VALIDATION OF RADARSAT-2 POLARIMETRIC SAR MEASUREMENTS OF OCEAN WAVES

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ABSTRACT
Four C-band fully polarimetric synthetic aperture radar (POLSAR) images of ocean waves from the RADARSAT-2 SAR are used to measure ocean slopes and wave spectra. A new technique has been developed to measure wave slopes in the SAR azimuth and range directions. The POLSAR ocean wave parameter measurements were validated with in situ observations from an NOAA National Data Buoy Center (NDBC) buoy. The results show that wave parameters measured using the new method are in good agreement with in situ NDBC measurement products.

Index Terms— Polarimetric SAR, Ocean wave, RADARSAT-2

1. INTRODUCTION

Synthetic Aperture Radar (SAR) systems have been widely used in observing oceanic phenomena, such as ocean waves, shallow sea bottom topography, internal waves, boundary currents, oil spills, ship wakes and related processes [1]. In the recent decades, considerable efforts have gone into retrieving quantitative surface wave information from SAR images [2]-[3]. To extract ocean wave spectra from SAR images accurately, several nonlinear methods have been developed following the theory presented by Hasselmann et al. [4]. Most basic methods use an iterative technique to derive wave spectra from SAR image spectra. Initial estimates, and inputs of the forward SAR imaging model, are obtained by using a linear transfer function similar to that proposed by Lyzenga [5]. Thereafter, the revised image spectrum is used to iteratively correct the previous estimate of the wave spectrum. The accuracy of the method is related to the imaging mode of SAR. Hasselmann et al. [6] improved the method by incorporating closed form descriptions of the nonlinear transfer function. However, their improvement still can not avoid the need for iterations. Further improvements for the nonlinear algorithm were suggested by Engen and Johnsen [7] and Lehner et al. [8]. In their method, the cross-spectra are generated between different looks of the same ocean wave scene. The virtue of the method is that it not only can resolve the 180° ambiguity of wave direction, but it also reduces the effects of speckles.

An inversion algorithm with fully polarimetric SAR image data has been developed to measure wave slopes in range and azimuth directions [9]-[11]. Using Fourier transforms, the complete directional ocean wave slope spectrum can be determined by the orthogonal slope information. The advantage of the polarimetric method is that a nearly direct measurement of the slope is made without the use of a parametrically complex modulation transfer function (MTF).

The new algorithm for ocean wave parameters retrieved from fully polarimetric SAR image data [12]-[13] is described in section 2 and the validation of RADARSAT-2 polarimetric SAR measurements of ocean waves is given in the following sections.

2. ALGORITHM

In this presentation, we consider polarimetric SAR measurements of ocean waves using linearly polarized SAR images and the polarization orientation angle method. We use various sea states to validate RADARSAT-2 polarimetric SAR measurements of ocean wave spectra; specifically, we consider C-band quad-polarization SAR data.

The formulae for polarimetric SAR measurements of ocean wave spectra are as follows[15]:

\[
\frac{\Delta \sigma_{HH}}{\sigma_{HH}^0} - \frac{\Delta \sigma_{VV}}{\sigma_{VV}^0} = -\left(8 \tan \theta \frac{\partial \xi}{\partial x} + 1 + \sin^2 \theta \frac{\partial \eta}{\partial y}\right)(1a)
\]

\[
\frac{\Delta \sigma_{VH}}{\sigma_{VH}^0} - \frac{\Delta \sigma_{HV}}{\sigma_{HV}^0} = A \frac{\partial \xi}{\partial x} + B \frac{\partial \eta}{\partial y}(1b)
\]

where,

\[
A = \frac{a_2}{a_0} - a_3, \quad B = \frac{a_1}{a_0}(2a)
\]
\[
\begin{align*}
    a_n &= \frac{1}{4} \left[ 1 + \left( \frac{1 + \sin^2 \theta}{1 - \sin^2 \theta} \right) \left( 1 + \cos^2 (2\varphi) \right) \right] - \frac{2 \sin^2 \theta}{1 - 8 \sin^2 \theta + 8 \sin^2 \theta} \frac{\cos(2\varphi)}{\sin(2\varphi)} + \frac{1 + 2 \tan^2 \theta}{2} \sin^2 (2\varphi). \\
    a_r &= \frac{1}{4} \left[ 1 + \left( \frac{1 + \sin^2 \theta}{1 - \sin^2 \theta} \right) \cos(2\varphi) \left( 1 - \left( \frac{1 + \sin^2 \theta}{1 - \sin^2 \theta} \right) \right) \right] - \frac{2 \sin^2 \theta}{\tan^2 \theta (1 + \cos^2 (2\varphi))} - \frac{4 \tan^2 \theta \cos(2\varphi) + 2 \tan^2 \theta \sin^2 (2\varphi)}{\sin^2 \theta} \\
    a_z &= 4 - 0.5(1 - \sin^2 \theta) \\
    a_3 &= \tan \theta \left( 1 - \sin^2 \theta \right)
\end{align*}
\]

Figure 2a is the azimuthal direction wave slope and Figure 2b is the range direction wave slope. The slope spectrum is shown in Figure 3.

