AMBIGUOUS SYNTHETIC APERTURE RADAR MODES FOR WIDE SWATH SHIP MONITORING AND DIGITAL ELEVATION MODEL GENERATION IN A SINGLE PASS

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ABSTRACT

One relevant application of synthetic aperture radar (SAR) is ship monitoring. Conventional SAR modes, however, are limited in their ability to detect small ships over wide swaths (> 100 km) due to their low azimuth resolution. A novel SAR mode is presented in which the pulse repetition interval (PRI) is continuously varied and is much smaller than the minimum PRI imposed by the swath width, producing images that are corrupted by strong range ambiguities. For the same observed swath, this mode has significantly better detection performance than ScanSAR due to higher azimuth resolution and ambiguity blurring effect due to the PRI variation. Waveform alternation can be moreover explored to further blur ambiguities and increase the mapped swath. Spaceborne demonstrations using experimental TerraSAR-X acquisitions are presented. The idea of SAR systems affected by SAR ambiguities is then extended to the case of a cluster of small satellites, whose acquired data are jointly processed to create an accurate, high-resolution digital elevation model (DEM) of the observed scene in a single pass. This technique is demonstrated through a dedicated multi-baseline airborne campaign, carried out using DLR's F-SAR airborne sensor.

Index Terms—Digital elevation model (DEM), radar ambiguities, ship detection, small satellites, synthetic aperture radar (SAR).

1. INTRODUCTION

Ship monitoring is an important application of spaceborne synthetic aperture radar (SAR) [1]. Typically, a SAR acquisition is performed in an area of interest, data are processed using standard SAR focusing algorithms and then post-processed to obtain a detection map. Comparing the detection map with external information, e.g., from an automatic identification system (AIS), enables the identification of ships lacking an AIS transponder or vessels not broadcasting AIS messages. Ideally, mapping wide swaths is desirable, as this reduces the number of acquisitions required to cover a given area of interest.

In SAR acquisitions, however, the width of the imaged swath is inversely proportional to the achievable azimuth resolution. At typical satellite altitudes of 500-600 km, a ground swath of 100 km can be imaged with an azimuth resolution in the order of 15 m. This is usually achieved in systems with limited antenna length in the azimuth direction by ScanSAR (or TOPS) acquisitions, in which the synthetic aperture time is shared over multiple sub-swaths [2]. For instance, TerraSAR-X in ScanSAR mode enables mapping of a ground swath of 100 km with an azimuth resolution of 18.5 m, a ground range resolution of 3.5 m and a noise equivalent sigma zero (NESZ) of -19 dB. Different combinations of ground range resolutions and NESZs can be achieved by changing the chirp bandwidth. The detection performance of a small ship (defined here as a ship with a size of 100-150 m^2, e.g., 20 m × 6 m) at a given false alarm rate generally depends on a variety of factors, but can be estimated to a first approximation based on the ship intensity statistics and the disturbance statistics. The intensity of the ship pixels can be assumed to be lognormally distributed with parameters that can be estimated from available SAR images, while a K-distribution can be assumed for the sea clutter. The detection performance depends on the clutter-to-noise ratio (CNR) and the shape factor of the K-distribution. Based on the ship intensity statistics retrieved from TerraSAR-X, the detection probability using ScanSAR images is expected to be around 0.1-0.3, at a false alarm rate such that no more than one false alarm occurs over a 1000 km^2 area [3].

One way to explain the low performance is that the average transmit power is not high enough to guarantee better performance. However, after further consideration, a mode with a coarse azimuth resolution, namely ScanSAR (or TOPS), is chosen because it is the only classical SAR mode that allows mapping of the desired wide swath. The hypothesis underlying the classical SAR modes is that the level of azimuth and range ambiguities in the SAR image should be controlled, i.e., the total ambiguity-to-signal ratio (ASR) should not exceed -15 dB. Indeed, ambiguities also pose a problem for ship detection for the following two reasons: 1) the ambiguity of a ship could be interpreted as a ship, i.e., it could lead to false alarms (this can be the case even with an ASR in the order of -15 dB – please note that

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this effect is not taken into account when evaluating the performance of ScanSAR in the previous example); 2) the ambiguity of the sea clutter contributes to an increase in the disturbance level, making it more difficult to detect ships with the same false alarm rate.

