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Micro-motion extraction from land and maritime targets with spaceborne SAR using sub-aperture phase analysis

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Abstract— **Micro-motion information from very high-resolution SAR imagery has the potential to provide additional insights in support of advanced target detection and recognition. Due to the implicit assumption in the imaging process that a scene is stationary, target motions and micro-motions result in residual phase shifts and modulations that can be retrieved to obtain kinematic characteristics. In this paper, an approach exploiting sub-aperture processing and phase analysis is introduced to analyse micro-motions of both land and maritime targets. The effectiveness of the proposed approach is demonstrated on real SAR data and validated using ground truth measurements.**

Keywords— **very high-resolution SAR, synthetic aperture radar, micro-Doppler, micro-motion, phase retrieval, target characterization.**

I. Introduction

Advances in space technologies in prior decades have laid the basis for a new era of space-based sensing with Synthetic Aperture Radar (SAR) imaging. While spaceborne SARs in the past were used principally for Defence and Earth Science (e.g. ERS-1 and 2, Envisat, Sentinel-1), the potential to deploy constellations of micro-satellites equipped with antennas with significant gain and steering capabilities has transformed the SAR field. The opportunity to create novel SAR products has attracted the interest of space agencies, governments, and the private sector, with innovative micro-satellite constellations already deployed by companies such as ICEYE, Capella Space, and Umbra. These companies generate data which are not only commercially valuable but also scientifically unique. The key feature of these sensors is the capability to produce very high-resolution data with relatively long observation times, thus allowing for advanced characterization of targets and monitoring of scene dynamics during the observation time. Of particular interest is the capability to extract motion and micro-motion characteristics of targets, such as land vehicles, infrastructure, and vessels, enabling a range of new capabilities and applications from single-pass SAR images.

Over the years, SAR micro-motion extraction has been investigated with a number of different processing approaches and use cases, first with data from airborne SAR [1] which demonstrated the feasibility of the micro-motion extraction in SAR and attracted the interest of other researchers [2]–[6], who subsequently investigated various processing and system approaches. More recently, this topic has attracted interest thanks to the increasing availability of SAR data and the capabilities discussed above. Use cases that have been investigated include infrastructure monitoring [7]–[10], maritime surveillance [11], and target detection [12]. In particular, the research relying on the sub-pixel offset tracking method exploited the effect on the intensity of the resulting SAR image, tracked over multiple sub-apertures, to measure the micro-motion of the targets. This approach was proven to be effective but with some limitations due to the strong parameter selection dependence and intensive computational requirements. An approach using a modified Back Projection Algorithm (BPA) [9], [10] has similarly shown promising results, but requires the availability of data at a lower level of processing (i.e. CPHD or RAW) that are not always accessible. To overcome these issues, this paper presents a more efficient approach which is applicable to Single Look Complex (SLC) data. This method still relies on the formation of sub-apertures, but the later steps involving image registration using cross-correlation are replaced. As an alternative, this method measures the wrapped residual phase across sub-apertures for a set of pixels in a region of interest (ROI).

The remainder of the paper is organised as follows; Section II describes the sub-aperture phase analysis method, while Section III illustrates the results obtained on two real datasets containing a van, and a ship. Section IV concludes the paper.

II. Sub-aperture Phase Analysis

The steps of the proposed micro-motion extraction technique are illustrated in Fig. 1. The starting point for the processing is the SLC SAR image[1], from which the area containing the target is extracted as the ROI. The the brightest target's pixels in the ROI are selected. The next step is the creation of sub-apertures in azimuth. This step is fundamental

[1]Azimuth multi-look images are not suitable as multi-looking averges away the micro-motion information.

