Multi-Static Synthetic Aperture Radar for Earth Monitoring: Challenges, Innovative Solutions, and Demonstrations Using Swarms of Drones

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Abstract*—Spaceborne synthetic aperture radar (SAR) is an essential tool for Earth observation. The combination of multiple SAR images taken from different viewing angles allows forming accurate digital elevation models and high-resolution tomograms that unveil the three-dimensional structure of vegetation, ice, and dry soil. Whereas nowadays such images are mostly acquired sequentially, compromising product quality and hindering the monitoring of fast dynamics, multi-static SAR systems enable the simultaneous acquisition of all required data, paving the way for effective and powerful monitoring of our planet. One fundamental challenge is the conception of multi-static concepts that allow the generation of high-quality digital elevation models and tomograms from large sets of noisy and undersampled radar data acquired by clusters of smallsats with small antenna apertures. Swarms of drones, equipped with radars and localization systems, represent an affordable option to test multi-static concepts and acquire multi-static data with sub-hour temporal resolution.

***Keywords*—synthetic aperture radar (SAR), interferometry, digital elevation models (DEMs), tomography, multi-static concepts, satellite swarms, drones.**

I. Introduction

Earth science benefits tremendously from spaceborne synthetic aperture radar (SAR) [1]-[3]. High-resolution wide-swath SAR systems allow for frequent imaging of the Earth's surface on a global scale and constellations of low-cost SAR sensors further reduce the revisit time on local areas and guarantee a timely response to natural disasters. SAR images can be combined to create accurate digital elevation models (DEMs) and high-resolution tomograms (Fig. 1) that unveil the three-dimensional structure of vegetation, ice, and dry soil [4]-[10]. The sequential acquisition of such images, however, compromises the product quality and, perhaps more importantly, hinders the monitoring of fast dynamics.

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II. Multi-Static SAR Systems

Multi-static SAR systems enable the simultaneous acquisition of all data required to form DEMs or tomograms and pave the way for effective and powerful monitoring of our planet [11]-[12]. An important application example is the assessment of permafrost degradation by the difference of DEMs acquired at short time intervals, from which accurate estimates of volume changes over time can be derived [13]-[15]. Another example is the mapping of biomass changes using single-pass tomograms that helps to retrieve important variables of the carbon cycle. Whereas several concepts based on smallsats have been proposed in recent years for SAR imaging, e.g., to collect the raw data samples using multiple satellites in order to enlarge the swath and/or reduce power requirements [16]-[19], multi-static SAR will play a game-changing role for interferometry and tomography, as well as for novel techniques, such as multiple-input multiple-output SAR tomography [20], and concepts that exploit large bistatic angles, as also envisioned in the European Research Council (ERC)-funded project "Distributed Radar Interferometry and Tomography Using Clusters of Smallsats (DRITUCS)".

