Staggered SAR: Recent Advances and Design Trade-Offs

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Abstract

Staggered synthetic aperture radar (SAR) is an established concept for high-resolution wide-swath SAR imaging based on multiple elevation beams and continuous variation of the pulse repetition interval (PRI) that is the baseline acquisition mode for the Tandem-L mission proposal and an attractive solution for the NISAR mission and further future SAR missions for frequent global monitoring. Significant developments in the staggered SAR theory have been recently made concerning the characterization of nadir echo and its suppression through processing, the understanding of the advantages of uncorrelated ambiguities for interferometry, the reduction of the data volume to be downlinked, and the simultaneous operation in single-/dual- and quad-pol mode. This paper reviews these advances and discusses some design trade-offs.

1 Introduction

Synthetic aperture radar (SAR) is a remote sensing technique, capable of providing high-resolution images independent of weather conditions and sunlight illumination. This makes SAR very attractive for the systematic observation of dynamic processes on the Earth's surface [1]. However, conventional SAR systems are limited, in that a wide swath can only be mapped at the expense of a degraded azimuth resolution, i.e., by reducing the pulse repetition frequency (PRF). This limitation can be overcome by using systems with multiple receive apertures, displaced in along-track, which simultaneously acquire multiple samples for each transmitted pulse [2]-[6]. These systems, however, require a very long antenna to map a wide swath.

If a relatively short antenna with a single aperture in along-track is available, an attractive solution to map a wide swath is given by SAR systems that exploit a wide beam illuminator on transmit and digital beamforming (DBF) in elevation to form multiple receive beams, which follow the directions of arrival of the radar echoes of multiple transmitted pulses and can therefore simultaneously image multiple subswaths [7]-[8]. A drawback of these systems is the presence of "blind ranges" between the multiple imaged subswaths, as the radar cannot receive while it is transmitting. However, if such systems are operated in staggered SAR mode, i.e., if the pulse repetition interval (PRI) is continuously varied and data are sufficiently oversampled in azimuth, it is possible to get rid of blind ranges and map a wide continuous swath [9]-[12]. The staggered SAR concept is the baseline acquisition mode for Tandem-L, a proposal for a polarimetric and interferometric spaceborne SAR mission to monitor dynamic processes on the Earth's surface with unprecedented accuracy and resolution, and as an attractive solution for the NASA-ISRO Synthetic Aperture Radar (NISAR) mission and further future SAR missions for frequent global monitoring [13]-[17].

The use of a variable PRI to image a large continuous swath has been first suggested in [18] and later independently discovered by DLR [7], while a robust and optimized concept of a staggered SAR, based on novel sequences of PRIs, interpolation methods, and processing strategies, which allow meeting outstanding ambiguity requirements with state-of-the-art antenna technology, is presented in [11], where onboard processing for data volume reduction is an integrating part of the staggered SAR concept [19].

Further advances, however, have been recently made that add to the staggered SAR theory and offer the system designer multiple implementation options. The aim of this paper is to review these advances and discuss some design trade-offs between these implementation options.

2 Ambiguities and nadir echoes

Staggered SAR operation has significant effects on ambiguities and nadir echoes, for which a dedicated analysis was carried out in [11]-[12]. In particular, the smeared nature of ambiguities is an important characteristic of staggered SAR. This section includes some further considerations and reports on some recent analyses and results concerning azimuth and range ambiguities, as well as nadir echoes.

2.1 Azimuth ambiguities

The azimuth ambiguity-to-signal ratio (AASR) is evaluated in staggered SAR from impulse response simulations as difference of integrated side-lobe ratios (ISLRs) and improves as the mean PRF of the system increases, where in general a moderate azimuth oversampling is required compared to a constant PRF SAR to achieve the same AASR performance and azimuth ambiguities appear as smeared [11]-[12].