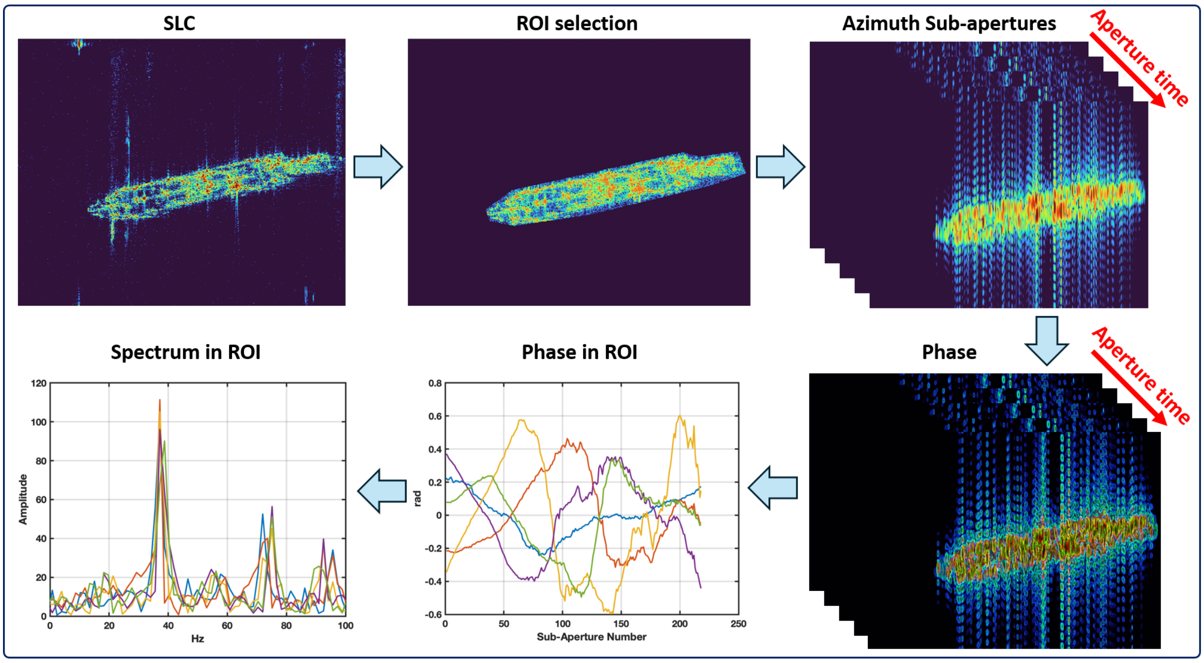

Fig. 1. Flow diagram of the processing scheme for the sub-aperture phase analysis approach.

to the processing, and care must be taken in the selection of the number of sub-apertures and the overlap factor between sub-apertures. The number of sub-apertures created should be sufficient to sample the highest micro-motion frequency of interest whilst at the same time azimuth resolution should not be excessively deteriorated. Similar to time-frequency analysis, overlap between subsequent sub-apertures is used to overcome this inherent trade-off. Once the data-cube containing all sub-apertures is produced, the phase value for each pixel in the ROI can be calculated. An optional following step of phase unwrapping may be required depending on maximal target displacement. The final step is the calculation of spectra from the phase time-series. These can be retrieved and analysed on a pixel-by-pixel basis, integrated incoherently or used in more advanced processing strategies such as component decompositions.

III. Experimental analysis

In this section the results obtained by applying the proposed method to real SAR data acquired by Umbra are presented. Two scenarios are shown: a long dwell land target scenario where high level of clutter is expected, and a short dwell maritime scenario.

A. *Land target*

In the land scenario, the extraction target was a Volkswagen Transporter van in a SAR image captured by an Umbra satellite over the Glasgow area on the 16th of May 2024. Ground truth data was gathered using a triaxial accelerometer sensor on the bonnet, as shown in Fig. 2. During the acquisition, the vehicle was idling between 800 and 900 RPM as shown by a photograph of the van tachometer, also shown in Fig. 2.

Fig. 2. Volkswagen Transporter van with accelerometer and an tachometer (inset) during the SAR acquisition.

The acquisition details and the processing parameters are reported in Table 1. The output of the sub-aperture phase

Table 1. Land target acquisition and processing.

Platform	UMBRA-05
Centre frequency	9.6 GHz
Range / azimuth resolution	0.73 m / 0.09 m
Range / azimuth pixel spacing	0.66 m / 0.08 m
Processed aperture time	16.4 s
Number of sub-apertures	3938
Sub-aperture duration	0.4167 s
Sub-aperture overlap	90%
Sampling frequency in sub-aperture time	120 Hz

analysis compared with the accelerometer ground truth is shown in Fig. 3. The results presented are the non-coherent integration of the spectra of pixels selected in the ROI and show that the method is able to clearly observe a frequency of 87 Hz which matches the main ground truth component, but in this case it does not detect the two weaker components at 29 and 58 Hz. By analysing the characteristics of the van engine (4 strokes, 4 cylinders), which fires twice per revolution, it can be shown that the 29 Hz component matches the engine's RPM of 870, confirmed by the on-board measurement. The three components measured by the accelerometer are therefore the engine RPM and its higher-order harmonics that spread throughout the van body, and only the 87 Hz propagates to the parts of the chassis observed by the sub-aperture phase analysis.

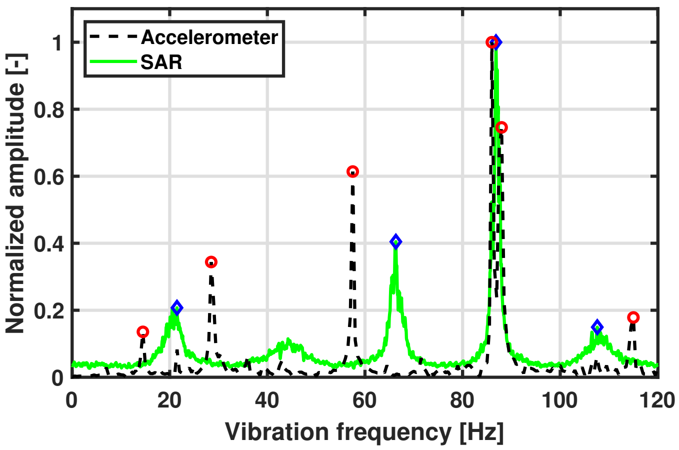

Fig. 3. Sub-aperture phase analysis results for the land target (Volkswagen Transporter van). The accelerometer data shown correspond to the vertical axis of the sensor.

