IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium | 979-8-3503-6032-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/IGARSS53475.2024.10642825

On Micro-Motion Extraction from High Resolution X-band SAR products

C. Clemente *, D. Tonelli †, A. Lotti†, F. Rollo*, C. Ilioudis*, S. Diaz Riofrio*, F. Biondi*, E. Tubaldi*, M. Macdonald*, D. Zonta†, M. Zavagli‡, M. Costantini ‡, F. Minati ‡, F. Vecchioli ‡, P. Milillo ¶, M. Zimmermanns ‖, E. Imbembo‖, M.M. Corvino ‖
**University of Strathclyde*, Glasgow, UK
†*University of Trento*, Trento, Italy
‡*B-Open Solutions s.r.l*, Rome, Italy
¶*University of Houston*, Houston, US
‖*European Space Agency*

***Abstract*—With the increase of high spatial and temporal resolution SAR data availability, novel applications and information extraction techniques become possible. Among these, the extraction of micro-motion information has the potential to unlock a range of applications, such as infrastructure monitoring, maritime surveillance and natural disaster damage assessment. However, sensors, acquisition modes and products have not been designed with in mind the optimization of micro-motion extraction and its applications, therefore, careful considerations need to take place when selecting the most suitable data and designing processing algorithms. In this paper practical and processing considerations when dealing micro-motion extraction from high-resolution SAR sensors are discussed and supported with experimental results obtained from Capella, Umbra and TerraSAR-X data.**

I. Introduction

Thanks to the advent of new players in the commercial field of SAR based remote sensing, such as Capella Space, Umbra Lab and Iceye, there is a dramatic increase in availability of high resolution X-band SAR data, providing very high spatial and temporal resolutions, to a scale not seen before. While missions such as TerraSAR-X/TanDEM-X and Cosmo-SkyMed/CSG paved the way to the development of novel techniques and applications of X-band SAR, the new generation of commercial missions has the potential to fully unlock the potential of X-band based Earth Observation. The high spatial and temporal resolution, combined with long-dwell times allow also the rethinking of what information can be extracted from SAR data, such as advanced scene/feature analysis, spatial diversities and targets' micro-motions/micro-Doppler. In particular, the capability to measure micro-Doppler related information from spaceborne SAR has a disruptive impact, potentially enabling a range of novel applications and products to be developed for both security and general civilian applications. For example, being able to extract additional target's features, such as the vibrational modes impressed by an engine on a particular maritime or land target, would enhance automatic target recognition capabilities, while for example being able to quantify periodical motions of infrastructures to be monitored would provide early warning or continuous monitoring tools enabling novel commercial services and products to be developed. In the last years the exploitation of the radar micro-Doppler phenomenon has seen significant interest, this has been mainly focused on short-range and ground based radar systems [1], [2], [3], driven by applications with a large consumer demand (i.e. automotive, domotics) and pressing issues such as UAV recognition. However, much more limited interest, instead, was in the modeling, extraction, and exploitation of target's micro-motion information from Synthetic Aperture Radar. The reason for this lies probably in the fact that SAR presents additional challenges in both modeling and extraction of micro-Doppler signatures. Indeed, following the first attempts to model and demonstrate the possibility to extract micro-Doppler from airborne SAR [4], [5], only few other works investigated this topic [6], until a resurgence of interest driven by the availability of novel spaceborne SAR constellations and commercial demand for more advanced target characterizations and applications. Indeed, in the last years the use of micro-Doppler information from SAR has received an increased interest in the SAR community targeting a number of interesting applications such as critical infrastructure monitoring [7], [8] and marine targets characterization [9], [10].

In this paper, the capability to extract micro-motion information in high resolution Spaceborne SAR is discussed, focusing on the main aspects to be taken into account when dealing with the data acquired by a range of sensors. The paper analyses the effect of target micro-motion in different acquisition modes, as well as the peculiarities of the products made available from the data provider. The discussions will be supported with experimental results obtained with Umbra Lab, Capella Space and TerraSAR-X data, in scenes where controlled targets with ground truth were deployed.

