NewSpace SAR: Disruptive Concepts for Cost-Effective SAR System Design

Michelangelo Villano[a], Maxwell Nogueira Peixoto[a], Luca Dell'Amore[a], Se-Yeon Jeon[a], Nertjana Ustalli[a], Jan Krecke[b], Josef Mittermayer[a], Gerhard Krieger[a], and Alberto Moreira[a]
[a] German Aerospace Center (DLR), Microwaves and Radar Institute, Wessling, Germany
[b] University of Auckland, Department of Electrical, Computer and Software Engineering, Auckland, New Zealand

Abstract

Synthetic aperture radar (SAR) is a key remote sensing technique for Earth observation. Future high-resolution wide-swath SAR missions will deliver weekly images of our planet, thereby allowing quantification of several essential climate variables. While this is a huge step forward compared to current systems, some applications require even more frequent temporal sampling or simultaneous acquisitions from slightly different observation angles. NewSpace SAR denotes all groundbreaking solutions that enable frequent and enhanced SAR imaging at affordable costs. Besides the technological developments, e.g., mass-produced platforms for constellations of SAR satellites, application-driven SAR system design approaches play a fundamental role. In particular, disruptive concepts based on waveform or phase encoding, and/or distributed and fractionated SAR allow relaxing the design constraints, reducing complexity, size, and cost of the SAR instrument. These solutions will help spreading the on-going NewSpace revolution to SAR remote sensing and posing the basis for future Earth observation missions that will yield remarkable societal benefits.

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].

More than 15 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 [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.

TerraSAR-X data have been used to demonstrate several applications of SAR to environmental monitoring. However, while very powerful and flexible, TerraSAR-X can map in stripmap mode only 2% of the Earth's landmass during its 11-day repeat cycle, due to its relatively small orbit duty cycle (the satellite can operate 3 minutes per orbit) and its 30-km swath width. Sensors launched more recently, such as Sentinel-1 and ALOS-2, have much larger mapping capability but at lower spatial resolution. This limitation is not only due to technology development, but is also inherent in the SAR acquisition principle (azimuth resolution versus swath width coverage "dilemma").

A brute force solution to this problem consists of flying a constellation of satellites on the same orbit, as done for Cosmo-SkyMed and Radarsat Constellation Mission (RCM). This solution affords an increase in mapping capability by a factor equal to the number of satellites of the constellation, but becomes costly or even unfeasible, if the mapping capability has to be boosted by one or even two orders of magnitude.

2 SAR missions for frequent global mapping

In recent years there has been increased interest in the scientific community in understanding and quantifying dynamic processes within the Earth system occurring at different spatial and temporal scales, as well as their interdependency and interaction. Many of these processes are currently inadequately researched and understood. An important reason for this is the lack of suitable observation data for analyzing such interactions. **Figure 1** summarizes the requested observation intervals for the systematic monitoring of some exemplary dynamic processes on the Earth surface.

The imaging performance and/or measurement resolution and accuracy of existing remote sensing configurations are often inadequate to draw reliable conclusions as to the dynamics of large-scale processes. The measurement of dynamic processes requires a continuous, extended and systematically planned observation strategy in order to detect changes and quantify them with sufficient accuracy. Depending on the processes to be observed, changes have to be measured on variable spatial and temporal scales and then related to one another. The combination of short revisit times and extended acquisitions over several years is required when it comes to accurate and high-resolution monitoring of fast developing, highly dynamic processes, such as the relaxation following an earthquake, as well as slowly developing processes, such as the inter-annual variation of forest biomass.

SAR represents the ideal candidate to provide answers to these questions, but spaceborne SAR sensors currently in operation do not have the resolution and mapping capability needed to meet these scientific requirements. In particular, a SAR sensor is required, capable of mapping the entire Earth surface twice a week in fully-polarimetric mode and with a spatial resolution of approximately 5 m (this corresponds to a mapping capability two orders of magnitude better than that of TerraSAR-X in stripmap mode). In response to these needs, a proposal for a highly innovative L-band SAR mission, Tandem-L, was started at DLR with a joint pre-phase A study with the Jet Propulsion Laboratory (NASA/JPL) in 2008 and has reached the phase B1 in 2018 [3].