3. VALIDATIONS

In this presentation, the fully polarimetric SAR data from the RADARSAT-2 are used to estimate ocean wave slopes. Tables 1 gives details of the four acquired RADARSAT images and corresponding buoy data provided by the National Oceanic and Atmospheric Administration (NOAA)/National Data Buoy Center (NDBC).

<table>
<thead>
<tr>
<th>Image code</th>
<th>Acquired time</th>
<th>Buoy time</th>
<th>Image central site</th>
<th>Buoy site</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05:47:58</td>
<td>05:50:00</td>
<td>51°07'18&quot;N</td>
<td>51°09'17&quot;N</td>
</tr>
<tr>
<td></td>
<td>28 Feb 2009</td>
<td>28 Feb 2009</td>
<td>178°53'10&quot;W</td>
<td>179°00'02&quot;W</td>
</tr>
<tr>
<td>2</td>
<td>02:25:04</td>
<td>02:50:00</td>
<td>46°04'06&quot;N</td>
<td>46°03'00&quot;N</td>
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<tr>
<td></td>
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<td>11 Jan 2009</td>
<td>131°02'22&quot;W</td>
<td>131°01'12&quot;W</td>
</tr>
<tr>
<td>3</td>
<td>03:30:55</td>
<td>03:50:00</td>
<td>56°18'12&quot;N</td>
<td>56°17'59&quot;N</td>
</tr>
<tr>
<td></td>
<td>19 Feb 2009</td>
<td>19 Feb 2009</td>
<td>147°57'46&quot;W</td>
<td>148°01'16&quot;W</td>
</tr>
<tr>
<td>4</td>
<td>14:09:15</td>
<td>14:50:00</td>
<td>46°07'05&quot;N</td>
<td>46°08'37&quot;N</td>
</tr>
<tr>
<td></td>
<td>17 Mar 2009</td>
<td>17 Mar 2009</td>
<td>124°33'25&quot;W</td>
<td>124°30'37&quot;W</td>
</tr>
</tbody>
</table>

Table 1. RADARSAT-2 data acquired and buoy information

Figure 1 shows the C-band SAR image in the VV polarization of this area in test image 1. The wave slopes estimated from the study area box are shown in Figure 2.

Figure 1. A C-band, VV polarization, RADARSAT-2 image.

Figure 2. (a) Image of wave slope in the azimuthal direction, and (b) the range direction.

Figure 3 Wave slope spectrum retrieved from a C-band fully polarimetric SAR Image.

\[1 \text{ RADARSAT-2 Data and Products © MacDONALD, DETTWILER and ASSOCIATES LTD. (2009) - All Rights Reserved.}\]
Figures 4-6 show the C-band VV polarization SAR images of the RADARSAT-2 fully polarimetric SAR images, and the slope spectra, respectively.

Figure 4 The VV polarization image\(^1\) (a) and wave slope spectrum (b) retrieved from a C-band fully polarimetric SAR Image on 11 Jan 2008.

Figure 5 The VV polarization image\(^1\) (a) and wave slope spectrum (b) retrieved from a C-band fully polarimetric SAR Image on 19 Feb 2009.

Figure 6 The VV polarization image\(^1\) (a) and wave slope spectrum (b) retrieved from a C-band fully polarimetric SAR Image on 17 Mar 2009.

The significant wave height, wavelength and wave direction are calculated by using the algorithm [12] and compared with corresponding quantities provided by the NDBC buoy
in Table 2. For all four SAR images, the results retrieved from RADARSAT-2 polarimetric SAR are in a very good agreement with those provided by NDBC (National Data Buoy Center) buoys.

Table 2. Estimated wave parameters from SAR for the four images in Table 1, compared to corresponding wave parameters provided by in situ buoy measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>image</th>
<th>Retrieval</th>
<th>buoy</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (m)</td>
<td>1</td>
<td>194.4</td>
<td>188.8</td>
<td>-5.6</td>
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<tr>
<td></td>
<td>2</td>
<td>377.1</td>
<td>399.5</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>208.3</td>
<td>229.2</td>
<td>20.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>252.9</td>
<td>263.7</td>
<td>10.8</td>
</tr>
<tr>
<td>Average error</td>
<td>12.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave direction (degree)</td>
<td>1</td>
<td>257.9</td>
<td>270.0</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>243.9</td>
<td>240.0</td>
<td>-3.9</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>97.5</td>
<td>135.0</td>
<td>37.5</td>
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<tr>
<td></td>
<td>4</td>
<td>276.6</td>
<td>285.0</td>
<td>8.4</td>
</tr>
<tr>
<td>Average error</td>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant wave height (m)</td>
<td>1</td>
<td>4.00</td>
<td>4.10</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.93</td>
<td>3.10</td>
<td>0.17</td>
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<td></td>
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<td>2.22</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
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<td>3.82</td>
<td>3.40</td>
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<tr>
<td>Average error</td>
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</table>

4. CONCLUSIONS

In this presentation, the algorithm to retrieve ocean wave slope spectrum from POLSAR images is summarized. Four C-band POLSAR images of the RADARSAT-2 SAR are used to validate POLSAR measurements of the ocean wave parameters. The results show that wave parameters measured using the new algorithm are in good agreement with in situ NDBC measurement products.

5. ACKNOWLEDGEMENT

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6. REFERENCES