In stripmap mode, the constraint to avoid strong ambiguities is that the pulse repetition interval (PRI), i.e., the interval between two consecutive transmit pulses, should be at least as large as the duration of the swath echo and small enough to properly sample the Doppler bandwidth resulting from the antenna length (or at least the Doppler bandwidth required to achieve the desired azimuth resolution). For example, TerraSAR-X allows mapping a 30 km ground swath in stripmap mode with an azimuth resolution of 3 m and a PRI in the order of 0.3 ms, which corresponds to a pulse repetition frequency (PRF) of about 3300 Hz. If the transmit and receive beams are widened in elevation by a factor of three, e.g., using phase spoiling, a swath larger by a factor of three would be imaged with the same azimuth resolution, but since the PRI is now much smaller than the duration of the swath echo, multiple echoes, referred to as range ambiguities, will come back to the radar simultaneously from different parts of the swath. In addition, the NESZ will decrease by a factor of nine for the same average transmit power due to the lower gain on both transmit and receive [4].

Recent developments in the context of high-resolution wide-swath SAR missions for Earth monitoring, such as DLR's Tandem-L mission proposal, have shown the advantages of modes based on continuous, pulse-to-pulse PRI variation, also known as staggered SAR [5]-[7]. This concept will also be used as baseline for the NASA-ISRO SAR (NISAR) mission, scheduled for launch in 2024 [8]. While the main advantage of the staggered SAR mode is the ability to map a wide continuous swath with high azimuth resolution by getting rid of rid of the blind ranges due to the transmit interference and this requires digital beamforming in elevation, an additional feature of the staggered SAR mode is that range ambiguities are smeared in both range and azimuth because of the continuous PRI variation.

If the SAR image acquired over a given area is to be used exclusively for ship detection and it can be assumed that the intensity of the ships to be detected is much higher than that of the disturbance, it can be shown that a SAR mode that observes a wide swath in stripmap with a PRI that is much smaller than that imposed by the swath width and varies from pulse to pulse can lead to significantly improved detection performance thanks to the high azimuth resolution.

2. STAGGERED AMBIGUOUS MODE FOR SHIP MONITORING

The novel proposed staggered ambiguous SAR mode for wide swath ship monitoring is essentially a stripmap mode (i.e., no beam steering is performed during the acquisition), characterized by a wide antenna beam in elevation (on both transmit and receive) that illuminates the full desired swath. If the antenna is a phased array and characterized by a height larger than that required to achieve the desired beamwidth in elevation, (phase-only) phase spoiling can be used and even optimized to achieve constant performance over the swath, as suggested in [9].

The pulse repetition interval is varied from pulse to pulse according to a periodically repeating sequence of PRIs. The PRIs of the sequence are set so that no two consecutive azimuth samples are missing in the raw data, according to the staggered SAR theory, although this condition is not so strict, i.e., it is still fine, if a few consecutive azimuth samples are missing. The average PRI (or equivalently the average PRF) is chosen to be in the order of or slightly higher than the Doppler bandwidth given by the antenna length. The requirement that two consecutive pulses are never missed in azimuth usually results in PRI variations in the order of 10% - 20% (this is also dependent on the pulse width, with longer pulse widths requiring a wider PRI span).

The design principles of the ambiguous staggered SAR mode for ship monitoring are discussed in [3], where the system parameters are derived from the application requirements, i.e., ship size, probability of detection and false alarm rate. The idea of an ambiguous SAR, although not based on a continuous variable PRI, was originally developed in [10] for a low power SAR satellite with a small antenna. Here it is important to point out that the described ambiguous staggered SAR mode is also suitable for small SAR satellites with low power.