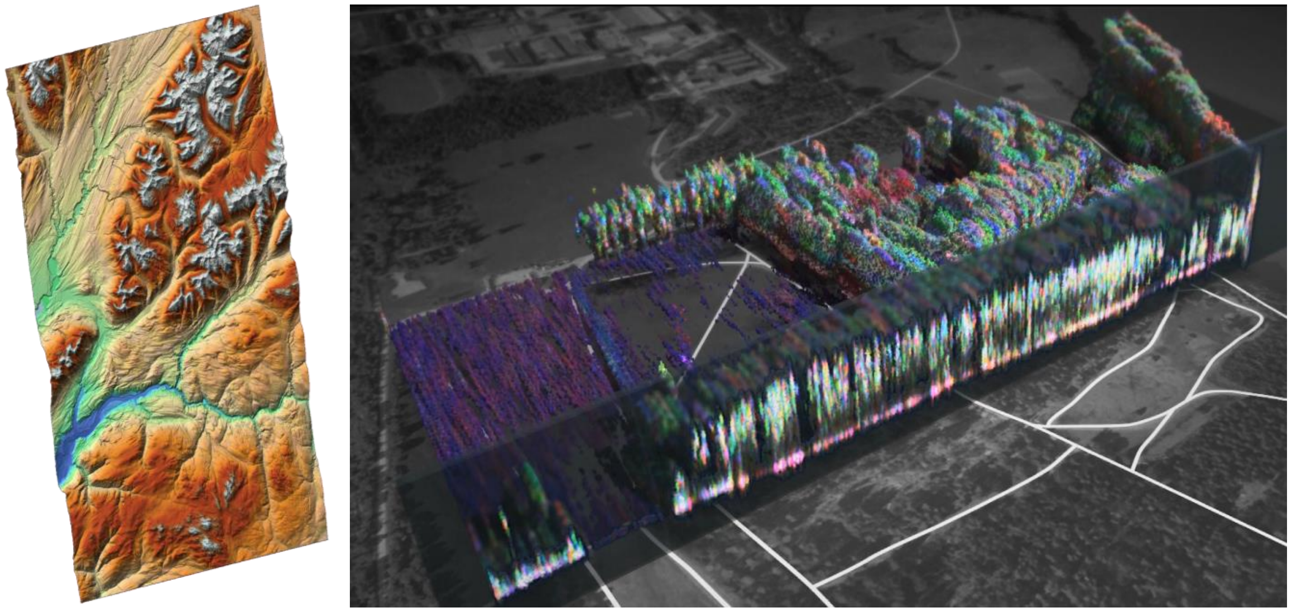

Fig. 1. Examples of digital elevation model (left) and tomogram showing the profile of a forest (right)..

A fundamental challenge is to design multi-static systems that do not demand expensive, high-quality SAR imagery to create digital elevation models and tomograms, but allow the generation of high-quality products from large sets of noisy and undersampled data acquired by clusters of smallsats with small antenna apertures. A promising solution is hinted in [21], where the smallsats of the cluster are arranged with different relative along- and across-track baselines and the acquired raw data are range-compressed and combined through beamforming to obtain a three-dimensional radar image of the observed scene, i.e., a tomogram, which might still be characterized by a high level of noise and ambiguities. A DEM is then extracted from the noisy tomogram through multi-look and height estimation for each pixel of a two-dimensional grid. The height estimation is essentially based on the selection of the height for which the response is maximum for each pixel of the aforementioned grid, but can also exploit the local spectral characteristics of the signal and/or signals at different positions to discriminate and coherently suppress azimuth ambiguities (Fig. 2). 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. A demonstration of this technique will be carried out in the coming months by acquiring tomographic data with numerous baselines over a mountainous area using the F-SAR airborne sensor of DLR and using subsets of the available tracks and/or azimuth samples.

An attractive feature of the cluster of smallsats is the opportunity to reconfigure it to acquire data that serve different applications, e.g., the unambiguous measurement of ocean currents using multi-baseline along-track interferometry [22]-[23].

III. SYNCHRONIZATION AND CALIBRATION

The synchronization of the satellites of the clusters can be achieved using the MirrorSAR concept and a dedicated synchronization link, through which a reference signal is directly sent to the receiver, combined with the radar echo and forwarded to the transmitter after up-conversion [24]-[25]. The forwarded radar signals are coherently demodulated within the transmitter using the same oscillator that generated the radar pulses, so possible frequency and phase drifts are cancelled as in a classical monostatic SAR. In order to avoid that the reference signal corrupts the radar data, an azimuth phase modulation can be employed to shift the reference signal outside the processed Doppler bandwidth.

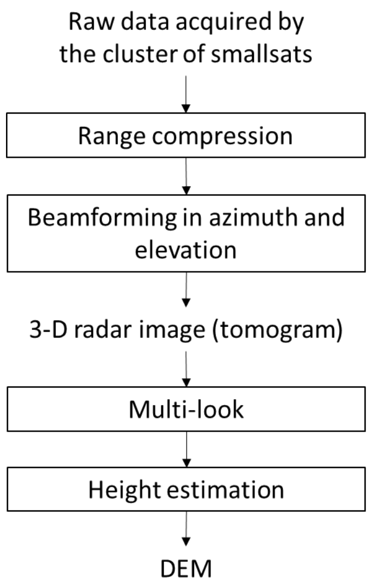

Fig. 2. Conceptual diagram of the generation of a DEM from noisy and undersampled data acquired by a cluster of smallsats.

