

Ambiguous Staggered SAR: Rationale and Advanced Processing Techniques for Clutter Suppression

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Abstract — Conventional synthetic aperture radar (SAR) modes can only map wide swath at the expense of a degraded azimuth resolution, limiting the detection of weak or small targets. In order to overcome this limitation without increasing the system complexity (e.g., using digital beamforming), a novel ambiguous staggered SAR mode is proposed, which utilizes a wide beam for both transmission and reception while continuously varying the pulse repetition interval and waveform and achieves high resolution over ultra-wide swath. However, due to lower receive beam gain and overlapping echoes, the resulting SAR images are affected by noise and range ambiguities from both point and extended targets as well as clutter. Spaceborne experiments using the TerraSAR-X satellite demonstrated the effectiveness of this mode for ship monitoring in open sea and coastal regions, achieving swath widths over 160 km with an azimuth resolution of 2.2 m, an eightfold improvement compared to the TerraSAR-X ScanSAR mode. Postprocessing techniques for ambiguous clutter suppression can enhance ship detection performance. By exploiting waveform diversity, such as up- and down-chirps and different matched filters, range-ambiguous clutter can be mitigated, further improving target detection capabilities.

Keywords — Ambiguities, clutter, high-resolution wide-swath imaging, maritime monitoring, multi-focus postprocessing, ship detection, synthetic aperture radar (SAR), staggered SAR, TerraSAR-X, waveforms

I. INTRODUCTION

Synthetic Aperture Radar (SAR) imaging plays a crucial role in maritime applications such as traffic monitoring, pollution control, and defense. Effective ship detection requires both wide-swath coverage for frequent observations and high resolution for improved detection performance. However, these requirements impose contradicting constraints on the pulse repetition frequency (PRF). A larger pulse repetition interval (PRI) enables wide-swath imaging but limits the unambiguous Doppler bandwidth, reducing azimuth resolution. Conventional SAR modes like ScanSAR and Terrain Observation by Progressive Scans (TOPS) provide wide coverage but at the expense of reduced azimuth resolution. Techniques like digital beamforming and multiple aperture recording can overcome these limitations but increase system complexity and cost. To address this, we propose two ambiguous high-resolution, wide-swath modes suitable for ship monitoring: the low PRF mode, which tolerates azimuth ambiguities [1], and the ambiguous staggered SAR mode, which tolerates range ambiguities [2]. The latter mode images a wide swath by using a wide-elevation beam for both transmission and reception while transmitting a sequence of distinct PRIs with a mean PRF exceeding the

Doppler bandwidth. A larger swath, but a coarser azimuth resolution, can be obtained with a ScanSAR mode with six sub-swaths that tolerate azimuth ambiguities, as proposed by NovaSAR [3]. This, however, leads to the detection of only medium to large ships with a false alarm rate of 10^{-7} .

Two experimental TerraSAR-X acquisitions in ambiguous staggered mode were performed over the North Sea, imaging ground swaths of 110 km and 160 km, respectively, with 2.2 m azimuth resolution [4], [5]. In the first experiment, [4], the 110-km ground swath was located 27 km far from the coast. In the second experiment, [5], a part of the Dutch coast was imaged and the acquisition incorporated staggered ambiguous mode along with alternating up- and down-chirps. This chirp alternation resulted in the complete blurring of the first-order range ambiguities.

Although the ambiguous clutter, which overlaps with the non-ambiguous radar echo returns, behaves as a noise-like disturbance, it increases the overall disturbance level, thereby limiting the detection of ships, especially small ones. Dual-focus postprocessing techniques, [7], which utilize different matched filters during processing, offer an effective method for clutter suppression, leading to improved detection performance.

