more rectangular
  - Assorted relationship:
    - Grey ice symbiotic relationship with grey-white ice
    - Land fast ice is adjacent to land
- First Classification
- Quadratic Classifier
- Modify and Classification

Radarsat-2

Segmentation

First Classification

Final Classification
Comparison of classification with expert analysis

2010.2.8 Radarsat-2 fine qual-pol
Classification accuracy: 92.8%
Kappa=0.88
Application

ENVISAT ASAR (2006.2.23)
ENVISAT ASAR (2007.1.16)

- Open water
- Grey ice
- Grey-white ice
MERIS (20090114)
CBERS-02B (2010.2.13)

- Open water
- Grey ice
- New ice
- Grey-white ice
2014.1.10, GF-1 Multispectral, 8m

New ice; Grey-white ice
Grey ice; Open Water
2. Sea ice thickness retrieval

① For SAR data

Surface scattering @X-Bragg model

\[
\begin{align*}
\langle \sigma_{HH}^0 \rangle_{\beta} &= 4k^4 \cos^4 \theta s^2 W_n (2k \sin \theta) \\
\left[ \frac{|F_H|^2}{2} (1 + \sin 2\beta_1) + \frac{|F_V|^2}{2} (1 - \sin 2\beta_1) - \frac{|F_H - F_V|^2}{8} (1 - \sin 4\beta_1) \right] \\
\langle \sigma_{VV}^0 \rangle_{\beta} &= 4k^4 \cos^4 \theta s^2 W_n (2k \sin \theta) \\
\left[ \frac{|F_V|^2}{2} (1 + \sin 2\beta_1) + \frac{|F_H|^2}{2} (1 - \sin 2\beta_1) - \frac{|F_H - F_V|^2}{8} (1 - \sin 4\beta_1) \right] \\
\langle \sigma_{HV}^0 \rangle_{\beta} &= 4k^4 \cos^4 \theta s^2 W_n (2k \sin \theta) \frac{|F_H - F_V|^2}{8} (1 - \sin 4\beta_1)
\end{align*}
\]
The small-scale-roughness parameters cancels out.

Depend on the dielectric constant $\varepsilon$ and the variation of slope $\beta_1$.

Ice thickness has high correlation with ice salinity (dielectric constant).

When the variation of slope is stable ($<\pm 9^\circ$), the changes in ice thickness can be estimated.
Field work

2012, 7-days

2013

2014, 6-days, Prosensing-Scat

2015

2014

2012, 7-days

2012

2009

Interlaken | Switzerland

年6月22-26日，瑞士·因特拉肯
VV/HH

\[ y = -6.304x + 26.244 \]
\[ R^2 = 0.73165 \]

RMS = 2.0 cm
R-rms = 9.1%

VH/VV

\[ y = 2.2002x + 43.158 \]
\[ R^2 = 0.59747 \]

RMS = 2.5 cm
R-rms = 10%

VH/HH

\[ y = 2.653x + 45.279 \]
\[ R^2 = 0.41254 \]

RMS = 3.0 cm
R-rms = 12%

\[
\frac{\sigma_{VV}^0}{\sigma_{HH}^0} > \frac{\sigma_{VH}^0}{\sigma_{VV}^0} > \frac{\sigma_{VH}^0}{\sigma_{HH}^0}
\]

RMS = 2.0 cm
R-rms = 9.1%
RMS = 2.5 cm
R-rms = 10%
RMS = 3.0 cm
R-rms = 12%
For VIR data

The sea ice shortwave albedo changes with the variation of sea ice thickness.

\[
\alpha = \alpha_{\text{max}} \left[ 1 - \frac{\alpha_{\text{sea}}}{\alpha_{\text{max}}} \exp(-\mu h) \right]
\]

(Grenfell, 1991)

\(\alpha\) is the shortwave albedo of sea ice;
\(\alpha_{\text{sea}}\) is the albedo of sea water, =0.06;
\(\alpha_{\text{max}}\) is the albedo of sea ice at infinite thickness, =0.7;
\(\mu\) is the attenuation coefficient of the albedo, =1.209.
Ice reflectance spectrum measurement

\[ \alpha_{\text{modis}} = 0.160 \alpha_{ch1} + 0.291 \alpha_{ch2} + 0.243 \alpha_{ch3} + 0.116 \alpha_{ch4} + 0.112 \alpha_{ch5} + 0.081 \alpha_{ch7} - 0.0015 \]

\[ \alpha_{\text{goci}} = 0.1727 \alpha_{ch1} + 0.726 \alpha_{ch2} + 0.0095 \alpha_{ch4} - 0.2102 \alpha_{ch5} + 0.6942 \alpha_{ch6} + 0.2473 \alpha_{ch7} - 0.0292 \]