As mentioned previously, the evaluation of the performance at the first stage, should take into account the statistical distribution of the intensity of the image pixels occupied by ships which can still be assumed to follow a log-normal distribution, although characterized by different and more favorable values of its parameters due to the higher resolution of this mode. As far as the disturbance is concerned, noise and the ambiguous clutter predominate over unambiguous clutter. The ambiguous clutter arises from the coherent combination in azimuth of range ambiguous echoes from different regions (due to the continuous PRI variation) and is therefore likely to be noise-like distributed. It is shown that for TerraSAR-X, operating in staggered ambiguous mode, an average detection probability of 0.97 is achieved for the same swath and average transmit power of the ScanSAR mode, where the detection probability was one order of magnitude lower for the same false alarm rate and ship size.

In addition to continuous PRI variation, the alternation of different (orthogonal) waveforms on transmit, e.g., up- and down-chirp, could be considered to further blur range ambiguities. This option is particularly important, if the number of available PRIs is limited, e.g., in the case of coarse quantization of available PRIs.

If the antenna is also a phased array in the azimuth direction, another option is to widen the antenna beam in the azimuth direction in order to achieve an even higher azimuth resolution. However, this implies that the average PRF must be increased to properly sample the Doppler spectrum. In this

case, it has to be assessed whether the benefits of the increased resolution outweigh the increased disturbance, as the lower antenna gain leads to a higher noise level and the increased PRF causes additional ambiguous clutter.

3. SPACEBORNE DEMONSTRATION USING TERRASAR-X

The ambiguous staggered SAR mode for ship monitoring was demonstrated by experimental TerraSAR-X acquisitions. In a first acquisition, an open sea area near the German Bight, located 27 km away from the coast, with an extension of 110 km in ground range (corresponding to a slant range of 98 km) and 100 km in azimuth, was imaged with the staggered ambiguous mode, achieving an azimuth resolution of 2.2 m. In this case, the PRI was varied, but the same waveform was transmitted. Please note that compared to conventional SAR modes, the swath is four times larger than stripmap and the azimuth resolution is eight times better than ScanSAR. Fig. 1 shows the focused data, where the ships and some striped patterns due their range ambiguities are visible (the red box shows the range ambiguity corresponding to the ship in the green box). The ambiguities would be further blurred and therefore below the detection threshold if a finer PRI variation were used, but this was not possible due to system limitations of TerraSAR-X. A detailed report of the experiment, including a comparison of the detected ship positions with AIS information, can be found in [11].

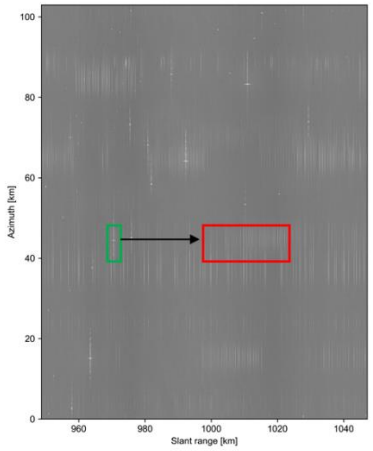

Fig. 1 Intensity of the focused image acquired by TerraSAR-X in staggered ambiguous mode over the full scene of about 10 000 km^2. The green rectangle highlights one of the large ships in the scene and its sidelobes, the red rectangle highlights a part of the image affected by the first-order range ambiguity of the ship in the green rectangle.

A limitation of the staggered ambiguous SAR mode is that it cannot be used near the coast, where the range ambiguity of the land would mask the ships due to its strong backscatter. Therefore, a second acquisition was conducted to understand if this limitation could be overcome by blurring the strong range ambiguity from the land by varying the waveform between up and down chirps from pulse to pulse. In this case, a swath of over 160 km, including a small part of the land, was imaged. The processing has been modified from traditional staggered SAR processing, in that range compression is now performed before resampling of the data to a regular grid [6]. As can be seen in the focused image of Fig. 2, in spite of the strong ambiguity from the land, ships near the coast are still visible and detectable.