II. AMBIGUOUS STAGGERED SAR

In the staggered ambiguous mode with alternating up- and down-chirps, a wide elevation transmit beam illuminates a wide swath and the radar echoes are collected with the same wide beam used in transmit. Unlike conventional systems with constant PRI, we transmit a sequence of different PRIs where the mean PRF of the sequence is greater than the PRF required to receive the echo from the full swath. The upper part of Fig. 1 depicts the transmission and reception of radar echoes for the simplified case of a sequence of $M = 5$ PRIs with a linear decreasing trend. The transmitted pulses, separated by varying PRIs, and consisting of alternated up- and down-chirps, are displayed on a time axis in the upper part of the upper panel. Each transmitted pulse is represented by a different color with the number indicating the pulse index; the up-chirp and down-chirp pulses are denoted with the symbols U and D , respectively. Immediately below, the received echoes corresponding to the first two transmitted pulses are shown on the same time axis. The radar echoes from the sea clutter are displayed with the same colors as the corresponding transmitted pulses. The radar echo return from a ship at a slant range R_0 (for simplicity, we assume the ship is not moving) overlaps to the

echo return from the sea clutter and it is marked in red followed by the symbol U or D indicating the corresponding transmitted pulse. It is important to note that while we receive the desired radar echo of the ship at slant range R_0 from pulse number 0, marked in red, we will also receive an ambiguous return from pulse number 1, shown in white with symbol D . This happens because the receive echo window is typically much shorter than the duration of the radar echo from the illuminated swath. This is also true for the sea clutter returns, which will overlap.

The received echoes are then rearranged, i.e., shifted at the same reception time as shown in the bottom panel of Fig. 1. As a result, the received radar echoes from the ship are at the same slant range R_0 for all range lines, while its ambiguous returns are located at different ranges for different range lines, as the time difference between the transmit pulses continuously varies. Please note that this also applies to the sea clutter returns, which consist of the sum of the non-ambiguous sea clutter component and the range-ambiguous sea clutter components from different pulses, as their duration in the received radar echo is longer than the PRIs. Due to the radar's inability to receive while transmitting, some "blind areas" will be present on the received data with width equal to the pulse length. These "blind areas" are marked in black in the upper and bottom panel of Fig. 1. Following the range compression of the rearranged data, achieved by alternating up and down chirps in Fig. 1, the ship at the slant range R_0 will be focused in range. In contrast, its first order range ambiguity (along with all the odd order range ambiguities) will be blurred in range during the range compression operation with a smearing factor proportional to the compression ratio of the transmitted chirp.

The blurring effect occurs because of the mismatch between the ambiguous returns, alternating between down- and up-chirps, and the reference signal, alternating between up- and down-chirps in the example shown in Fig. 1. Furthermore, after azimuth compression, the ambiguous energy of both even and odd order range ambiguities, due to PRI variation, is incoherently integrated and will spread almost uniformly across the whole Doppler spectrum [6]. The same applies to sea clutter echoes or land scatterers. This results in an increase in the disturbance level in the region affected by the ambiguities, which must be considered when selecting the threshold to detect the ships.

III. AMBIGUOUS STAGGERED SAR EXPERIMENT WITH TERRASAR-X

TerraSAR-X is a conventional phased-array SAR that can be operated with continuously varying PRI, because it has 512 different PRIs and can be commanded to transmit pulses based on a sequence of M distinct PRIs that then repeats periodically. An area in the North Sea along the Dutch coast was selected as test site for the demonstration.

The chosen elevation beam allows imaging a 160-km ground swath with minimum and maximum look angles of 53.08° and 57.29° , respectively. The 160-km ground swath is not defined by the 3-dB antenna beamwidth, but extends beyond it, as TerraSAR-X still provides adequate noise equivalent sigma zero, ensuring a sufficient signal-to-noise ratio for effective ship detection across the wide swath.