The remainder of the paper is organised as follows: Section II provides an overview of the main characteristics and considerations regarding spaceborne X-band SAR products when aiming at addressing the micro-motion estimation challenge. While Section III shows how three high resolution types of products can be used to extract micro-motion information in a controlled scenario. Finally, Section IV concludes the paper.

II. X-band data for micro-motion analysis: practical considerations

In order to extract micro-motion from SAR, the most common starting points are either the Single-Look Complex (SLC) or the range compressed SAR data. The selection of one domain or the other depends on the aspects such as the processing algorithm selected, expected Signal to Noise Ratio and, last but not least, the availability of one format of data rather than another. In particular, while for missions such as TerraSAR-X and Cosmo-SkyMED it is possible to access SLC data, the access to lower level data is generally harder to obtain, meaning that algorithms designed to operate on SLC data (including those defocusing the data) are generally applicable on the data from these sensors. Conversely, a more open policy is adopted by novel industrial reality such as Capella Space and Umbra Lab, not only making available a large set of data via their open data programmes, but also allowing access to either SLC and Compensated Phase History Data (CPHD) [11] products. It is worth mentioning, that having access to raw or CPHD data gives access to a larger amount of data that has not undergone the processing tailored at creating a good image and perhaps discarding portion of the data that are instead useful for the micro-motion extraction, such as parts of the synthetic aperture.
A fundamental aspect to be taken into account when identifying the most suitable SAR product to be used to perform micro-motion analysis is the overall duration of an acquisition, as the longer is the time a target exhibiting micro-motions is observed then there is better capability to integrate more periods of the micro-motion in the processing chain, thus enhancing the micro-motion parameter estimation capabilities. However, not all sensors or sensing mode provide sufficiently long synthetic aperture times to accomplish the micro-motion extraction/estimation task. For example, TerraSAR-X and Cosmo-SkyMED offer a stripmap mode that acquires for very short durations (e.g. Cosmo-SkyMED stripmap is in the order of 3s), making these products not very practical for micro-motion extraction unless used for specific scenarios such as maritime surveillance. On the contrary, their spotlight or staring spotlight modes provide longer observation times and at the same time finer spatial resolutions, making them suitable for the micro-motion extraction task. The new comers on the market (ICEYE, Capella and Umbra) are providing game changing capabilities in terms of aperture durations, with novel long dwell acquisition modes that can provide aperture times longer than 20 seconds, allowing not only very fine spatial resolution but also a *good look* at what a target is doing.

However, the use of long apertures implies a change of the cross-range direction during the acquisition, leading at artefacts in the final image introduced by the combination of the ghost targets created by the micro-doppler modulation and the change in cross-range [12], creating a bowtie effect in the image that would need to be taken into account and compensated to combine all the energy from the target with micro-motion [13]. Furthermore, in the Umbra data case, if the SICD product is used [14], a relevant consideration needs to be made: the actual aperture duration used to form each range gate is not constant. Indeed, as part of the image formation process the Polar Format Algorithm is used and in order to provide a rectangular product the returned data are taken from an inscription in the k-space. This means that a range dependent reduction of portions of phase history occurs after the inscription process. In simpler words it means that the aperture duration used for a given range gate is shorter than the nominal aperture duration provided in the product's metadata and the actual duration needs to be derived from the other metadata parameters.

III. Micro-motion from real High Resolution X-band data

In this section we show that by exploiting high resolution and long observation time of spotlight X-band data it is possible to extract accurately micro-motion characteristics of targets. In particular, in the following results obtained as part of an extensive measurement and alogithms' calibration campaign conducted by our team are presented. Three examples are shown, one collected by tasking Umbra Lab, one by tasking TerraSAR-X and one by tasking Capella Space to collect data over an area with controlled ground truths. In all cases we show the results when we deployed in the scene a corner reflector mounted on a shaker with controllable vibration amplitude and frequency, located in the Trento area in Italy, Fig. 1.