Tandem-L uses a deployable reflector antenna in combination with innovative digital beamforming (DBF) techniques. This increases the sensitivity and leads to a considerable reduction in transmit power. Because of this, the SAR instrument can be operated virtually continuously.

DBF allows forming multiple elevation beams, which simultaneously map multiple subswaths. In this way, a resolution of 7 m × 5 m (azimuth × ground range) over a 350 km wide ground swath can be achieved, as required for the aforementioned mission aimed at monitoring dynamic processes on Earth's surface [4].

A key element of the Tandem-L instrument is staggered SAR, a novel concept based on the continuous variation of the pulse repetition interval (PRI). The architecture with multiple elevation beams, in fact, yields "blind ranges" between the different subswaths. If the PRI is continuously varied, however, the ranges, from which the echoes are not received, because the radar is transmitting, will be different for each transmitted pulse. A proper selection of the PRIs together with an average oversampling of the signal in azimuth allows getting rid of the "blind ranges" and imaging a wide continuous swath with high resolution [5]-[7].

Staggered SAR is the baseline acquisition mode of the Tandem-L mission proposal, where a strategy for onboard data volume reduction able to cope with the increased amount of data has also been devised [8]. Analyses carried out within a collaboration between DLR and the Jet Propulsion Laboratory (JPL) have shown that staggered SAR also represents an appealing option for the NASA-ISRO Synthetic Aperture Radar (NISAR) mission, a mission with similar scientific objectives as Tandem-L, but where the system's size is constrained by available resources, and which is planned to operate with a lower pulse rate than would be optimum [9].

Besides the Tandem-L proposal and the NISAR mission, the Radar Observatory System for Europe (ROSE-L), a future SAR mission of the European Space Agency's Copernicus Programme, and JAXA's ALOS-4 mission also aim at frequent global mapping with similar scientific objectives.

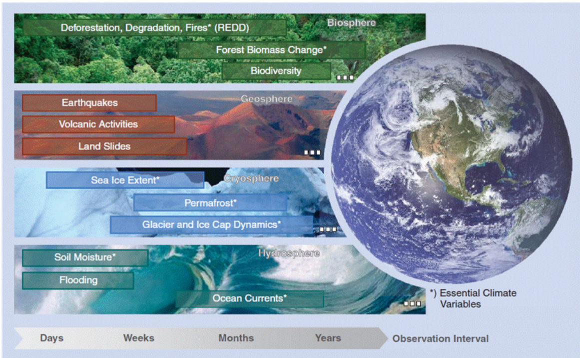


Figure 1 Requested observation intervals for systematic monitoring of dynamic processes on the Earth surface.

3 NewSpace SAR: A game changer for spaceborne 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 an even more frequent, ideally daily temporal sampling, as is apparent from **Figure 1**, 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, as already pointed out, 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 affordable costs. Besides the technological developments, e.g., mass-produced platforms for constellations of SAR satellites, an application-driven SAR system design approach plays a fundamental role. **Figure 2** visualizes the main principles and goals of NewSpace SAR. While an interesting concept for a distributed and fractionated SAR system denoted as MirrorSAR was already proposed in [10], some disruptive concepts based on waveform or phase encoding and multi-focus postprocessing are presented in the following that 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. These ideas also pave the way for implementation of SAR using small satellites.

3.1 The importance of ambiguity smearing and suppression

In the design of SAR systems, the definition of the antenna height and the selection of the pulse repetition frequency (PRF) are driven by the need for controlling range and azimuth ambiguities.

As ambiguities may impair the retrieval of information from SAR images, requirements are usually imposed on the ambiguity-to-signal ratio (ASR), i.e., on the total energy of the ambiguous signal relative to the total energy of the useful signal for an imaginary scene with uniform backscatter.

Depending on the wavelength of the system, which determines different backscatter dynamics, a minimum ASR between -20 dB and -25 dB is typically required, where these values are purely based on the experience from existing SAR systems and are not linked to the consequential impairment of the retrieval performance within one or more specific applications.

Furthermore, the ASR requirement unfortunately does not account for the statistical distribution of the ambiguous signal that indeed plays a primary role in the way the retrieval of information is impaired.