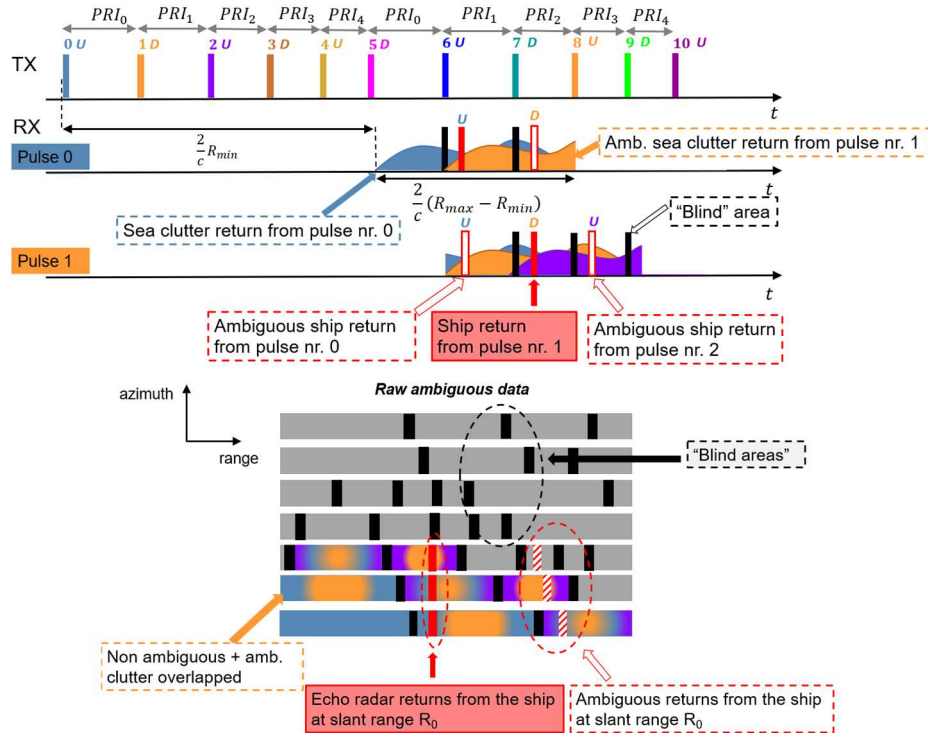


Fig. 1 Top: Transmitted pulses and corresponding received echoes. Bottom: Raw data obtained by rearranging side by side the received echoes.

Once the beam has been selected, other system parameters such as the PRI sequence, the pulse length and the chirp bandwidth, have to be chosen to ensure the best ship detection performance while respecting the TerraSAR-X technological constraints. For a pulse length of 45 μ s and a chirp bandwidth of 100 MHz, it is possible to design a sequence of $M = 43$ PRIs, as for the experiment in [4]. A ground range resolution of 1.75 m at near range and an azimuth resolution of 2.2 m are achieved, if no weighting windows are applied within the processing. The sequence of 43 PRIs is repeated 2800 times. The echoes, received by the radar between consecutive transmitted pulses, have different duration, as different PRIs are employed. Unlike in a SAR with constant PRI, the first samples of the received echoes correspond in a staggered SAR system to different slant ranges. Those echoes have therefore to be rearranged in a two-dimensional matrix with coordinates slant range and azimuth. This rearrangement associates each sample of radar echo with its corresponding range. Please note that each

received echo contains not only the desired return, but also the returns of preceding and succeeding pulses as they arrive back at the radar at the same time. After rearrangement, range compression is performed using alternating up- and down-chirps.

Subsequently, the data are resampled on a uniform grid, following the procedures outlined in [6]. Range cell migration correction and azimuth compression are then performed. Fig. 2 shows the intensity of the focused data for the entire scene, covering an area of about 37 760 km², where the strong returns from ships along with the coastline and the first- and second-order range ambiguities from the coast are visible. The red and green rectangles highlight the areas affected by first- and second-order range ambiguities of land scatterers, respectively. The smearing of the first-order range ambiguities and its appearance as noise-like disturbance are visible.