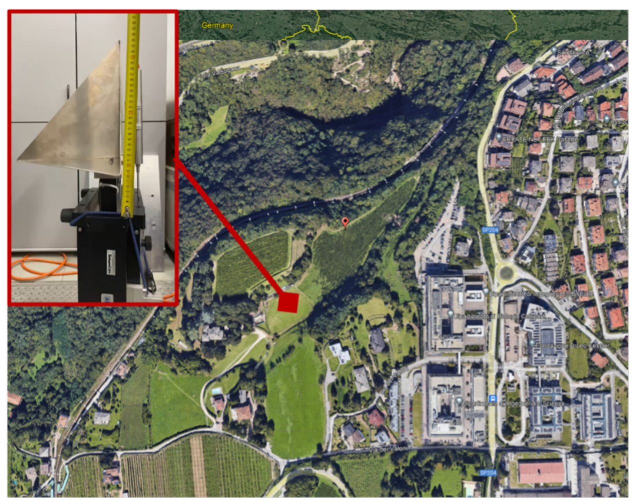


Fig. 1. Controllable shaker with corner reflector deployed in the Trento area, Italy.

In the first case, data were acquired from the Umbra-04 platform in Spotlight mode on the 11th of November 2023, with the shaker vibrating at a frequency of 2 Hz and with an amplitude of 4.5 cm (9 cm peak to peak). Circled in red in Fig. 2 it is possible to see the effect of the vibration of the corner reflector on the SLC product. The vibration produces paired echoes [5], [12], [13] in the azimuth direction, however due to the high squint variation during the observation, the effect assumes a "bowtie" shape, and as mentioned before this is something that needs to be taken into account when dealing with this type of acquisition for the specific purpose of the the micro-motion extraction algorithm design.

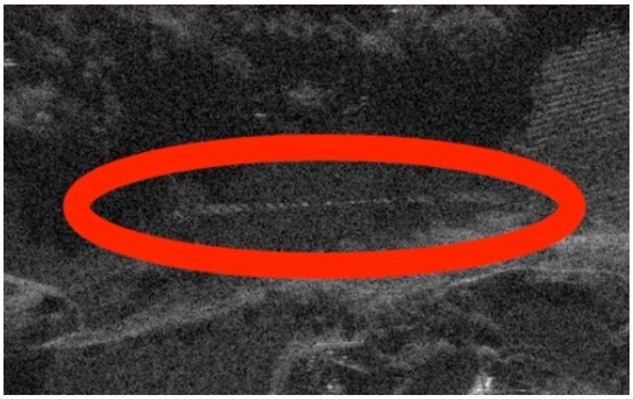


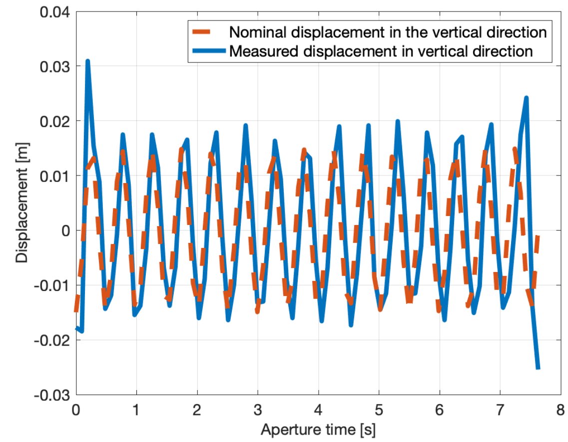
Fig. 2. Corner reflector vibration effect in the SLC Umbra-04 Product.

In the second case presented, data were acquired from the TerraSAR-X platform in Staring Spotlight mode on the 18th of December 2023, the shaker was vibrating at a frequency of 2 Hz and with an amplitude of 1.5 cm (3 cm peak to peak). In the red rectangle in Fig. 3 it is possible to see the effect of the vibration of the corner reflector on the final product.

