72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.

IAC-21-B1.2.7

NewSpace SAR: A Game Changer for Spaceborne Synthetic Aperture Radar

Michelangelo Villano[a]*, Josef Mittermayer[a], Nertjana Ustalli[a], Maxwell Nogueira Peixoto[a], Se-Yeon Jeon[a], Gerhard Krieger[a], Alberto Moreira[a]

[a] *German Aerospace Center (DLR), Microwaves and Radar Institute, Oberpfaffenhofen, 82234 Wessling, Germany*, michelangelo.villano@dlr.de
* Corresponding Author

Abstract

Synthetic aperture radar (SAR) is a key remote sensing technique for Earth observation. While future high-resolution wide-swath SAR missions will deliver weekly images of our planet at global scale, thereby allowing quantification of several essential climate variables, some applications require even more frequent temporal sampling or simultaneous acquisitions from slightly different observation angles. NewSpace SAR denotes all groundbreaking concepts and technologies that enable frequent and enhanced SAR imaging, also by complementing traditional systems, at much more affordable costs. Besides the technological developments, such as mass-produced platforms for constellations of small SAR satellites, application-driven system design plays a fundamental role. In particular, disruptive concepts based on waveform encoding and/or distributed and fractionated SAR help relaxing the design constraints and reducing complexity, size, and cost of the SAR instrument. A prominent example is the MirrorSAR concept that will be implemented in the planned German SAR mission High Resolution Wide Swath (HRWS), where three small satellites acting as radar transponders will allow forming a digital elevation model (DEM) with spatial resolution (4 m × 4 m) much finer than that of the state-of-the art TanDEM-X DEM (12 m × 12 m).
Keywords: Earth observation missions, NewSpace, synthetic aperture radar.

1. Introduction

Synthetic aperture radar (SAR) is a remote sensing technique that exploits the Doppler shift arising from the sensor movement relative to the ground to improve the resolution in the flight direction well beyond the diffraction limit of the radar antenna. SAR therefore achieves high-resolution imaging, while keeping an important feature of active microwave instruments, namely the ability to operate independently of weather conditions and sunlight illumination.

Furthermore, the joint exploitation of multiple SAR images, acquired in different polarizations (polarimetric SAR), from slightly different observation angles (SAR interferometry, polarimetric SAR interferometry, and SAR tomography) and/or at different times (differential and permanent scatterer interferometry), allows retrieving a huge amount of unique information.

SAR is nowadays an established tool for Earth observation: Several satellites have been launched and operated as of 1978, and many airborne SAR systems have allowed early demonstrations of novel techniques, which have later been implemented in spaceborne missions [1].

Several spaceborne SAR sensors are currently in operation, all characterized by a spatial resolution at least one order of magnitude higher than the sensors of the previous generation. Among the current sensors, TerraSAR-X and TanDEM-X are the first satellites flown in a closely controlled formation to generate a seamless global digital elevation model with unprecedented accuracy and resolution, i.e., 2 m height error at 12 m × 12 m horizontal resolution [2]. State-of-the-art sensors also offer a much higher flexibility in that several acquisition modes can be selected for different trade-offs between resolution and coverage thanks to the use of phased array antennas with electronic beam steering.

In the last decades, several concepts for high-resolution wide-swath SAR imaging have been devised that allow overcoming the intrinsic cross-track swath limitation imposed by the azimuth resolution through digital beamforming, multiple aperture signal recording, and variation of the pulse repetition interval [3-12]. These techniques have been refined and demonstrated through the last years and have been recently adopted for planned and future missions [13-18]. At the same time a number of emerging private companies have designed and launched constellations of low-weight commercial SAR systems [19-21].

2. NewSpace SAR

While high-resolution wide-swath SAR represents a huge step forward by delivering vital missing information for improved scientific predictions, upon which socio-political decisions can be based, several important applications would require even more frequent, ideally daily acquisitions, or simultaneous imaging from slightly different observation angles, i.e., single-pass tomography.

The existing concepts for high-resolution wide-swath imaging, however, cannot reach the requested frequent coverage while keeping the resolution high, and the costs of increasing the mapping capability by launching and operating a constellation of satellites would be prohibitive. On the contrary, radically new concepts are needed that are revolutionary from the space segment point-of-view as well and provide easy and affordable access to space.