Accurate measurement of the antenna pattern of the satellites is necessary to meet the imaging performance. Besides traditional approaches, an innovative in-orbit antenna pattern calibration concept is patent pending [26]-[27]. A dedicated calibration satellite with a spherical reflector onboard is flown on orbits with parameters slightly different than that of the radar satellite whose antenna has to be measured and reflects the pulses transmitted by the radar satellite. By changing the orbit parameters of the calibration satellite, different cuts of the two-dimensional two-way antenna pattern are measured.

IV. Fixed-Baseline Spacecraft Formations

Multi-static SAR systems require coordinated operation of multiple satellites flying in close formation. Whereas one consolidated option is the HELIX satellite formation adopted for TanDEM-X [28] and considered in an extended version as triple-helix for HRWS [29], interesting opportunities arise from the realization of spacecraft formations with fixed baselines.

In particular, maintaining a fixed-baseline in the across-track direction would be beneficial for multi-baseline across-track SAR interferometry for DEM generation and for multiple-satellite system aiming at the suppression of range ambiguities through proper shaping (nulling) of the combined multi-platform elevation pattern.

A fixed-baseline configuration cannot be obtained as a natural solution of the relative motion of the spacecraft, as it is the case for the HELIX formation of TanDEM-X, and requires implementation of a continuous control to avoid oscillation due to the natural dynamics and keep the desired spacecraft separation. Moreover, the forced solution of the relative motion requires an accurate design of safety procedures, to guarantee a safe flight in case of, e.g., engine failures. Continuous control can be obtained with low-thrust engines, such as ion or hall thrusters.

Detailed configurations and delta-velocity (delta-v) budget analyses have been reported in [30] following the idea of a previous study on across-track, fixed-baseline, passive interferometry in L-band [31]-[32]. It is shown that in order to keep a 80 m fixed, across-track baseline between two spacecrafts at 500 km orbit a delta-v in the order of 3 km/s is required yearly for formation maintenance, for a ratio of the ballistic coefficients equal to 2. The required delta-v increases in case of larger baselines, therefore this configuration is more suitable for high frequency bands (e.g., Ka band), where the same height of ambiguity can be achieved with smaller baselines.