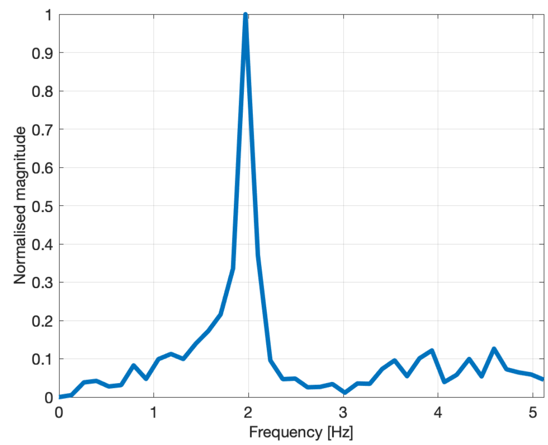
Fig. 3. Corner reflector vibration effect in the SLC TerraSAR-X product.

In this case, the paired echoes from the 1.5 cm vibration can be clearly seen over an area of several meters, however, even if not visible, also in this case the spotlighting creates a bowtie effect that would need to be compensated as in the previous case. Differently from the Umbra data case, for this product the entire nominal aperture is used to form the image in all pixels, therefore no particular precaution is required when considering the time to be used in the vibrating frequency estimation.

In this case we show also that by applying pixel offset tracking techniques to sub-apertures in the azimuth direction [9], it is possible to track the position of the ghost targets in order to extract the vibrating characteristics of the corner reflector.



(a)

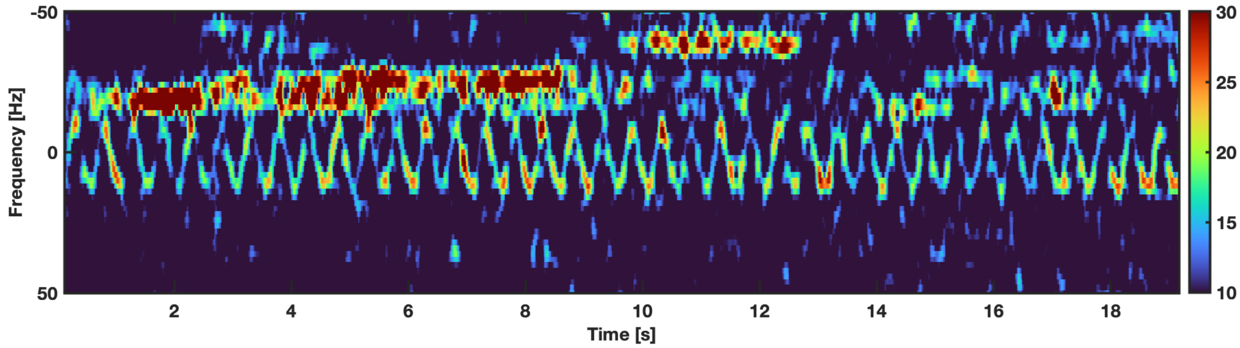


(b)

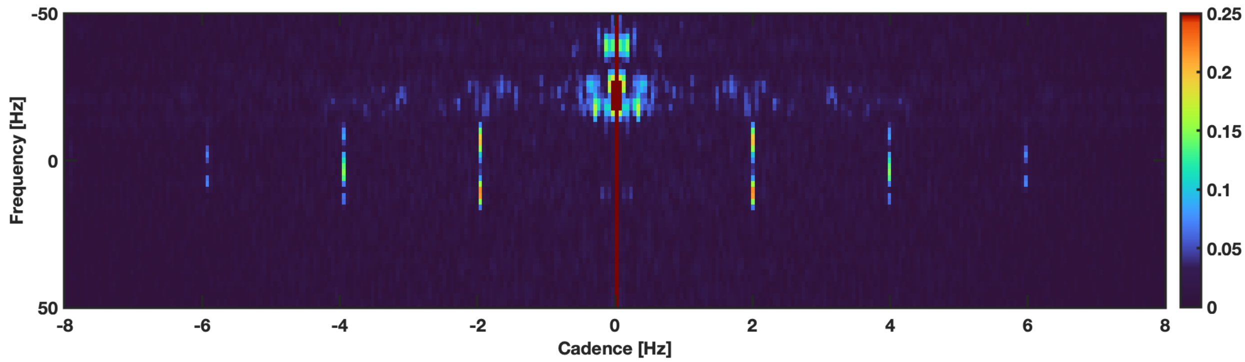
Fig. 4. Azimuth displacement of the ghost targets (a) and frequency of the displacement (b) for the TerraSAR-X experiment.