As for the selection of the mean PRF, in case onboard processing for data volume reduction is performed, the mean PRF that minimizes the total ambiguity-to-signal ratio (ASR) should be selected, as the mean PRF has no

impact on the amount data to be downlinked [11]-[12]. However, if no data volume reduction is performed, it makes sense to choose the minimum mean PRF for which the ASR requirement is met.

Figure 1 shows the worst value of the AASR, the range ambiguity-to-signal ratio (RASR), and the ASR across the swath as a function of the mean PRF on transmit for an exemplary staggered SAR system presented in [11]. If onboard data volume reduction is performed, the mean PRF that minimizes the ASR, i.e., about 2600 Hz, has to be selected and a ASR better than -29 dB is achieved across the swath; however, if no onboard data volume reduction is foreseen and a minimum ASR of -25dB is required, it makes sense to select the minimum mean PRF that allows meeting this requirement, i.e., about 2100 Hz, as this choice would result in a data rate reduction of almost 20%.

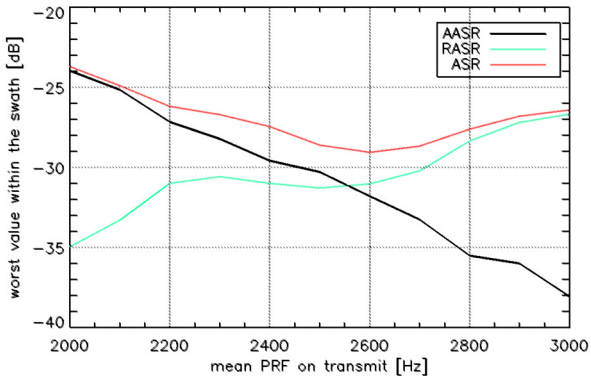
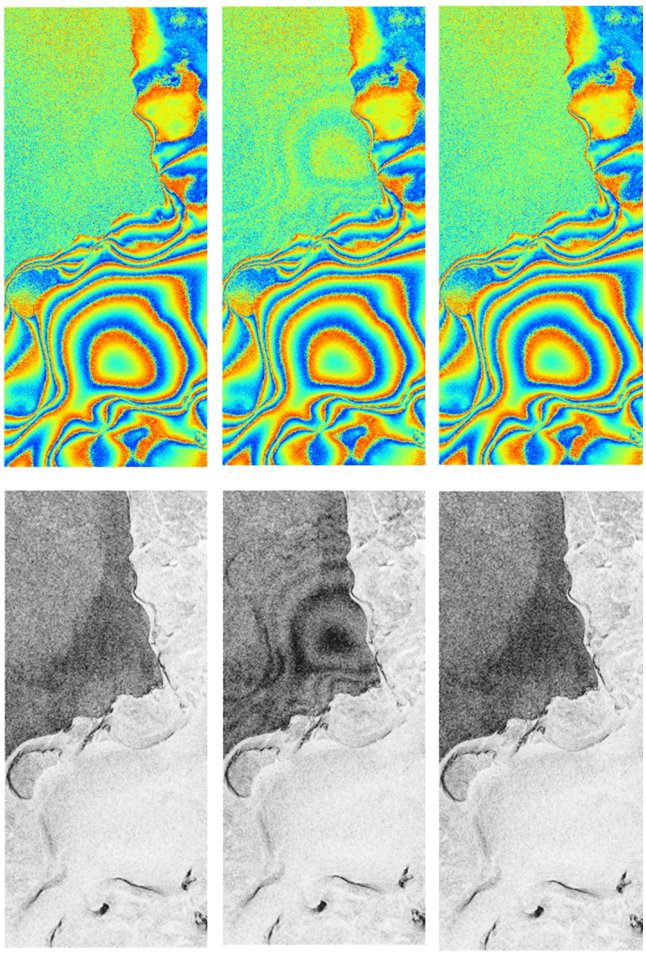


Figure 1 Worst value of the AASR, the RASR, and the ASR across the swath vs. mean PRF on transmit for an exemplary staggered SAR system (from [11])

If the data volume is further constrained and it is not possible to achieve the desired ASR in staggered SAR under that constraint, as discussed in the context of NISAR in [14]-[15], an attractive solution that might lead to a visible improvement of the image quality at the cost of an increased processing effort on ground is based on spectral estimation processing [21]-[22].