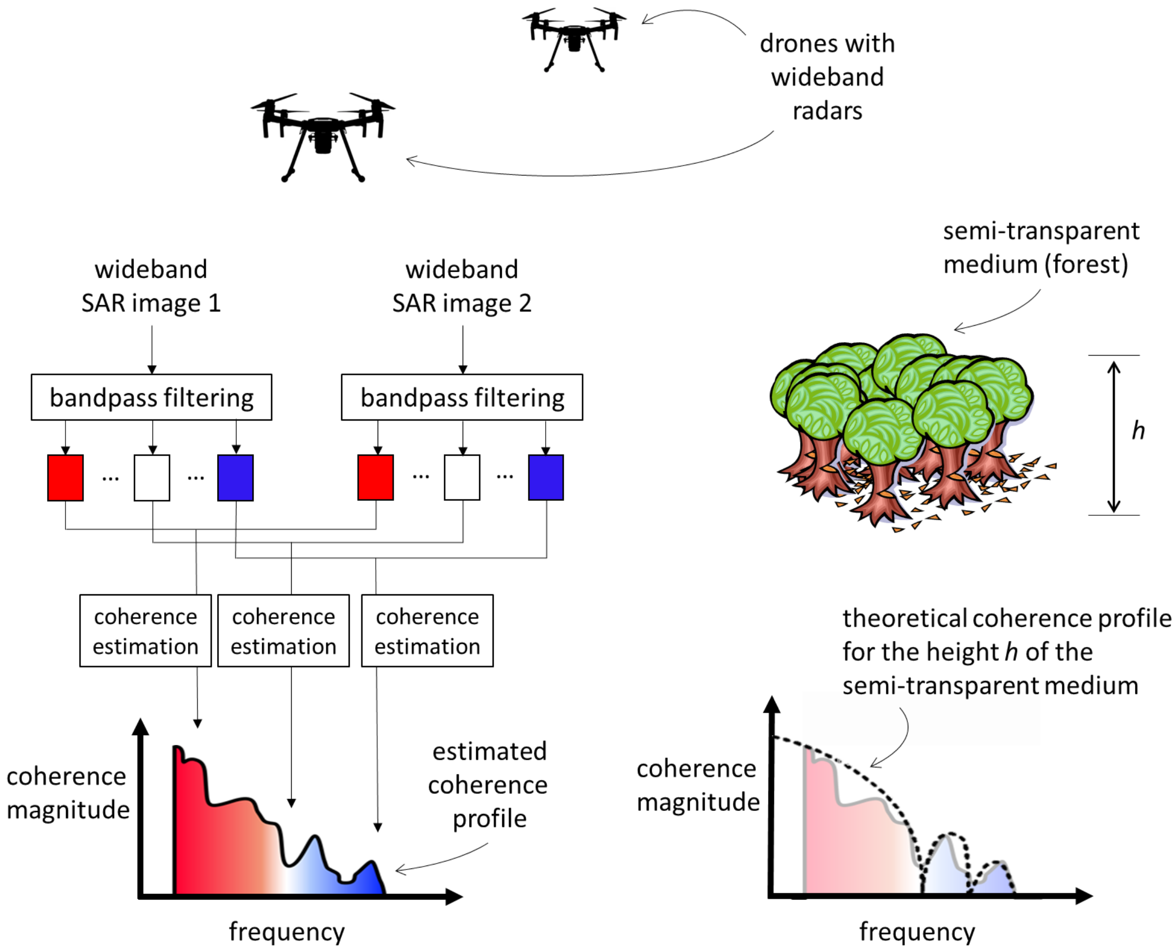

Fig. 3. Concept for the retrieval of three-dimensional volume parameters through wideband (multi-baseline) SAR interferometry.

V. DEMONSTRATIONS USING SWARMS OF DRONES

Multi-static concepts intrinsically require multiple transmitters and/or receivers and can be tested using swarms of drones, equipped with radars and localization systems, that can be deployed at an affordable cost [33]-[35]. While the main objective is the demonstration of spaceborne SAR techniques, swarms of drones can also be exploited to obtain a complete characterization of the bistatic scattering process of a surface and monitor local areas with sub-hour temporal resolutions. In this respect, the very large available bandwidth can be exploited for the generation of very accurate DEMs, where phase unwrapping errors can also be resolved using radargrammetry.

The wide fractional bandwidth of radar onboard drones can also be exploited to retrieve the three-dimensional structure of vegetation, ice, and dry soil through a novel technique based on systematic variation of the interferometric coherence as a function of the frequency [36]-[37]. Instead of obtaining the coherence for different wavenumbers by using different baselines under the assumption of a narrow band, interferograms formed using different portions of the range spectra of only two wideband images can be used. The resulting profile of coherence versus frequency is finally inverted by comparison with the expected profile resulting from theoretical models (Fig. 3). For the case of a frequency-dependent extinction coefficient, a third image might be needed so that coherence profiles for further baselines are available and can be used to characterize the frequency-dependent extinction of the medium.

VI. CONCLUSIONS

Multi-static SAR is a giant opportunity for radar remote sensing with a significant impact on numerous applications. Swarms of drones represent the ideal way to demonstrate multi-static SAR systems. The research in this field will pose the basis for future advanced Earth observation missions that will offer remarkable societal benefits and boost the emerging NewSpace sector [38].

REFERENCES

[1] Earth Observation Science Strategy for ESA: A New Era for Scientific Advances and Societal Benefits. European Space Agency (ESA), 2 volumes: ESA SP-1329/1, ESA SP-1329/2, Feb. 2015.

[2] National Academies of Sciences Engineering and Medicine, Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space, 2018.