NewSpace SAR denotes all groundbreaking solutions that enable frequent and enhanced SAR imaging at reduced costs. Besides the technological developments, e.g., mass-produced platforms for constellations of SAR satellites, an application-driven system design approach paves the way for implementation of SAR using small satellites, which can also be used in formations to reach or even exceed the performance of state-of-the-art SAR systems. Waveform encoding and multi-focus postprocessing allow relaxing the SAR design constraints, reducing complexity, size, and cost of the resulting SAR instrument, and still retrieving the desired information from SAR data. Finally, distributed and fractionated concepts such as MirrorSAR represent an innovative, low-cost approach to boost the performance of already existing full-fledged SAR systems.

3. Exploitation of small satellites for SAR

In the context of NewSpace SAR it is of interest to understand how small satellites with severely constrained power and antenna size can be exploited for SAR both as single satellites and in formations.

3.1 Dedicated applications

One possibility is to assess the worst performance, which can be tolerated for a dedicated application, and design a small satellite SAR system able to retrieve the desired information independently of the "noisy" visual appearance of the acquired images. In this context, the DLR Microwaves and Radar Institute has recently started a collaboration with the New Zealand Space Agency and the University of Auckland, which are interested in developing a dedicated SAR system to monitor illegal fishing and land deformation [22-23].

This idea of an application-driven system design (see Fig. 1), where the minimum image requirements are derived based on the application requirements, has been further developed leading to the exploitation of an "ambiguous" SAR, where a short antenna in the azimuth direction is employed to achieve high azimuth resolution and a low pulse repetition frequency (PRF) is selected to map a wide swath, as azimuth ambiguities can be tolerated for this specific application. Preliminary investigations led to the two X-band system design examples of Table 1, where SAR systems with antennas of 0.2 m^2 to 0.7 m^2 and average transmit powers of 46 to 72 W should allow detecting medium or even small ships over ground swaths of 50 km to 90 km with one false alarm per million of square kilometres and an average detection probability of about 0.7 [24-25].

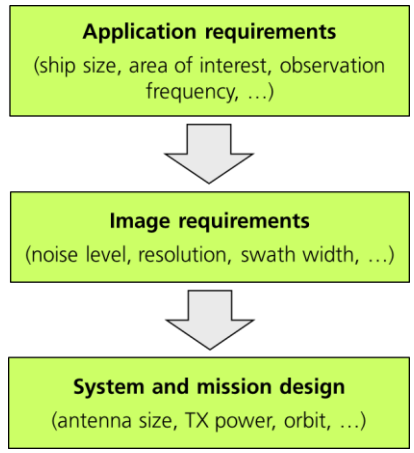

Fig. 1. Rationale of application-driven system design for the monitoring of illegal fishing vessels. The image requirements are derived based on the dedicated application requirements and drive the system and mission design.

Table 1. System design examples of ambiguous SAR for monitoring of illegal vessels.

	System A	System B
Ship size	40 m × 8 m	16 m × 5 m
No. of false alarms/10^6 km^2	1	1
Detection probability (variable across the swath)	0.5-0.98	0.4-0.95
Swath width on ground	90 km	50 km
Orbit height	500 km	
Incidence angle	30°	
Chirp bandwidth	300 MHz	
Wavelength	0.03 m (X-band)	
Antenna size	1.0 m × 0.2 m	1.8 m × 0.4 m
Average transmit power	46 W	72 W

3.2 Train of small satellites

While on the one hand small satellites could be employed for dedicated applications where low SNR and ambiguities are not critical, on the other hand, an image quality comparable to that of current large SAR satellites could be achieved through the exploitation of formations of small satellites. In particular, an interesting concept is based on a train of alternately-transmitting satellites, arranged in along-track, which transmit sequentially one pulse each, and the whole

train receives the echoes of all transmitted pulses, as conceptually depicted for a train of three satellites in Fig. 2. This allows reaching satisfactory NESZ levels with low power onboard the individual satellites [26-28]. A formation example with 21 small satellites at 10 Watts average power only is able to provide a resolution of 1 m at more than 70 km swath width [26].

Fig. 2. Conceptual idea of a train of alternately-transmitting satellites, where all satellites receive, and corresponding azimuth phase centres. The transmitting satellite is highlighted by the red arrow.

Furthermore, compared to concepts based on a single transmitter and several receive-only satellites, it provides intrinsic redundancy. Of particular interest is the extension of this concept to interferometric scenarios, which will be subject of further work.

4. Removal of nadir returns

A further constraint to account for within the design of SAR systems is represented by the nadir interference.

While this is conventionally avoided by constraining the PRF selection, i.e., by choosing with the help of the timing (or diamond) diagram PRFs for which neither transmit nor nadir interferences occur, a novel concept based on the combination of waveform encoding and dual-focus postprocessing allows designing a SAR system without the nadir interference constraint. It removes the nadir echoes by means appropriate postprocessing [29-30].