In case the acquired SAR images have to be exploited for interferometry, a major advantage of staggered SAR arises from the fact that azimuth ambiguities between the master and the slave images are uncorrelated. In [23] it was shown than coherent azimuth ambiguities might lead to phase biases and coherence modulations in the interferograms. Some preliminary results, using TanDEM-X interferograms, show through simulations that the biases and the coherence modulations are not visible for a staggered SAR system with the same AASR [24]. An example using a TanDEM-X interferogram acquired over the Franz Josef Land, Russia, is provided in **Figure 2**. This means that the AASR requirement for a staggered SAR system for interferometric applications can be significantly relaxed. The quantification and comparison of the corresponding requirement is subject of ongoing investigations.

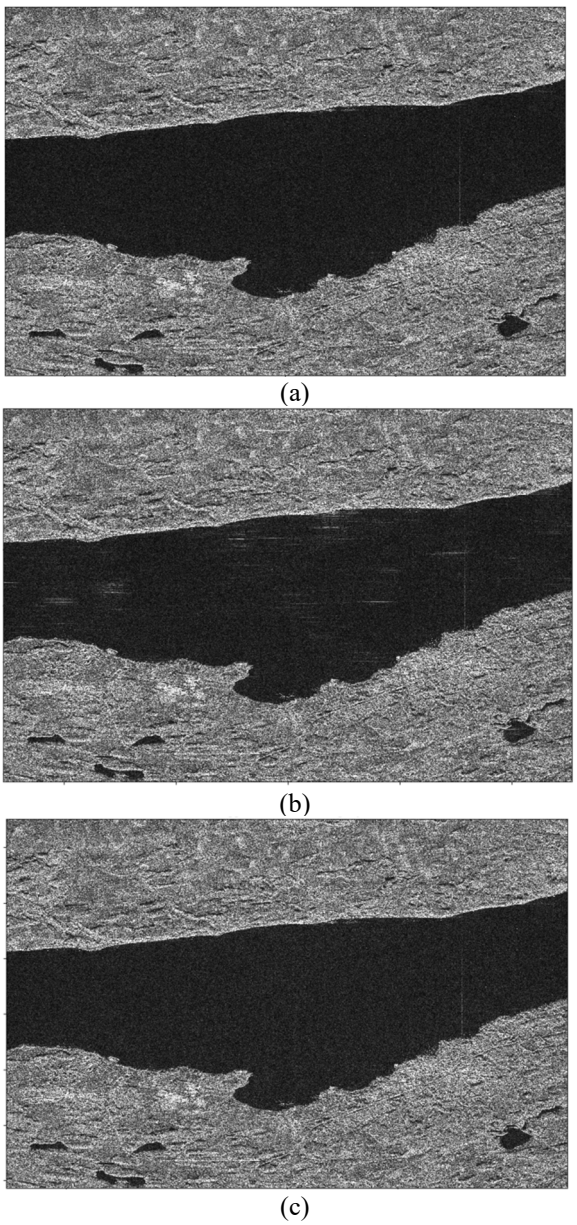


(a) (b) (c)

Figure 2 Interferometric phase (top) and coherence magnitude (bottom) of TanDEM-X interferogram acquired over the Franz Josef Land, Russia. (a) Ambiguity-free interferogram. (b) Interferogram affected by azimuth ambiguities for conventional stripmap mode (simulation). (c) Interferogram affected by azimuth ambiguities for staggered SAR operation mode with the same azimuth ambiguity-to-signal ratio (simulation). The horizontal and vertical axes represent the slant range and azimuth, respectively.