[3] A. Moreira, P. Prats-Iraola, M. Younis, G. Krieger, I. Hajnsek, and K. P. Papathanassiou, “A tutorial on synthetic aperture radar,” IEEE Geosci. Remote Sens. Mag., vol. 1, no. 1, pp. 6–43, Mar. 2013.

[4] R. Bamler and P. Hartl, “Synthetic aperture radar interferometry,” Inv. Probl., vol. 14, no. 4, pp. R1–R54, Feb. 1998.

[5] P. A. Rosen et al., “Synthetic aperture radar interferometry,” in Proceedings of the IEEE, vol. 88, no. 3, pp. 333-382, March 2000.

[6] R. F. Hanssen, Radar interferometry: data interpretation and error analysis, Springer, Dordrecht, The Netherlands, 2001.

[7] A. Reigber and A. Moreira, “First demonstration of airborne SAR tomography using multibaseline L-band data,” IEEE Transactions on Geoscience and Remote Sensing, vol. 38, no. 5, pp. 2142–2152, 2000.

[8] S. Tebaldini, “Single and multipolarimetric SAR tomography of forested areas: A parametric approach,” IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 5, pp. 2375–2387, 2010.

[9] F. Gini, F. Lombardini, and M. Montanari, “Layover solution in multibaseline SAR interferometry,” IEEE Transactions on Aerospace and Electronic Systems, vol. 38, no. 4, pp. 1344–1356, 2002.

[10] X. X. Zhu and R. Bamler, “Very high resolution spaceborne SAR tomography in urban environment,” IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 12, 4296–4308, 2010.

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

[12] G. Krieger and A. Moreira, “Spaceborne Interferometric and Multistatic SAR Systems”, In Bistatic Radars: Emerging Technology, M. Cherniakov (Editor), John Wiley & Sons, Sussex, UK, pp. 95-158 2008.

[13] I. Hajnsek et al., “The Ka-Band Interferometric Radar Mission Proposal for Cold Environments - SKADI,” ESA Living Planet Symposium 2022, Bonn, Germany, 23-27 May 2022.

[14] A. Kääb, “Remote sensing of permafrost-related problems and hazards,” Permafrost and Periglac. Process., 19(2), pp. 107-136, 2008.

[15] S. Westermann, C.R. Duguay, G. Grosse, and A. Kääb, Remote sensing of permafrost and frozen ground. In ed: M. Tedesco "Remote Sensing of the Cryosphere". Wiley. 2015.

[16] J. Mittermayer, G. Krieger, and M. Villano, “Multi-Static Dispersed Swarm Configurations for Synthetic Aperture Radar Imaging”, IEEE Geoscience and Remote Sensing Letters, vol. 19, pp. 1-5, 2022.

[17] D. Giudici, P. Guccione, M. Manzoni, A. M. Guarnieri, and F. Rocca, “Compact and Free-Floating Satellite MIMO SAR Formations,” in IEEE Transactions on Geoscience and Remote Sensing, vol. 60, pp. 1-12, 2022.

[18] D. Giudici, P. Guccione, D. Mapelli, J. Marini, and A. Monti Guarnieri “RAINBOW-SAR: Enhanced Observation Capability by Multiple Frequency Radar”, 7th Workshop on RF and Microwave Systems, Instruments & Sub-Systems + 5th Ka-Band Workshop, 10-12 May 2022.

[19] A. Renga, M. D. Graziano, M. Grasso, and A. Moccia, “Evaluation of design parameters for formation flying SAR,” EUSAR 2021; 13th European Conference on Synthetic Aperture Radar, 2021, pp. 1-4.

[20] G. Krieger, T. Rommel, and A. Moreira, “MIMO-SAR Tomography,” Proceedings of EUSAR 2016: 11th European Conference on Synthetic Aperture Radar, 2016, pp. 1-6.

[21] M. Nogueira Peixoto, M. Villano, G. Krieger, A. Moreira, and C. Waldschmidt, “A Novel Technique to Generate Digital Elevation Models in a Single Pass Using a Cluster of Smallsats,” IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2023), Pasadena, CA, USA, 16-21 July 2023.