\[ R^2 = 0.9 \]
Result

$R^2 = 0.89$

<table>
<thead>
<tr>
<th>DATE</th>
<th>Location</th>
<th>In-situ data (cm)</th>
<th>Retrieval result (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014.1.17</td>
<td>40°21'40&quot;</td>
<td>14.36</td>
<td>17.4</td>
</tr>
<tr>
<td>2014.1.19</td>
<td>122°8'17&quot;</td>
<td>20.57</td>
<td>19.0</td>
</tr>
<tr>
<td>2014.1.20</td>
<td>40°39'59&quot;</td>
<td>9.42</td>
<td>11.0</td>
</tr>
<tr>
<td>2014.1.21</td>
<td>122°9'45&quot;</td>
<td>24.21</td>
<td>26.7</td>
</tr>
<tr>
<td>2014.1.22</td>
<td>40°15'11&quot;</td>
<td>16.85</td>
<td>20.5</td>
</tr>
<tr>
<td>2015.1.17</td>
<td>122°7'23&quot;</td>
<td>17.41</td>
<td>19.90</td>
</tr>
<tr>
<td>2015.1.17</td>
<td>122°8'17&quot;</td>
<td>20.43</td>
<td>24.00</td>
</tr>
<tr>
<td>2015.1.31</td>
<td>122°3'52&quot;</td>
<td>21.06</td>
<td>19.70</td>
</tr>
</tbody>
</table>

RMS = 6.82 cm  Relative RMS = 14.2%
3. The velocity of sea ice estimation

Feature tracking algorithm is used to track sea ice drift.

Given two subsequent images, estimate the point/facet translation.

\[
\text{speed} = \sqrt{u^2 + v^2} \times \text{resolution} / \text{time}
\]

\[
\text{direction} = \arctan(v / u)
\]
Method

Geometric registration

Feature tracking

Interpolation

Sea ice drifting product

Searching window: $15 \times 15$ pixels

2010.1.18
02:10 (ASAR)
02:42 (ERS-2)
Unit: m/s

ASAR ERS-2

Correction
Results V.S. Manually collected

Sea ice drift speed

![Graph showing the relationship between extracted ice speed (m/s) and manually collected speed (m/s). The graph shows a linear trend with a correlation coefficient $R^2 = 0.83$ and RMSE = 0.17 m/s.]

Sea ice drift direction

![Graph showing the relationship between extracted ice direction (degree) and manually collected direction (degree). The graph shows a linear trend with a correlation coefficient $R^2 = 0.98476$ and RMSE = 12.73°.]

Our results are consistent with manually derived results both speed and direction.
4. Sea ice hazard risk assessment

- The Bohai marine industry is very well developed, including fishery, transportation, and oil industry, etc.
- Sea-ice greatly threatens the security of shipping and maritime operations.
- It is very important to evaluate the damaging effects of sea ice on marine transportation and offshore oil plants.

Most of ships in the Bohai Sea have no ice breaking capabilities.
For different hazard-bearing bodies, we define different sea-ice-hazard index.

- For marine transportation, $I_1$
  - $I_1 = \text{Ice concentration} \times \text{Ice thickness}
  - A bigger value means harder breaking ice and less navigable.

- For offshore construction (e.g. oil-platform), $I_2$
  - $I_2 = I_1 + \text{Ice concentration} \times \text{Ice thickness} \times \text{Ice velocity}
  - A bigger value means a higher extruding pressure and impulse force imposed by sea ice.
According to the Sea-ice-hazard Emergency Plan, Sea-ice-hazard Bulletin from the State Oceanic Administration People’s Republic of China (SOAPRC)

- Ice concentration (%): 0-15, 15-50, 50-80, 80-100
- Ice thickness (cm): 0-10, 10-20, 20-30, >30
- Ice velocity (m/s): 0-0.2, 0.2-0.4, 0.4-0.6, >0.6

$I_1$ for marine transportation

- No hazard: 0~1.5
- Low hazard: 1.5~10
- Mild hazard: 10~24
- Severe hazard: >24

$I_2$ for offshore construction

- No hazard: 0~1.8
- Low hazard: 1.8~14
- Mild hazard: 14~38.4
- Severe hazard: >38.4
Example 1. A normal ice year

2006.2.3-10:13 (ASAR)
2006.2.3-11:00 (Modis)

2006.2.4-13:20 (Modis)
$I_1$ for marine transportation

$I_2$ for offshore construction
Example 2. A heavy ice year

2010.2.12-12:55 (Modis)

2010.2.13-09:50 (ASAR)
2010.2.13-10:20 (Modis)
$I_1$ for marine transportation

$I_2$ for offshore construction
A Polarimetric Decomposition Method for Ice in the Bohai Sea Using C-Band PolSAR Data
Xi Zhang, Wolfgang Dierking, Jie Zhang, and Junmin Meng

Abstract—In recent years, there has been an increased interest in using synthetic aperture radar (SAR) to detect and monitor sea ice in the Bohai Sea for providing offshore exploration and supporting marine transport. Two important tasks are the classification of sea ice and the determination of sea ice thickness, which can be achieved by considering the specific scattering mechanisms of the different ice types. This paper describes a three-component scattering model to decompose polariometric SAR (PolSAR) data of sea ice. The total backscatter is modeled as the incoherent summation of surface, double-bounce, volume, and residual components. The model predicts the volume scattering contribution of ice and the contribution of ice to the total backscatter in the Bohai Sea. The results show that the proposed polarimetric decomposition approach helps to distinguish different ice types and offers a proxy for sea ice thickness.