B. Maritime target

In the maritime scenario, the extraction target was a cooperative vessel sailing in Galway Bay, Republic of Ireland. The data were acquired by an Umbra satellite over the Galway Bay area on the 12th of September 2024. In order to collect the ground truth data, the ship was fitted with 8 triaxial accelerometers, as shown Fig. 2. During the acquisition, the vessel was navigating at 3 nautical knots and the engines were running at approximately 720 RPM.

The acquisition details and the processing parameters for this case are reported in Table 2.

Table 2. Maritime target acquisition and processing.

Platform	UMBRA-08
Centre frequency	9.6 GHz
Range / azimuth resolution	0.31 m / 0.94 m
Range / azimuth pixel spacing	0.28 m / 0.84 m
Processed aperture time	1.09 s
Number of sub-apertures	218
Sub-aperture duration	0.5 s
Sub-aperture overlap	99.15%
Sampling frequency in sub-aperture time	100 Hz

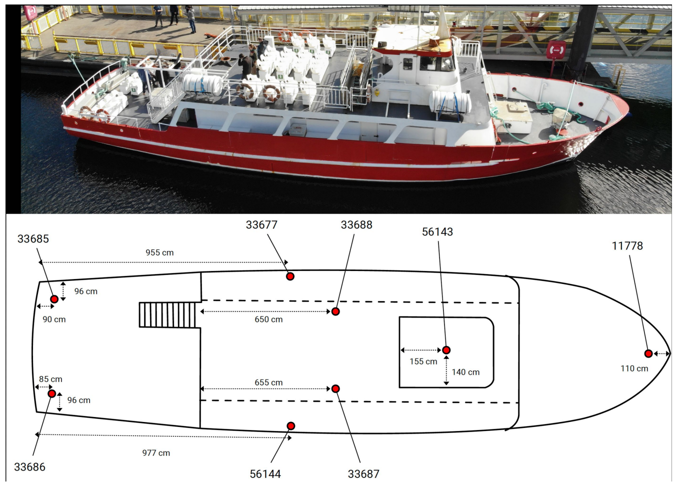

Fig. 4. Galway Girl (top) and diagram of accelerometer positions (bottom).

The results obtained with the sub-aperture phase analysis for this case are shown in 5, where in this case the results are obtained by non-coherently integrating the thresholded target pixels in the ROI. The results clearly show that the proposed method manages to measure the two main vibrational components of the target. In particular, the main component detected at 36 Hz is in agreement with the engine RPM of 720. Indeed, the boat is equipped with 2 synchronized Volvo Penta D12 (4 strokes, 6 cylinders) engines. This type of engine fires 3 times per crankshaft revolution, and as it was running at 720 RPM = 12 rev/s, there were 36 firing events in the engine per second. It is also worth noting that the component at lower frequency measured by the accelerometers is the effect of the sea motion and too low to be correctly measured in this very short SAR observation.

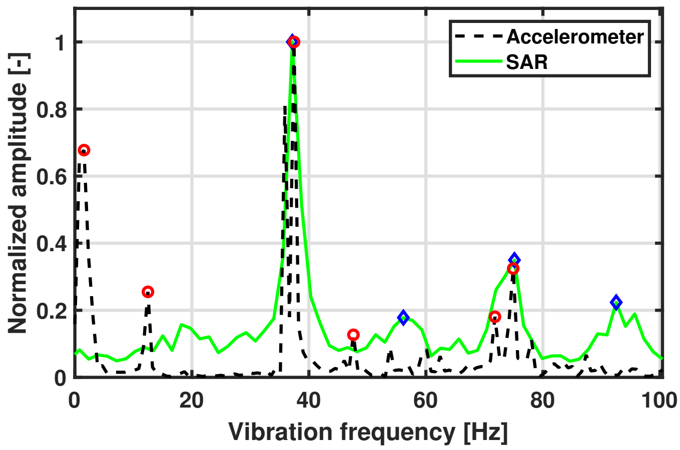

Fig. 5. Sub-aperture phase analysis results for the maritime target (Galway Girl). The accelerometer data shown correspond to the vertical axis of the sensor.

IV. Conclusion

This paper presents a new single-pass SAR micro-motion measurement method. Operating on SLC data, this approach uses overlapped sub-apertures to restore time resolution in the data whilst also preserving a high degree of azimuth resolution, in a manner similar to time-frequency analysis techniques. Following this stage, the phase of individual pixels in each sub-aperture can be measured to produce phase histories.

Successful initial measurements of the primary micro-motion components of both land and maritime targets were demonstrated. In the land case, a peak was observed at 87 Hz that matched the main spectral peak in the ground truth measured by an accelerometer on the bonnet of an idling van. In the maritime case, a large peak was detected at 36 Hz as well as a smaller peak at 75 Hz, where the former corresponded to the main response observed in the ground truth, and the latter to the second highest peak associated with the vibration of the ship. These results demonstrate the efficacy of this technique with many future applications.

Further refinements and extensions to this processing that are being investigated include the optimisation of the parameters used for the extraction process, methods of integrating results from individual pixels, and approaches to mitigate the effects of clutter.

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