The tracking result in form of pixel displacement can then be converted to the radial velocity first [15] and then the value of the displacement can be derived by applying integration and corrections depending on the acquisition geometry, Fig. 4. The oscillating behaviour of the target is clearly visible, Fig. 4-(a) with the vibrating amplitude aligned with that of the ground truth as well as the vibrating frequency matching the nominal 2 Hz, Fig. 4-(b).

The last analysis involves data collected using Capella on the 18th of December 2023 in Trento, with the shaker vibrating at 2 Hz and with an amplitude of 1.5 cm. In this case, we show results obtained from the CPHD data, and therefore exploiting the phase of the received signal. In the following we show results obtained by applying a new processing procedure [16] to the CPHD, derived by modifying the Backprojection algorithm (BPA). Typically, an image formed using the BPA is the coherent sum of every pulse's contribution to every



(a)



(b)

Fig. 5. Spectrogram (a) and Cadence Velocity Diagram (b) from the data of the Capella experiment.

image pixel, adjusted for their respective time delays and phase shifts, instead the contributions of every pulse are concatenated to form a 3D radar data cube, instead of being coherently summed allowing to extract time series for each pixel containing the micro-Doppler information of the target. Furthermore, the contribution of multiple pixels can be coherently and/or incoherently integrated for extended targets.

Figure 5 shows the spectrogram and the cadence velocity diagram [17] obtained by integrating incoherently the 14 pixels identified containing the micro-Doppler contribution of the corner reflector. The oscillating behaviour of the corner reflector is clearly visible in the spectrogram, with a micro-Doppler frequency oscillating between ± 15 Hz, with a cadence (the actual vibrating frequency of shaker) of 2 Hz, as also highlighted in the cadence velocity diagram and in agreement with the true value. As fundamentally, the CVD is the Fourier transform along the rows of the spectrogram, then Fig. 5-b is of easy interpretation, with the periodic terms integrating and becoming more evident. In particular, the 2 Hz cadence term is clearly visible around the ± 15 Hz. It is also noticeable the presence of a 4 Hz term due to the double counting of the oscillation (when the Doppler rises and when decreases).

IV. Conclusions

High Resolution X-band SAR data have the potential to unlock advanced information extraction capabilities and, as a consequence, new downstream applications. In this paper practical and processing considerations regarding the use of high resolution X-band SAR data for the purpose of micro-motion extraction have been presented. The discussion has been supported by experimental results, part of an extensive measurement campaign, showing results from high resolution data from Umbra, Capella and TerraSAR-X spotlight products. It was shown that processing approaches working on the SLC data as well as approaches exploiting raw SAR data have the potential to provide accurate estimations of target's micro-motions. In summary, spaceborne SAR based micro-motion extraction is still at its early days, its potential still need to be fully unlocked and would benefit from the new high-resolution X-band products with the expectation to become highly relevant research field in the coming years.

V. Acknowledgment

This research is funded by the European Space Agency under the projects *"Bridge Monitoring Based on Single Pass SAR Images"* , *"EO4Security- Innovative SAR Processing Methodologies For Security Applications-Topic B2: Micro-Doppler Processing"*, Fondazione CARITRO (grant number 2021.0224) and the Agreement DPC/ReLUIS 2024-2026 (WP6). This work was in part performed at the University of Houston under a contract with the NASA Commercial Smallsat Data Acquisition Program (QKWEF8XLMTT3). Thanks to Airbus Defence and Space GmbH, Capella Space and Umbra Lab for the access to the datasets.