Index Terms—Polarimetric radar, scattering, sea ice, synthetic aperture radar (SAR)

I. INTRODUCTION

Sea ice covers about 10% of the Earth's ocean surface. While the largest parts are located above 60°N and 60°S, the southernmost frozen sea in Northern Hemisphere is the fast ice in the Bohai Sea between 37°30’–119°20’E (Fig. 1). The ice in the Bohai Sea gets only a few months old. It begins to form as early as December and melts completely by the following March. The region surrounding the Bohai Sea generates 22.0% of China's gross domestic product [1]. Sea ice constitutes a serious hazard to offshore transport and marine exploration in the Bohai Sea. Throughout the last 100 years (especially in 1936, 1947, 1957, 1969, 1977, and 2010), ice in the Bohai Sea has negatively impacted shipping and the infrastructure of the petroleum industry, leading to significant financial losses [2], [3]. Therefore, the detection and monitoring of Bohai Sea ice is important for offshore exploration and marine transport in winter.

In winter, up to half of the Bohai Sea is covered by new ice. The ice extent and thickness vary significantly dependent on meteorological conditions (temperature and wind). In a warm winter, the ice thickness is approximately 10–30 cm, while it is 30–100 cm in cold winters [4]. The surface salinity of the Bohai Sea is 28–30 psu. Although the water in the Bohai Sea is less saline than the Pacific Ocean, the salinity of sea ice in the Bohai Sea is relatively high because of the young age of the ice, namely between 3 and 8 psu on average [4]. According to field investigations, the density of new sea ice is 914 ± 915 kg/m³ and the density of old sea ice is 920 ± 957 kg/m³ [4].

Sythetic aperture radar (SAR) is a powerful remote sensing tool to monitor sea ice [5], [6] due to its high spatial resolution, wide coverage, and its ability to penetrate the ice surface, so that subsurface ice structures can be reconstructed. However, owing to the complexity of the sea ice surface and volume structure, the radar backscattering characteristics can be highly variable. Surface properties of the sea ice (such as (level ice roughness or ice ridges)) have a significant influence upon the observed polarimetric SAR (PolSAR) signatures. In addition, polarimetry is also sensitive to the shape and orientation of brine cells that influence absorption and scattering less within the ice. Therefore, to infer geo-physically realistic properties of the ice, surface and volume contributions need to be separated. The result of the decomposition can be useful for discriminating sea ice types and estimating sea ice thickness.

Several target decomposition theories have been described for various applications. For natural terrain, Freeman and Duden [7] proposed a three-component scattering model to decompose the polarimetric SAR signatures into surface, double-bounce, and volume scattering contributions [7]. Extensions of this decomposition have been published for urban [8], wetland [9], agricultural [10], and glacier ice applications [11]. However, none of these methods are suitable for describing sea ice scattering, because of the high absorption and scattering of radar waves in the ice volume that complicate modeling.

The objective of this paper is to separate the radar return from sea ice into different scattering components using a polarimetric decomposition technique. We put forward a new polarimetric model of sea ice volume backscattering by considering absorption and scattering from inhomogeneities such as brine cells, and refraction in the sea ice surface. At the present stage, we use a number of simplifications in the model assumptions, including: reflection symmetry of the volume model, a dipole shape, and uniform orientation distribution for all volume inclinations. These assumptions were necessary because a combined model with surface, double-bounce, and volume has too many unknowns for inversion if only a single PolSAR image is available. Although the proposed decomposition model does not reflect the full complexity of the scattering process within...
Sea ice drift tracking in the Bohai Sea using geostationary ocean color imagery

Wenhui Lang
Qing Wu
Xi Zhang
Junmin Meng
Ning Wang
Yajing Cao
First-year level sea-ice thickness retrieval in Labrador Sea using C-band polarimetric SAR data

LIU Mei-jie¹,²,³, DAI Yong-shou¹, ZHANG Jie², ZHANG Xi², MENG Jun-min²

Characterization of level sea-ice thickness in the labrador sea using C-band polarimetric SAR data
VI. Research Planning

- Develop sea ice thickness extracting method for active and passive remote sensing data.
- Evaluate and develop the sea ice monitoring method for Sentinel-1 SAR data.
- Study the occurrence probability of sea-ice hazard and the spatial distribution characteristics of sea-ice-hazard risk in the Bohai Sea using multi-source remote sensing data.
Thanks for your attention!