Observations from ambiguity simulations in staggered SAR and waveform-encoded SAR, i.e., a SAR with pulse-to-pulse waveform variation, where the ambiguous signal is smeared and appears as a noise-like disturbance rather than as an ensemble of focused artifacts (**Figure 3**), suggest that ambiguous signals with the same energy but with different standard deviations might have very different effects on the retrieval of the some parameters for some specific applications [6]-[7], [11]-[13].

It is therefore of paramount importance to understand in detail how the ambiguity statistics influence the retrieval of information for different applications and design the system accordingly [14].

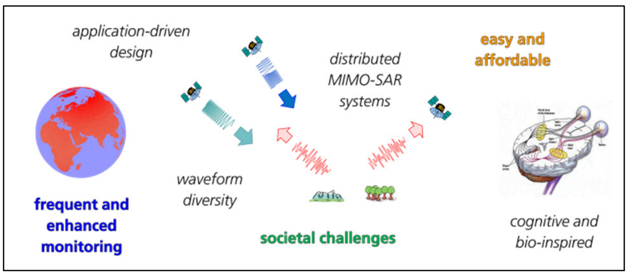
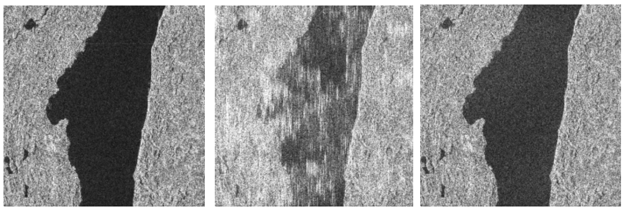


Figure 2 Principles and goals of NewSpace SAR.



(a) (b) (c)

Figure 3 Range ambiguity smearing and suppression as a result of waveform variation (from [11]). (a) Reference, ambiguity-free image. (b) Image corrupted by strong range ambiguities for a conventional SAR. (c) Image corrupted by the same range ambiguities as (b) for a SAR with waveform variation.

3.2 A novel azimuth phase code for range ambiguity smearing and suppression

Range ambiguity smearing is inherently achieved through PRI variation (staggered SAR) or waveform alternation. An additional option for obtaining range ambiguity smearing in a SAR with constant PRI that always transmits the same waveform is the exploitation of azimuth phase coding. While in the original idea proposed in [15], azimuth phase codes are exploited to generate a phase modulation, which results in a Doppler frequency shift of the ambiguous signal, here a novel phase code is proposed, which compensates for the quadratic component of the Doppler modulation of the range ambiguities. In this way, the ambiguous signal for a point-like target has a single Doppler frequency component in the raw data and is smeared in the azimuth direction over the extent of the synthetic aperture in the focused SAR image.

Azimuth phase coding consists of applying a phase shift $\phi[n]$ to the n-th transmitted pulse, which is then compensated when processing the received raw data by multiplying the range line corresponding to the n-th pulse by $\exp(-j\phi[n])$. This removes the introduced phase shift for the useful signal, but leaves a residual phase modulation for range ambiguous echoes, as they correspond to different transmitted pulses. As a result, the range ambiguous signals are therefore modulated by a residual phase sequence $\phi_R[n] = \phi[n+\rho] - \phi[n]$, where ρ is the order of the range ambiguous echo.

The novel proposed phase code $\phi[n]$ is built from the periodic sequence $\phi_R[n]$ of residual phases defined by

$$\phi_R[n] = \frac{4\pi}{\lambda} R_A(t[n]), \qquad -N \leq n < N \tag{1}$$

where λ is the wavelength, $R_A(t)$ is the range variation as a function of azimuth (slow) time for the ambiguous target, $t[n]$ is the time of transmission of the n-th pulse and N is defined as the maximum value n such that $\phi_R[n] - \phi_R[n-1] \in [0, \pi]$, for $0 < n \leq N$. In other words, the residual phase $\phi_R[n]$ follows the Doppler phase modulation of the ambiguous target, while its instantaneous frequency $|f_{inst}| \leq PRF/2$. For this reason, this phase code is denoted as "Doppler-matched" phase code. **Figure 4** provides an illustration of the residual phase.

