ENHANCING GLOBAL MARITIME DOMAIN AWARENESS THROUGH SAR WITH MULTIPLE APERTURES

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ABSTRACT
This paper investigates and demonstrates enhancements to Maritime Domain Awareness (MDA) through the use of a multi-aperture space-based SAR. In contrast to a single channel SAR, it shows how modes can be designed to record data over a wide swath (enabling wide area surveillance) at high resolution (offering improved vessel detectability and potential for classification). This paper also explores how these same data can be processed using different algorithms to enhance ship detection through clutter suppression and outlines how to estimate vessel headings and speeds. Additionally, it shows that in littoral zones, ambiguities from on-shore clutter can be minimized. Demonstrations of the claims are made using data collected by RADARSAT-2 in a dual-aperture configuration.

1. INTRODUCTION
Radars equipped with multiple digitizers and appropriate signal routing architecture, as illustrated in Figure 1, can record multiple receive patterns simultaneously, albeit with fewer elements, a wider antenna pattern and smaller receive gain than a full aperture single-channel SAR. Also, by transmitting or receiving with different antenna patterns from pulse to pulse, multiple antenna patterns can be obtained through time-multiplexing. Data recorded by such systems, which include RADARSAT-2 and TerraSAR-X, can be grouped into different channels according to the two-way transmit/receive array pattern and can be processed using multi-dimensional techniques, such as digital beamforming, to offer improvements over classical single channel SARs such as Sentinel, RCM, Cosmo SKYMED and RADARSAT-1.

In combination with an appropriate mode (PRF, echo-window timing and elevation beam pattern), multiple apertures in the azimuth direction permit High-Resolution Wide-Swath (HRWS) measurements, [1, 2, 3], and also make possible Moving Target Indication (MTI) enabling estimation of the velocity of detected targets, [4, 5, 6, 7].

This paper quantifies these improvements by applying specific algorithms for signal processing of dual-channel measurements from RADARSAT-2 and comparing with data that would have been collected with a single channel.

Fig. 1. Apertures formed by combining the receive array measurements. On the left, a single aperture formed using all antenna elements. On the right, two apertures, one formed from all elements on the left half of the array, the second formed from the remaining elements.

2. ARRAY SYNTHESIS MODEL
The vector signal measured by each array element as a function of angle-of-arrival, \( u \), is modeled by

\[
\mathbf{z}_r(u) = \begin{bmatrix}
    e^{-2j\beta x_0 u} \\
    e^{-2j\beta x_1 u} \\
    \vdots \\
    e^{-2j\beta x_{N-1} u}
\end{bmatrix}
+ \begin{bmatrix}
    \nu_0 \\
    \nu_1 \\
    \vdots \\
    \nu_{N-1}
\end{bmatrix}, \tag{1}
\]

where \( \beta = 2\pi/\lambda \) (\( \lambda \) is the radar wavelength) and \( x_i \) is the along-track position of the \( i \)th element of the array, and \( \nu_i \) is the additive noise contribution from element \( i \). Specifically, for a system with \( N = 16 \), the combining operation of the left side of Figure 1 is given by \( z(u) = \mathbf{t}^\dagger \mathbf{z}_r(u) \), where \( \mathbf{t} \) is a 16-element column vector with ones in each position (\( \dagger \) denotes Hermitian conjugate). The measurements on the right side are given by

\[
\begin{bmatrix}
    z_a(u) \\
    z_f(u)
\end{bmatrix} = \begin{bmatrix}
    \mathbf{t}_a^\dagger \\
    \mathbf{t}_f^\dagger
\end{bmatrix} \begin{bmatrix}
    \mathbf{z}_r(u)
\end{bmatrix}, \tag{2}
\]

where \( \mathbf{t}_a \) is a column vector with ones in the first eight positions and zeros in the last eight and \( \mathbf{t}_f \) is \( \mathbf{t}_a \) flipped upside down. Given the dual-aperture measurements, a single aperture equivalent system would have measured \( z(u) = z_a(u) + z_f(u) \). Thus, in this paper, single channel data are...
synthesized by summing the dual-aperture data to obtain vessel and clutter statistics as well as imagery. One concludes that optimal linear processing of the dual channel data for ship-detection will yield performance that is at least as good as the equivalent single channel system.

3. MEASURED RADARSAT-2 DATA

We consider two dual-channel measurement modes for RADARSAT-2. In both modes the entire array is used on transmit. For mode-1, \( t_a \) and \( t_f \) are as defined in Equation 1, while for mode-2, an amplitude weighting is applied (i.e. the non-zero elements of \( t_f \) and \( t_a \) are set to values less than or equal to one) to form wider patterns with a shorter effective phase-centre separation. Other radar parameters are as summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>mode-1</th>
<th>mode-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse bandwidth (MHz)</td>
<td>1819</td>
<td>860</td>
</tr>
<tr>
<td>Near range (Km)</td>
<td>1016</td>
<td>1089</td>
</tr>
<tr>
<td>Ground swath width (Km)</td>
<td>40</td>
<td>108</td>
</tr>
<tr>
<td>Near incidence angle (deg)</td>
<td>40.9</td>
<td>40</td>
</tr>
<tr>
<td>Wavelength (m)</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>Polarization</td>
<td>VV</td>
<td>HH</td>
</tr>
<tr>
<td>Pulse length (( \mu s ))</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>Pulse bandwidth (MHz)</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Effective velocity (m/s)</td>
<td>7548</td>
<td>7540</td>
</tr>
</tbody>
</table>

Table 1. RADARSAT-2 measurement parameters.