The acquired raw data are focused using a filter "matched" to the nadir echo, so that the nadir echo can be removed with a negligible corruption of the useful signal, as the nadir echo is focused and located at specific ranges, while the useful signal is smeared. The latter focused data, in which the nadir echo has been removed, are then transformed back into raw data through an inverse focusing operation and finally focused using a filter that is "matched" to the useful signal, thus obtaining an image in which the nadir echo is significantly attenuated, while the useful signal is only minimally affected.

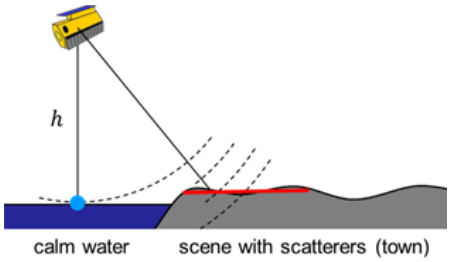

Fig. 3. Schematic representation of the scene selected for the TerraSAR-X experiment for validation of nadir echo suppression.

This technique has been recently validated through a dedicated TerraSAR-X experiment with up- and down-chirp alternation. In particular, a TerraSAR-X data set has been acquired over Tianjin, China, where a calm water surface is causing nadir interference on a town (see Fig. 3). Fig. 4 shows from left to right the nadir interference in focused SAR data for a conventional SAR without waveform variation, appearing as a bright vertical stripe, the "smeared" nadir echo as a result of waveform variation, and the nadir echo-free image after dual-focus postprocessing [31].

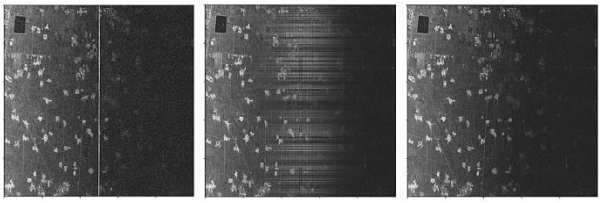

Fig. 4. Terra-SAR demonstration of nadir echo removal through waveform variation and dual-focus post-processing. From left to right nadir interference in focused SAR data for a conventional SAR without waveform variation, appearing as a bright vertical stripe, "smeared" nadir echo as a result of waveform variation and nadir echo-free image after postprocessing.

5. MirrorSAR

The MirrorSAR concept is based on a set of mutually separated transmitter and receiver satellites where the latter act essentially as mirrors that route spatial samples of the ground scattered radar waves to the transmitter(s) where the relayed radar signals are then coherently demodulated and combined before transmitting the non-redundant information to the ground (Fig. 5). As the receiver satellites become rather simple in this approach, it becomes possible to scale their number without cost explosion, thereby paving the way for novel applications like multi-baseline SAR interferometry and single-pass tomography [32].

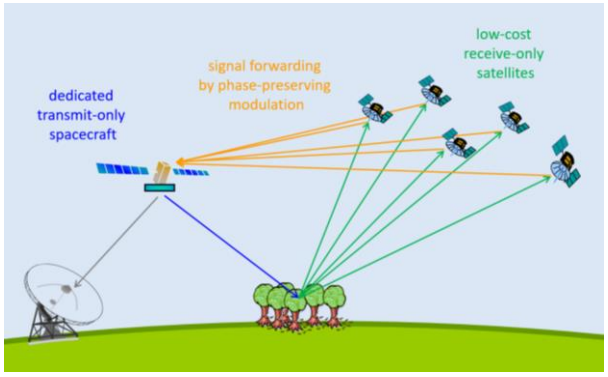

Fig. 5. Schematic representation of the MirrorSAR concept.

Currently, Germany plans to start the phase B of the next X-band spaceborne mission in 2022, consisting of a High-Resolution Wide-Swath (HRWS) SAR satellite with digital beamforming capabilities and three small, receive-only satellites in close formation flight with the goal to build a multistatic SAR interferometer. These small satellites represent an adaptation of the MirrorSAR concept, an innovative, low-cost approach to boost the performance of already existing full-fledged SAR systems [33-35].

6. Conclusions

This paper presents some NewSpace SAR concepts that allow cost-effective SAR system design. The exploitation of small satellites for SAR is discussed, both as single satellites for dedicated applications and as formations for imaging and interferometry. Novel techniques are introduced that exploit waveform encoding, also in combination with postprocessing of the acquired data, in order to suppress the nadir interference in SAR. Finally, the enhancement of the HRWS mission by the MirrorSAR concept is mentioned, as an example that NewSpace can also boost the performance of conventional systems.