The phase code is therefore obtained from the following recursive relation

$$\phi[n+\rho] = \phi_R[n] + \phi[n] \tag{2}$$

The resulting phase of a range ambiguous target in the raw data is given by

$$-\frac{4\pi}{\lambda} R_A(t[n]-t_A) - \phi_R[n] \tag{3}$$

where t_A is time of closest approach. The two "quadratic" terms in (3) cancel out leaving only a concatenation of linear phases, as shown in **Figure 5**. Each phase ramp is characterized by an instantaneous frequency given by

$$f_{A,k} = \frac{2}{\lambda}\frac{v^2}{R_A(0)}\left(t_A - k\frac{2N}{PRF}\right), \qquad k \in \mathbb{Z} \tag{4}$$

where k is an index indicating the period of the residual phase sequence to which the frequency itself corresponds. The contribution of this point-like target to the focused image will therefore also be as a concatenation of single frequency tones, but the amplitude of each tone will be scaled according to the value at its frequency of the Doppler frequency windows applied in the focusing of the SAR image. The target will therefore appear smeared in azimuth over the extent of the synthetic aperture (**Figure 6**).

Moreover, the relation in (4) between the frequencies of the tones and the azimuth position of the ambiguous target will imply that the ambiguous targets will be selectively attenuated according to their position in azimuth, if a processed bandwidth smaller than PRF or a processing window in azimuth is applied to the data.

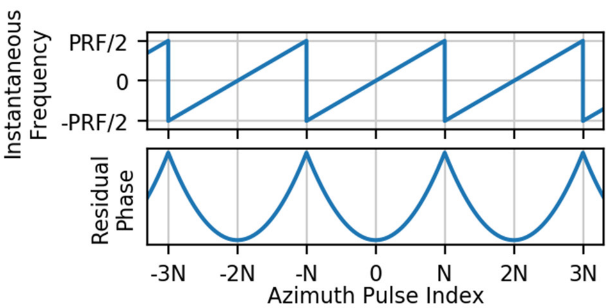


Figure 4 Instantaneous frequency and residual phase for the proposed Doppler-matched phase code.

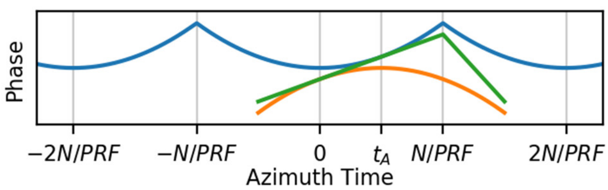


Figure 5 Residual phase of the phase code (blue), phase of the raw data from a range ambiguous point-like target without the use of azimuth phase coding (orange) and after the phase demodulation with the use of Doppler matched azimuth phase coding (green).

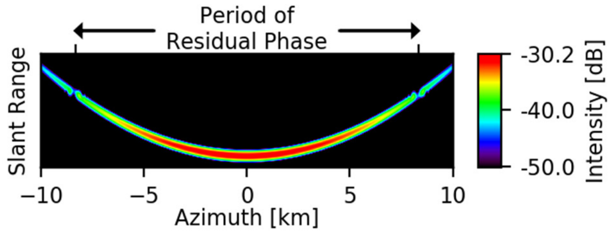


Figure 6 Example of impulse response of a range ambiguous target for the Doppler-matched azimuth phase coding. A slant range extension of 100 m is shown.

Since pointwise multiplication in the time domain is equivalent to convolution in the frequency domain, this modulation by the residual phase of the Doppler matched phase code can be seen as a matched filter in the frequency domain that compresses the Doppler spectrum of the ambiguous signal to a certain frequency, which is dependent on the azimuth position of the target. From this point of view, if one looks at the range-compressed data, after the phase code demodulation, in the range-Doppler domain, one should see the ambiguous scene almost completely focused. **Figure 7** shows an example of ambiguity smearing provided by Doppler-matched azimuth phase coding though a simulation based on real TerraSAR-X data.

The concept of a Doppler-matched azimuth phase code can be extended by applying a further alternated $[0,\pi]$ phase modulation, which shifts the tones in the Doppler frequency by PRF/2 for first order ambiguities.

Furthermore, the implementation with rounded phases, using e.g., only 8 different phases, still leads to very similar performance.