For both modes, as compared to the corresponding equivalent single channel mode, each channel will enjoy higher azimuth resolution after SAR compression. On the other hand, the shorter receive antenna also reduces the receive gain and, although this loss is somewhat mitigated by a longer integration time from the wider pattern, the overall effect is a lower Signal to Noise Ratio (SNR). By combining the channels, however, the SNR can be recovered, and depending on the type of target and clutter and on the speed of the target, the Signal to Clutter-Plus-Noise Ratio (SCNR) can also be improved. It should be noted that the mode-2 data are quite similar to a mode used to form a commercially available wide-swath, fine-resolution single-channel product. We will demonstrate that in addition to being used to form a wide-swath, high-resolution product, these data can also be used to compute a coherent estimate of target across-track speed.

4. INCREASED SWATH WIDTH AND IMPROVED AZIMUTH RESOLUTION

According to the HRWS principle, the use of multiple apertures aligned in the along-track direction allows the radar to be operated at a reduced PRF, thereby making it possible to measure a wider swath while retaining azimuth resolution, [1, 2, 3]. This feature of multi-aperture systems is particularly attractive for MDA as it directly addresses the area coverage problem. It is interesting to investigate mode-2 data, processed with the method of [8], since this mode is an instance of such a HRWS mode. Indeed Figure 2 illustrates that compared to the single channel mode, the azimuth resolution is improved. This advantage is coupled with the illustration in Figure 3 where it is shown that the single channel mode at the specified PRF (or equivalently swath) has poorer ambiguity characteristics than the dual aperture case. In littoral zones, azimuth ambiguities can be particularly problematic because, despite land-masking, algorithms can incorrectly assign vessel status to large RCS clutter that displaces from land onto the water.

5. SPEED ESTIMATES AND IMPROVED SCNR

The MTI principle allows for coherent estimation of the across-track velocity of moving targets. To test this concept, data were collected using mode-1 over Vancouver in 2009 and processed with the EDPCA method of [4]. Ground truth are obtained from shore-based Automatic Identification System (AIS), and the results are plotted in Figure 4. One clearly sees a good agreement between AIS measurement and the radial speed estimates from the dual-channel radar measurements. It is clear that the dual channel measurements enjoy a better SCNR; thus vessel detection is more likely.

5.1. Along-track speed estimation

Coupled with the higher azimuth resolution that one expects from the HRWS principle, it is also interesting to consider improvements in the estimation of the along-track velocity. This paper examines the bi-directional along-track motion approach described in [9, 10], but with a modification available from the multiple channels. With this method, the grating lobes of the synthetic array (at angles \( \theta_k \) with \( \sin \theta_k = u_k = k\lambda f_p/(2v_{\text{eff}}) \), \( k \in \{\ldots, -1, 0, 1, \ldots\} \), are used as beams to acquire two measurements displaced in time. The parameters in Table 1 give time differences between the different beams, \( r\lambda f_p/(2v_{\text{eff}}^2) \), at the near range as 1.0231 s for mode-1 and 0.5204 s for mode-2. During this time, moving targets can displace in azimuth.

Multi-channel data provide the option to steer the element pattern of the synthetic array towards the grating lobe directions, which, in the estimation algorithm used in this paper, are directed symmetrically around the detected target direc-

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1Available from the MacDonald Dettwiler and Associates Ltd. RADARSAT-2 order desk.
Fig. 2. Imagery for mode-2 data. Single channel equivalent data (left) have poorer azimuth resolution.

Fig. 3. Plot of ship target and ambiguities (dB). Single channel equivalent data (left) have poorer azimuth ambiguity characteristics.

Fig. 4. Ship speed estimates (Radar versus AIS) and SCNR increase over single channel measurements for 21 targets using mode-1.
Fig. 5. Target SCNR for two beams using mode-2. The fore pattern is steered forward, the aft pattern backward by the angle on the x-axis.

rather than the zero-Doppler clutter direction, thereby increasing the target SCNR. This increase in SCNR aids in the sub-pixel shift estimation thereby decreasing variance in the along-track velocity estimator. Figure 5 illustrates that by beam-steering the receive gain pattern, the SCNR from a measured target is increased by about 1.5 dB

6. CONCLUSION

This paper argues that a multi-channel capability on space-based SARs improves maritime domain awareness. The incremental cost of realizing multiple receive chains offers the flexibility to image wide swaths at high resolution (not possible on a single channel SAR) and the ability to coherently (more accurately) estimate ship target radial velocities. It also offers post-collection receive pattern beam-steering which, when incorporated into the bi-directional along-track velocity estimation approach, improves estimation accuracy. Practically, wider coverage and improved SCNR increase the chance of ship-detection, high-resolution aids in ship classification, and, finally, improved velocity estimation provides improved ship heading information.

7. REFERENCES