References

[1] Carmine Clemente, Alessio Balleri, Karl Woodbridge, and John James Soraghan, "Developments in target micro-doppler signatures analysis: radar imaging, ultrasound and through-the-wall radar," *EURASIP Journal on Advances in Signal Processing*, vol. 2013, no. 1, March 2013.

[2] Francesco Fioranelli, Hugh Griffiths, Matthew Ritchie, and Alessio Balleri, Eds., *Micro-Doppler Radar and its Applications*, The Institute of Engineering and Technology (IET), 2020.

[3] Carmine Clemente, Francesco Fioranelli, Fabiola Colone, and Gang Li, *Radar Countermeasures for Unmanned Aerial Vehicles*, Oct. 2021.

[4] T. Sparr, "Micro-doppler analysis of vibrating targets in sar," *IEE Proceedings - Radar, Sonar and Navigation*, vol. 150, pp. 277–283(6), August 2003.

[5] Maurice Ruegg, Erich Meier, and Daniel Nuesch, "Vibration and rotation in millimeter-wave sar," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 2, pp. 293–304, 2007.

[6] Carmine Clemente and John J. Soraghan, "Vibrating target micro-doppler signature in bistatic sar with a fixed receiver," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 50, no. 8, pp. 3219–3227, 2012.

[7] Filippo Biondi, Pia Addabbo, Silvia Liberata Ullo, Carmine Clemente, and Danilo Orlando, "Perspectives on the structural health monitoring of bridges by synthetic aperture radar," *Remote Sensing*, vol. 12, no. 23, 2020.

[8] Filippo Biondi, Pia Addabbo, Carmine Clemente, Silvia Liberata Ullo, and Danilo Orlando, "Monitoring of critical infrastructures by micro-motion estimation: The mosul dam destabilization," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 13, pp. 6337–6351, 2020.

[9] Filippo Biondi, Pia Addabbo, Danilo Orlando, and Carmine Clemente, "Micro-motion estimation of maritime targets using pixel tracking in cosmo-skymed synthetic aperture radar data—an operative assessment," *Remote Sensing*, vol. 11, no. 14, 2019.

[10] Davide Armenise, Filippo Biondi, Pia Addabbo, Carmine Clemente, and Danilo Orlando, "Marine targets recognition through micro-motion estimation from sar data," in *2020 IEEE 7th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*, 2020, pp. 37–42.

[11] Robert H. Johnston and Wade C. Schwartzkopf, "Compensated phd – a sensor-independent product for sar phd," in *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, 2019, pp. 4519–4522.

[12] B. Corbett, D. Andre, and M. Finnis, "Localising vibrating scatterer phenomena in synthetic aperture radar imagery," *Electronics Letters*, vol. 56, no. 8, pp. 395–398, 2020.

[13] Darren Muff, Malcolm Stevens, David Blacknell, Matthew Nottingham, Claire Stevenson, and Hugh Griffiths, "Detecting vibrating targets in fine resolution sar imagery," in *EUSAR 2018; 12th European Conference on Synthetic Aperture Radar*, 2018, pp. 1–6.

[14] *Sensor Independent Complex Data (SICD), Volume 1, Design & Implementation Description Document, Version 1.2.1, 2018-12-13*.

[15] R. Keith Raney, "Synthetic aperture imaging radar and moving targets," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-7, no. 3, pp. 499–505, 1971.

[16] Finlay Rollo and et al., "Spie sensors and imaging conference," 2024.

[17] Svante Björklund, Tommy Johansson, and Henrik Petersson, "Evaluation of a micro-doppler classification method on mm-wave data," in *2012 IEEE Radar Conference*, 2012, pp. 0934–0939.