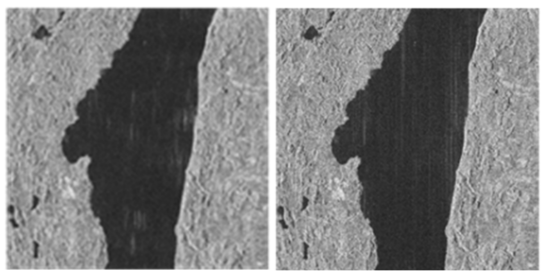


Figure 7 Simulation of range ambiguities appearing on a lake for conventional SAR (left) and the novel concept of Doppler-matched azimuth phase coding (right).

3.3 Experimental validation of nadir echo suppression through waveform encoding and dual-focus postprocessing

Besides range and azimuth ambiguities 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 allow designing a SAR system without the

nadir interference constraint and removing (not only smearing) the nadir echoes by means appropriate post-processing [10].
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.
A validation of this technique through a dedicated TerraSAR-X experiment with up- and down- chirp alternation is currently being performed. 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 (**Figure 8**). **Figure 9** shows the range-compressed data matched to the useful signal with the nadir echo smeared in the range direction (mostly visible in the areas highlighted by the red rectangles), the range-compressed data matched to the nadir echo, which is now well focused, and finally the range-compressed data after blanking of the nadir echo, inverse focusing and refocusing matched to the useful signal, where the nadir echo has been significantly suppressed [16].

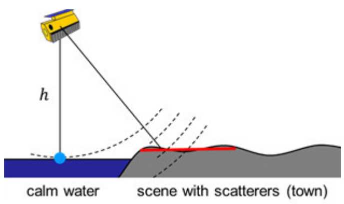
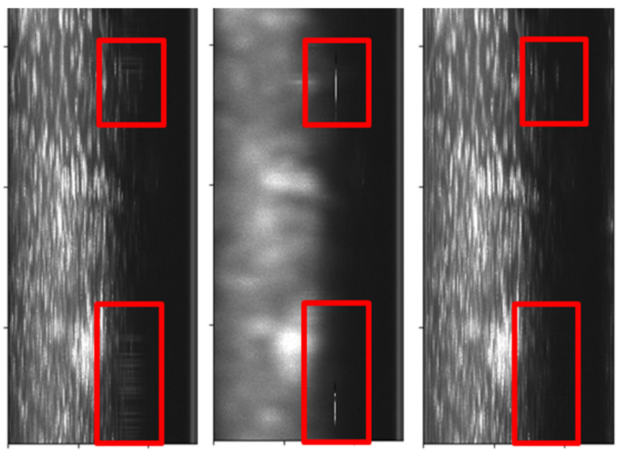


Figure 8 Schematic representation of the scene selected for the TerraSAR-X experiment for validation of nadir echo suppression.



(a) (b) (c)

Figure 9 Range compressed data (a) matched to the useful signal, (b) matched to the nadir echo, (c) after dual-focus postprocessing. The red rectangles highlight areas where the nadir echo is visible/has been suppressed.

3.4 Exploitation of small satellites for SAR

In the context of NewSpace SAR it is also of interest to understand how small satellites with severely constrained power and antenna size can be exploited for SAR.
One possibility is to assess the worst performance, which can be tolerated for a dedicated application, and design a 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 SAR system to monitor illegal fishing and land deformation [17]-[18].
Further investigations show that a X-band SAR system with an antenna of 2 m × 0.4 m and an average transmit power of about 15 W might be sufficient to detect medium or even small ships with a low false alarm rate. **Figure 10** shows the requirements in terms of noise-equivalent sigma zero (NESZ) and SAR image resolution to detect a ship of 30 m × 7 m with a false alarm rate of 10^{-10} and detection probabilities of 0,5 (green curve), 0.7 (blue curve), and 0.9 (red curve). A peculiarity of the proposed design example is that a PRF much smaller than the nominal Doppler bandwidth is used to map a wide swath and that azimuth ambiguities are exploited to further improve the detection performance [19].