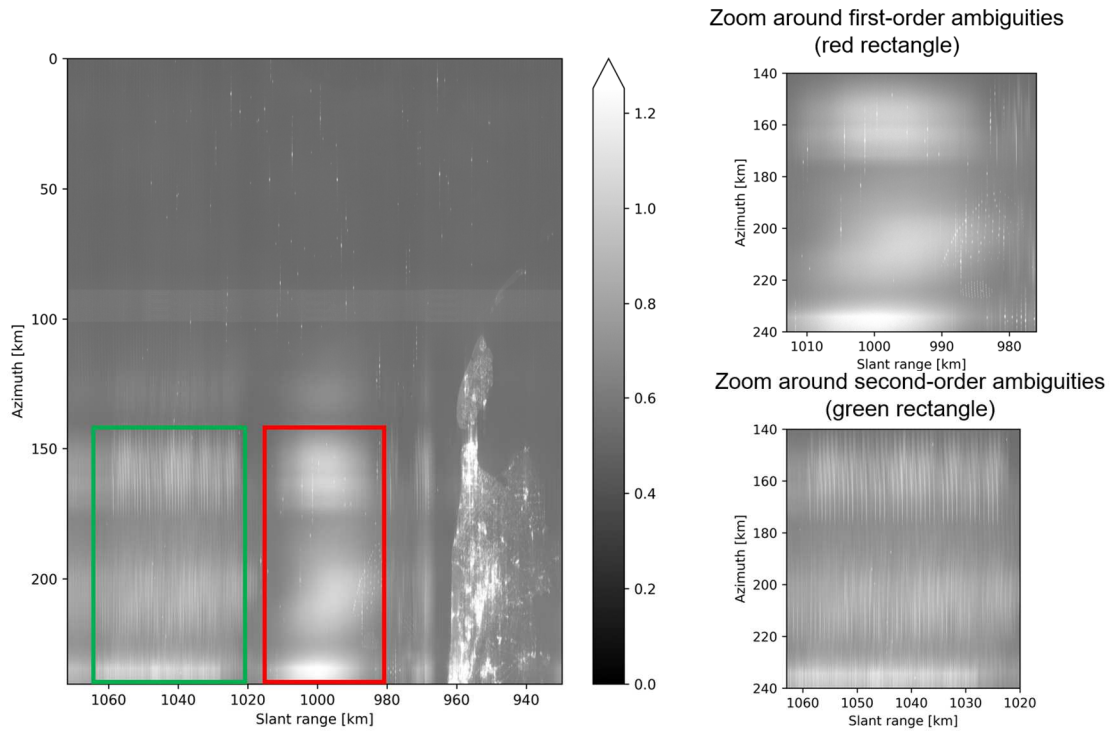


Fig. 2 Intensity of the focused image acquired by TerraSAR-X in staggered ambiguous mode with alternating up- and down-chirps over the full scene. The red rectangle and the green rectangle highlight the first-order and the second-order range ambiguities from the coast.

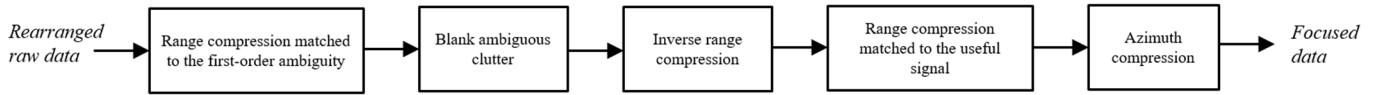


Fig. 3 Block diagram of the dual-focus postprocessing in range compressed domain.

Table 1 Detection performance comparison with the AIS data.