References

[1] A. Moreira et al., "A tutorial on synthetic aperture radar," IEEE Geosci. Remote Sens. Mag., vol. 1, no. 1, pp. 6–43, Jan. 2013.

[2] G. Krieger et al., "TanDEM-X: A satellite formation for high-resolution SAR interferometry," IEEE Trans. Geosci. Remote Sensing, vol. 45, no. 11, pp. 3317–3341, 2007.

[3] A. Currie and M. A. Brown, "Wide-swath SAR," Proc. Inst. Elect. Eng.—Radar, Sonar, Navigat., vol. 139, no. 2, pp. 122–135, 1992.

[4] G. D. Callaghan and I. D. Longstaff, "Wide swath spaceborne SAR using a quad element array," Proc. Inst. Elect. Eng.—Radar, Sonar, Navigat., vol. 146, no. 3, pp. 159–165, 1999.

[5] M. Suess, B. Grafmüller, and R. Zahn, "A novel high resolution, wide swath SAR system," in Proc. IGARSS, 2001.

[6] G. Krieger, N. Gebert, and A. Moreira, "Unambiguous SAR Signal Reconstruction from Nonuniform Displaced Phase Center Sampling", IEEE Geoscience and Remote Sensing Letters, vol. 1, no.4, pp. 260-264, Oct. 2004.

[7] N. Gebert, G. Krieger, and A. Moreira, "Digital Beamforming on Receive: Techniques and Optimization Strategies for High-Resolution Wide-Swath SAR Imaging", IEEE Trans. Aerospace and Electronic Systems, vol. 45, no. 2, pp. 564-592, 2009.

[8] G. Krieger, N. Gebert, M. Younis, F. Bordoni, A. Patyuchenko, and A. Moreira, "Advanced Concepts for Ultra-Wide-Swath SAR Imaging," Proceedings of the EUSAR, Friedrichshafen, Germany, 2008.

[9] A. Freeman, G. Krieger, P. Rosen, M. Younis, W.T.K. Johnson, S. Huber, R. Jordan, A. Moreira, "SweepSAR: Beam-forming on Receive using a Reflector-Phased Array Feed Combination for Spaceborne SAR," IEEE Radar Conference, Pasadena, USA, May 2009.

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

[11] M. Villano, et al., "Staggered SAR: Performance Analysis and Experiments with Real Data," IEEE Trans. Geosci. Rem. Sens., vol. 55, no. 11, pp. 6617-6638, Nov. 2017.

[12] M. Villano and M. N. Peixoto, "Characterization of Nadir Echoes in Multiple-Elevation-Beam SAR with Constant and Variable Pulse Repetition

Interval," IEEE Transactions on Geoscience and Remote Sensing, online available.

[13] A. Moreira, G. Krieger, I. Hajnsek, K.P. Papathanassiou, M. Younis, P. Lopez-Dekker, S. Huber, M. Villano, M. Pardini, M. Eineder, F. De Zan, and A. Parizzi, "Tandem-L: A Highly Innovative Bistatic SAR Mission for Global Observation of Dynamic Processes on the Earth's Surface," IEEE Geoscience and Remote Sensing Magazine, vol. 3, no. 2, pp. 8–23, June 2015.

[14] S. Huber, F. Queiroz de Almeida, M. Villano, M. Younis, G. Krieger, A. Moreira, "Tandem-L: A Technical Perspective on Future Spaceborne SAR Sensors for Earth Observation," IEEE Transactions on Geoscience and Remote Sensing, vol. 56, no. 8, pp. 4792-4807, Aug. 2018.

[15] P. A. Rosen, S. Hensley, P. Agram, E. Gurrola, L. Harcke, S. Shaffer, C. Veeramachaneni, "Impact of Gaps in the NASA-ISRO SAR Mission Swath," Proceedings of the European Conference on Synthetic Aperture Radar (EUSAR), Aachen, Germany, 5-7 June 2018.

[16] M. Villano, M. Pinheiro, G. Krieger, A. Moreira, P. Rosen, S. Hensley, C. Veeramachaneni, "Gapless Imaging with the NASA-ISRO SAR (NISAR) Mission: Challenges and Opportunities of Staggered SAR," Proceedings of the European Conference on Synthetic Aperture Radar (EUSAR), Aachen, Germany, 5-7 June 2018.