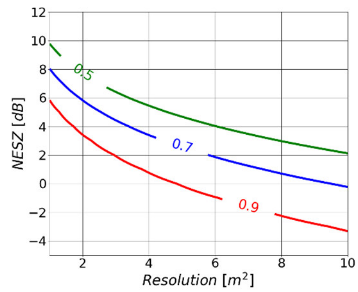


Figure 10 Requirements in terms of NESZ and resolution to detect a ship of 30 m × 7 m with a false alarm rate of 10^{-10} and detection probabilities of 0.5 (green curve), 0.7 (blue curve), and 0.9 (red curve).

While on the one hand small satellite could be employed for dedicated applications, where low SNR and ambiguities are not critical, on the other hand image quality comparable to that of current 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 [20]-[21]. This allows reaching satisfactory NESZ levels with low power onboard the individual satellites. 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. In December 2020, Germany has approved the next X-band spaceborne mission which consists 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 are based on a fractionated concept for a space transponder and represents an innovative, low-cost approach to boost the performance of already existing full-fledged SAR systems [22].

4 Conclusions

This work introduces NewSpace SAR as the ensemble of disruptive solutions that allow cost-effective SAR system design. Novel techniques are discussed that exploit waveform and phase encoding, also in combination with post-processing of the acquired data, in order to suppress nadir echoes ambiguities and smear ambiguities. Finally, the exploitation of small satellites for SAR is discussed, both as single satellites for dedicated applications and as formations for imaging and interferometry.

5 Literature

[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. Moreira et al., "Tandem-L: A highly innovative bistatic SAR mission for global observation of dynamic processes on the Earth's surface," *IEEE Geosci. Remote Sens. Mag.*, vol. 3, no. 2, pp. 8–23, Jun. 2015.

[4] S. Huber et al., "Tandem-L: A Technical Perspective on Future Spaceborne SAR Sensors for Earth Observation," *IEEE Trans. Geosci. Rem. Sens.*, vol. 56, no. 8, pp. 4792-4807, Aug. 2018.

[5] 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.

[6] 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.

[7] M. Villano, "Staggered Synthetic Aperture Radar," PhD Thesis, Karlsruhe Institute of Technology, DLR-Forschungsbericht 2016-16, ISSN 1434-8454, Wessling, Germany, 2016.

[8] M. Villano, G. Krieger, A. Moreira, "Onboard Processing for Data Volume Reduction in High-Resolution Wide-Swath SAR," *IEEE Geosci. Rem. Sens. Lett.*, vol. 13, no. 8, pp. 1173-1177, Aug. 2016

[9] M. Villano et al., "Gapless imaging with the NASA-ISRO SAR (NISAR) mission: Challenges and opportunities of staggered SAR," *Proc. European Conference on Synthetic Aperture Radar (EUSAR)*, Aachen, Germany, 5-7 June 2018.

[10] 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.

[11] 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.

[12] 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.

[13] L. Dell'Amore, M. Villano, and G. Krieger, "Assessment of Image Quality of Waveform-Encoded Synthetic Aperture Radar Using Real Satellite Data," Proc. *International Radar Symposium 2019*, Ulm, Germany, 26-28 June 2019.

[14] N. Ustalli and M. Villano, "Impact of Ambiguity Statistics on Information Retrieval for Conventional and Novel SAR Modes," *Proc. IEEE 2020 Radar Conference*, Florence, Italy, 21-25 September 2020.

[15] J. Dall and A. Kusk, "Azimuth phase coding for range ambiguity suppression in SAR," *in IEEE Int. Geosci. Rem. Sens. Symp. IGARSS 2004*, vol. 3, pp. 1734–1737.

[16] S.-Y. Jeon et al, "A TerraSAR-X Experiment for Validation of Nadir Echo Suppression through Waveform Encoding and Dual-Focus Post-Processing", *European Conference on Synthetic Aperture Radar (EUSAR) 2021*, accepted.

[17] J. Krecke et al., "Design of SmallSat SAR for Dedicated New Zealand Applications", *European Conference on Synthetic Aperture Radar (EUSAR) 2021*, accepted.

[18] J. Krecke et al., "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*, in review.

[19] 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*, submitted.

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

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

[22] J. Mittermayer et al., "A MirrorSAR Case Study Based on the X-Band High Resolution Wide Swath Satellite (HRWS)", *European Conference on Synthetic Aperture Radar (EUSAR) 2021*, accepted.