Ship length	Ship with AIS	Detected	Lost	% of detected ships
$l \leq 25$ m	76	47	29	61%
$25 \text{ m} < l \leq 150$ m	82	69	13	84%
$l > 150$ m	29	29	0	100%
No information	76	67	9	88%

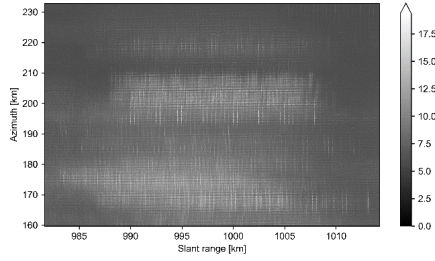


Fig. 4 Zoom around the first-order range ambiguity region highlighted by the red rectangle in Fig 4 after range compression matched to the ambiguity.

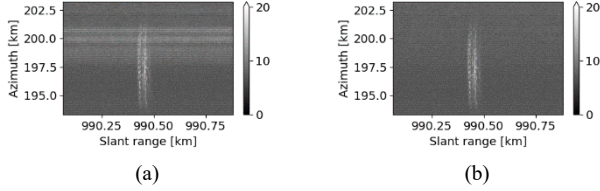


Fig. 5 Zoom on a range compressed ship: (a) before dual-focus postprocessing, and (b) after dual-focus postprocessing.

The detection of ships includes two main stages. In the first stage, the overall image intensity is compared to an adaptive threshold based on the variable background level. Pixels that exceed this threshold are identified as potential ship candidates. In the second stage, the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm is applied to cluster pixels exceeding the threshold and belonging to the same ship.

The effectiveness of the ambiguous staggered SAR mode is evaluated using maritime positioning data from the Automatic Identification System (AIS). The AIS dataset contains a total of 263 ships, 76 of which lack length information. Table 1 shows the detection performance in terms of detected and missed ships based on AIS data for different ship lengths. All large ships (length $l > 150$ m) are correctly detected, while 13 medium-sized ships ($25 \text{ m} < l \leq 150 \text{ m}$) were missed, and only 61% of small ships ($l \leq 25 \text{ m}$) are successfully detected.

IV. CLUTTER SUPPRESSION WITH DUAL-FOCUS POSTPROCESSING

As discussed in Section III, although land-ambiguous clutter appears smeared and behaves as “noise-like”, it still contributes to background disturbance, reducing ship detection performance in the affected region, i.e., the highlighted region by the red rectangle in Fig. 3. One possible approach to mitigating this issue is dual-focus postprocessing, as proposed in [7] and experimentally demonstrated in [8] for nadir echo removal.

The key idea is to focus the rearranged raw data using a filter matched to the range ambiguity rather than one matched to the useful signal. There are two possible methods for blanking range-ambiguous clutter: either in range-compressed data, as shown in Fig. 3, or in fully focused data. Determining which approach is preferable will be the subject of future work.

After range compression of the raw data using a filter matched to the first-order range ambiguities, the ambiguous

clutter becomes focused in range, while non-ambiguous ships returns remain smeared. Fig. 4 provides a zoomed-in view of the first-order range ambiguity of the range compressed data, where the strong return from ambiguous land clutter is evident. The removal of the range-ambiguous clutter can be performed using an adaptive threshold, blanking pixels with intensities above a certain threshold. In [7], it is shown that a simple yet effective threshold selection criterion is the minimization of image contrast after range focusing matched to the range ambiguity. Once the range-ambiguous clutter has been removed, the data is “inversely” focused back into raw data and then refocused using a filter matched to the useful signal. For instance Fig. 5 compares the range-compressed data around a medium-sized ship using a filter matched to the main signal, both before and after dual-focus postprocessing. A visible reduction in ambiguous clutter returns is observed after dual-focus postprocessing. The threshold used to blank the ambiguous land signal, following range compression matched to the ambiguity, was chosen to achieve a contrast of 1 within the analyzed patch.

V. CONCLUSION

An experimental TerraSAR-X acquisition in staggered ambiguous mode, imaging a ground swath of 160 km with a 2.2 m azimuth resolution, was conducted over the North Sea. The data was processed, and the detection results were validated using AIS data. The use of dual-focus postprocessing to further improve ship detection by suppressing range-ambiguous clutter is discussed and preliminary results shown.

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