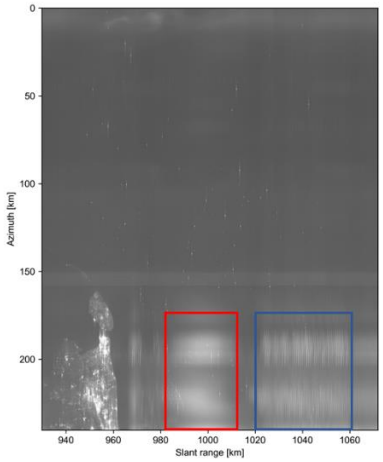

Fig. 2 Intensity of the focused image acquired by TerraSAR-X in staggered ambiguous mode with alternating up- and down- chirps over the full scene of about 33 600 km^2. The red rectangle and the blue rectangle highlight the first order and the second order range ambiguities from the land, respectively.

4. GENERATION OF DIGITAL ELEVATION MODELS IN A SINGLE-PASS USING CLUSTERS OF SMALL SATELLITES

The idea of exploiting low-quality SAR images corrupted by noise and ambiguities for specific applications can be extended to the case of multi-static SAR systems, where the echoes of the signals transmitted by one or more radar antennas are recorded by multiple receivers on different platforms.

Multi-static SAR enables the simultaneous acquisition of all the data required for the generation of digital elevation models (DEMs) or tomograms in a single pass, paving the way for effective and powerful monitoring of our planet [12]. An important application example for the generation of DEMs in a single pass is the assessment of permafrost degradation through the difference of DEMs acquired at short time intervals, from which accurate estimates of volume changes over time can be derived.

Following the idea of the ambiguous SAR, a cost-effective, multi-static SAR system can be devised that enables the generation of high-quality DEMs from large sets of noisy and undersampled data acquired by a cluster of receive-only smallsats with small antenna apertures, e.g. using a further transmit-only satellite. The smallsats should be flown in formation with different along- and across-track baselines [13]. The raw data acquired by each receiving satellite are independently focused (the full Doppler bandwidth is processed). The height of each pixel is then

estimated by maximizing the generalized likelihood, as detailed in [13]. The height estimation is essentially based on comparing estimated covariance matrices from the data with a model based on the Gaussian statistics for distributed scatterers (Fig. 3). In this way, multi-channel azimuth ambiguity suppression and multi-baseline SAR interferometry for robust phase unwrapping are combined in a distributed SAR system. This approach represents a radical paradigm shift from state-of-the-art systems and techniques and takes advantage of the fact that a large amount of the information contained in the currently-used multi-dimensional data sets is redundant. While in ship detection the use of ambiguous SAR imagery enables significantly improved detection over a wider swath, in this case the use of ambiguous SAR imagery can help reduce the antenna size of the radar satellites and therefore make single-pass, multi-baseline interferometric SAR system more affordable.

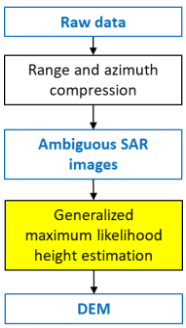

Fig. 3 Conceptual diagram of the generation of a DEM from noisy and undersampled data acquired by a cluster of smallsats.

To demonstrate this technique tomographic data with numerous baselines have been acquired over a mountainous area in Southern Germany using the F-SAR airborne sensor of DLR. This data set allowed processing of subsets of the available tracks and/or azimuth samples to assess to which extend subsampled data can still produce a high-quality DEM. The first results of the processing of the data were reported in [13]. Fig. 4 shows a DEM generated from undersampled F-SAR acquisitions emulating a cluster of eight smallsats with small aperture (total aperture of all satellites in the order of the total aperture of the two TanDEM-X satellites). Besides some wrong height estimates, in spite of the significant slopes in the area, the overall topography of the area is retrieved with accuracy comparable to TanDEM-X's one. Additional postprocessing steps might further improve the DEM quality.

5. CONCLUSIONS

This work demonstrates how low-quality, noisy and ambiguous SAR imagery can be effectively utilized for specific applications such as wide-area ship monitoring and single-pass DEM generation. Space and airborne demonstrations show that these concepts are mature for implementation in future missions.