[22] M. Goldstein and H. A. Zebker, “Interferometric radar measurement of ocean surface currents,” Nature, vol. 328, no. 20, pp. 707–709, Aug. 1987.

[23] R. M. Goldstein, T. P. Barnett, and H. A. Zebker, “Remote Sensing of Ocean Currents,” Science, pp. 1282–1285, 1989.

[24] G. Krieger et al., “Mirror-SAR: An Advanced Multistatic MIMO-SAR for High-Resolution Wide-Swath Earth System Monitoring,” IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2017, Fort Worth, Texas, USA, 23-28 July 2017.

[25] N. Ustalli, G. Krieger, J. Mittermayer, M. Villano, and C. Waldschmidt, “MirrorSAR Concept: Phase Synchronization Analysis,” Proceedings of the Kleinheubacher Tagung 2022, Miltenberg, Germany, 27-29 September 2022.

[26] J. Mittermayer, G. Krieger, and M. Villano, Verfahren zur Vermessung eines Antennendiagramms einer Antenne auf einem ersten Flugobjekt mittels eines zweiten Flugobjekts, German Patent Application Nr. 10 2023 112 705.5, filed May 15, 2023. Patent pending.

[27] J. Mittermayer, G. Krieger, and M. Villano, “In-Orbit Antenna Pattern Measurement of a LEO Radar Satellite by a Small Measurement Satellite Flying in Formation”, CEOS SAR Workshop 2023, accepted.

[28] G. Krieger et al., “TanDEM-X: A Satellite Formation for High-Resolution SAR Interferometry,” IEEE Trans. Geosci. Remote Sens., vol. 45, no. 11, pp. 3317–3341, Nov. 2007.

[29] J. Mittermayer et al., “MirrorSAR: An HRWS Add-On for Single-Pass Multi-Baseline SAR Interferometry,” IEEE Trans. Geosci. Remote Sens., vol. 60, pp. 1-18, 2022.

[30] F. Scala, G. Krieger, and M. Villano, “Investigation of Fixed Across-Track Baselines for Distributed Spaceborne SAR Systems”, EUSAR 2024, submitted.

[31] M. Martín-Neira, M. Piera, F. Scala, C. Colombo, A. Zurita and B. Duesmann, “Formation Flying L-Band Aperture Synthesis Mission Concept,” IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2022, Kuala Lumpur, Malaysia, 17-22 July 2022.

[32] F. Scala, C. Colombo, B. Duesmann, and M. Martin-Neira, “Analysis and design of future multiple satellite formation flying L-band missions in low Earth orbit,” 73rd International Astronautical Congress, IAC 2022, Paris, France, 18-22 Sept. 2022.

[33] P. Hügler, F. Roos, M. Schartel, M. Geiger, and C. Waldschmidt, “Radar Taking Off: New Capabilities for UAVs”, IEEE Microwave Magazine, vol. 19, no. 7, pp. 43 – 53, 2018.

[34] https://www.uni-ulm.de/in/korato/

[35] M. Engel, A. Heinzel, E. Schreiber, S. Dill, and M. Peichl, “Recent results of a UAV-based Synthetic Aperture Radar for remote sensing applications,” EUSAR 2021; 13th European Conference on Synthetic Aperture Radar, 2021, pp. 1-5.

[36] S. Kim, V. Mustieles Perez, G. Krieger, and M. Villano, “Three-Dimensional Structure Inversion Through Wide Fractional Bandwidth, UAV-Based SAR Interferometry,” IRS 2023, Berlin, Germany, 24-26 May 2023.

[37] S. Kim, G. Krieger, M. Villano, and V. Mustieles Perez, Verfahren zum Bestimmen einer vertikalen Struktur eines halbtransparenten Mediums aus SAR-Daten eines SAR-Systems, German Patent Application Nr. 10 2023 113 349.7, filed May 22, 2023. Patent pending.

[38] M. Villano et al., “NewSpace SAR: A Game Changer for Spaceborne Synthetic Aperture Radar,” 72nd International Astronautical Congress, IAC 2021, Dubai, United Arab Emirates, 25-29 October 2021.