[17] T. Motohka, Y. Kankaku, S. Miura, S. Suzuki, "ALOS-4 L-Band SAR Mission and Observation," Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2019, Yokohama, Japan, 28 July - 2 August 2019.

[18] M. Zonno, J. Matar, F. Queiroz de Almeida, M. Rodriguez Cassola, G. Krieger, "Sentinel-1 Next Generation: trade-offs and assessment of mission performance," ESA Living Planet Symposium 2019, Milan, 13-17 May 2019.

[19] D. Werner, "A New Hope for Commercial Space-based Radar", Space News Magazine, March 28, 2016.

[20] D. Castelletti, G. Farquharson, C. Stringham and D. Eddy, "Operational readiness of the Capella Space SAR system," IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium, Hawaii, 2020.

[21] V. Ignatenko, P. Laurila, A. Radius, L. Lamentowski, O. Antropov, D. Muff, "ICEYE microsatellite SAR constellation status update: evaluation of first commercial imaging modes," IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium, Hawaii, 2020.

[22] 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 Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 14, pp. 3162-3169, 2021.

[23] J. Krecke, M. Villano, N. Ustalli A. C. M. Austin, J. E. Cater, G. Krieger, "Design of SmallSat SAR for Dedicated New Zealand Applications," European Conference on Synthetic Aperture Radar (EUSAR), Leipzig, Germany, 29 March -1 April 2021.

[24] N. Ustalli, G. Krieger, and M. Villano, "A Low-Power, Ambiguous Synthetic Aperture Radar Concept for Continuous Ship Monitoring", IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, in review.

[25] N. Ustalli, M. Villano, and G. Krieger, "Design of a Low-Cost Synthetic Aperture Radar for Continuous Ship Monitoring," IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 2021, Brussels, Belgium, 11-16 July 2021.

[26] J. Mittermayer, G. Krieger, and M. Villano, "Multi-Static Dispersed Swarm Configurations for Synthetic Aperture Radar Imaging", IEEE Transactions on Geoscience and Remote Sensing, in review.

[27] J. Mittermayer et al., "Small Satellite Dispersed Synthetic Aperture Radar", in Proceedings of the 4S Symposium - Small Satellites Systems and Services, May 2016.

[28] J. Mittermayer et al., "Small Satellite Dispersed SAR - An Exemplary Configuration", in Proceedings of the European Conference on Synthetic Aperture Radar (EUSAR), June 2016.

[29] M. Villano, G. Krieger, and A. Moreira, "Nadir Echo Removal in Synthetic Aperture Radar via Waveform Diversity and Dual-Focus Post-Processing," IEEE Geosci. Rem. Sens. Lett., vol. 15, no. 5, pp. 719-723, May 2018.

[30] M. Villano, G. Krieger, and A. Moreira, "Waveform-Encoded SAR: A Novel Concept for Nadir Echo and Range Ambiguity Suppression," Proc. European Conference on Synthetic Aperture Radar (EUSAR), Aachen, Germany, 5-7 June 2018.

[31] S.-Y. Jeon, T. Kraus, U. Steinbrecher, G. Krieger, and M. Villano, "Experimental Demonstration of Nadir Echo Removal in SAR Using Waveform Diversity and Dual-Focus Postprocessing," IEEE Geoscience and Remote Sensing Letters, online available.

[32] G. Krieger, M. Zonno, M. Rodriguez-Cassola, P. Lopez-Dekker, J. Mittermayer, M. Younis, S. Huber, M. Villano, F. Queiroz de Almeida, P. Prats-Iraola, A. Moreira, "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.

[33] J. Mittermayer, G. Krieger, A. Bojarski, M. Zonno, M. Villano, M. Pinheiro, M. Bachmann, S. Buckreuss, and A. Moreira, "MirrorSAR: An HRWS Add-On for Single-Pass Multi-Baseline SAR Interferometry," IEEE Transactions on Geoscience and Remote Sensing, in review.

[34] J. Mittermayer, G. Krieger, A. Bojarski, M. Zonno, M. Villano, and A. Moreira, "A MirrorSAR Case Study Based on the X-Band High Resolution Wide Swath Satellite (HRWS)," European Conference on Synthetic Aperture Radar (EUSAR), Leipzig, Germany, 29 March -1 April 2021.

[35] J. Mittermayer, G. Krieger, M. Villano, and A. Moreira, "A Novel MirrorSAR Concept for Augmenting the Next German Synthetic Aperture Radar Mission HRWS with Single-Pass Interferometry," 13th IAA Symposium on Small Satellites for Earth Observation (SSSEO) 2021, Berlin, Germany, 26-29 April 2021.