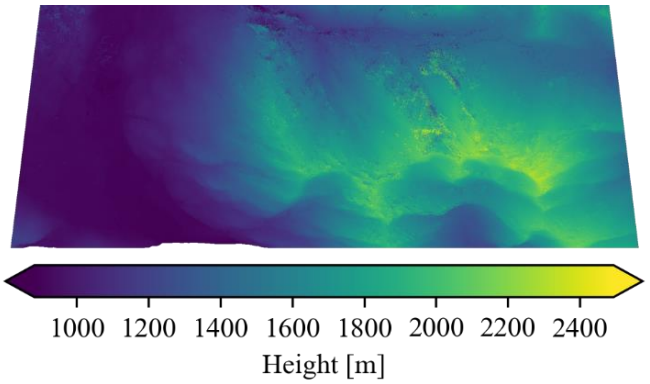

Fig. 4 DEM generated on a mountainous area in Southern Germany from undersampled acquisitions emulating a cluster of eight smallsats.

11. REFERENCES

[1] D. Crisp, "The state-of-the-art in ship detection in synthetic aperture radar imagery," Defence Sci. Technol. Org., Port Wakefield, SA, Australia, Res. Rep. DSTO-RR-0272, 2004.

[2] A. Moreira, P. Prats-Iraola, M. Younis, G. Krieger, I. Hajnsek and K. P. Papathanassiou, "A tutorial on synthetic aperture radar," *IEEE Geosci. Rem. Sens. Mag.,* vol. 1, no. 1, pp. 6-43, March 2013.

[3] N. Ustalli and M. Villano, "High-resolution wide-swath ambiguous synthetic aperture radar modes for ship monitoring," *Remote Se*ns., vol. 14, no. 13, p. 3102, Jun. 2022.

[4] M. Villano, G. Krieger, and A. Moreira, "Staggered SAR: High-resolution wide-swath imaging by continuous PRI variation," *IEEE Trans. Geosci. Remote Se*ns., vol. 52, no. 7, pp. 4462–4479, Jul. 2014.

[5] J. Krecke, M. Villano, N. Ustalli, A. C. M. Austin, J. E. Cater and G. Krieger, "Detecting Ships in the New Zealand Exclusive Economic Zone: Requirements for a Dedicated SmallSat SAR Mission," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 14, pp. 3162-3169, 2021.

[6] M. Villano, G. Krieger, and A. Moreira, "A novel processing strategy for staggered SAR," *IEEE Geosci. Remote Sens. Le*tt., vol. 11, no. 11, pp. 1891–1895, Nov. 2014.

[7] M. Villano, G. Krieger, M. Jäger, and A. Moreira, "Staggered SAR Performance analysis and experiments with real data," *IEEE Trans. Geosci. Remote Sens*., vol. 55, no. 11, pp. 6617–6638, Nov. 2017.

[8] M. Pinheiro et al., "Processing and performance analysis of NASA-ISRO SAR (NISAR) staggered data," *Proc. IEEE Int. Geosci. Remote Sens. Symp.*, Yokohama, Japan, Jul. 2019, pp. 8374–8377.

[9] M. Villano, G. Krieger, and A. Moreira, "Advanced spaceborne SAR systems with planar antenna", *Proceedings of the 2017 IEEE Radar Conference (RadarConf),* Seattle, WA, USA, 8–12 May 2017; pp. 152–156.

[10] N. Ustalli, G. Krieger and M. Villano, "A Low-Power, Ambiguous Synthetic Aperture Radar Concept for Continuous Ship Monitoring," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.,* vol. 15, pp. 1244-1255, 2022.

[11] N. Ustalli, M. N. Peixoto, T. Kraus, U. Steinbrecher, G. Krieger and M. Villano, "Experimental Demonstration of Staggered Ambiguous SAR Mode for Ship Monitoring With TerraSAR-X," *IEEE Trans. Geosci. Remote Sens*., vol. 61, pp. 1-16, 2023.

[12] G. Krieger and A. Moreira, "Spaceborne bi- and multistatic SAR: potential and challenges", *IEE Proceedings - Radar, Sonar and Navigation,* vol. 153, no. 3, 2006.

[13] M. Nogueira Peixoto, G. Krieger, A. Moreira, C. Waldschmidt, and M. Villano,, "Producing a Digital Elevation Model Using a Cluster of Small-Aperture SAR Satellites: An Airborne Demonstration," *Proc. EUSAR 2024,* Munich, Germany, 23-26 April 2024.