2.2 Range ambiguities

In a staggered SAR system not only azimuth ambiguities, but also range ambiguities appears smeared. While some examples of smeared azimuth ambiguities based on simulation using real backscatter scenes have been shown in [11]-[12], **Figure 3** shows how range ambiguities appear smeared in staggered SAR. The simulation has been performed using real TerraSAR-X data acquired over the Greater Munich Area, Germany and refers to the scenario where a city causes range ambiguities on a lake. While range ambiguities appear only slightly defocused for a conventional SAR with constant PRF, in a staggered SAR they resemble a noise-like disturbance.



(a)

(b)

(c)

Figure 3 Simulation of the smearing effect of range ambiguities in a staggered SAR using a real backscatter scene. (a) Reference image without range ambiguities. (b) Image contaminated by range ambiguities for a conventional SAR with constant PRF. (c) Image contaminated by range ambiguities for a staggered SAR assuming the same ambiguity strength (i.e., geometry, antenna pattern and backscatter) as in (b).

2.3 Nadir echoes

An inherent consequence of the pulsed operation of SAR is that the echoes of periodically transmitted pulses, propagating back from the nadir, i.e., the point with the closest distance to the radar, come back at the radar simultaneously with the echoes of interest. Although the radar antenna is designed to limit the energy transmitted to and received from the nadir direction, due to the smaller range and the specific characteristics of the scattering process (specular reflection), the nadir echo may be even stronger than the desired one and may therefore significantly affect the quality of the SAR image.

In a conventional SAR with constant PRF the nadir echoes line up on the same ranges and might corrupt the resulting SAR image, appearing as a bright stripe in the image itself. This is mitigated by selecting in the timing (or diamond) diagram a PRF for which neither transmit nor nadir interferences occur.

A drawback of staggered SAR is that, since blind ranges are different for each azimuth position, nadir echoes cannot be avoided by means of PRF selection and will indeed be present in the staggered SAR raw data.

Recent analyses show that the nadir echo will appear in staggered SAR at different ranges in the range-compressed data – a detailed mathematical analysis is presented in [25], will be consequently smeared over azimuth after SAR focusing, and will not appear as a single bright stripe as in a conventional SAR.

A simulation based on the same TerraSAR-X data used in Section 2.2 and on a nadir echo model derived from a dedicated TerraSAR-X acquisition shows in **Figure 3** the reference focused image for staggered SAR without nadir echo contribution and the focused images for both a constant PRI SAR, whose PRI is equal to the mean PRI of the staggered SAR, and a staggered SAR. In the latter image the smeared nadir echo is barely visible even on the dark background (lake) [25].

Moreover, in case onboard processing is not performed, the nadir echo signal can be suppressed within the processing [25]. In the range-compressed data, in fact, it is possible to identify the samples corrupted by the nadir echo and substituting them with values obtained from interpolation of neighboring azimuth samples, i.e., exploiting the correlation among neighboring azimuth samples intrinsic in staggered SAR data.

3 Data volume reduction

The azimuth oversampling required to achieve an acceptable AASR is one of the main drawbacks of the staggered SAR concept. This implies on the one hand that a higher antenna is needed to suppress the increased range ambiguities, but this is not a severe problem as range ambiguities appears smeared and part of their energy is removed when processing a smaller Doppler bandwidth [12], and on the other hand that strategies have to be devised to reduce the amount of data onboard prior to downlink.

The work in [19], which has to be considered as an integrating part of the staggered SAR concept presented in [11], presents a simple scheme to perform the resampling to a regular grid onboard and downsample the data after having applied a low-pass (or band-pass) finite impulse response (FIR) filter.

While the idea is apparently simple, the implementation is challenging mainly due the need for saving at least 15 range lines and the memory limitations of the space-qualified hardware. In this sense a clever implementation based on partial summing is presented in [26], which re-

ports on a project for the development of a prototype for staggered SAR onboard processing.
An additional option is to perform a predictive quantization as proposed in [27]-[29]. This implementation allows for a limited data volume reduction compared to the aforementioned approach, but also requires a reduced memory and computational effort onboard and does not prevent further post-processing of the acquired data, e.g., for nadir echo removal.

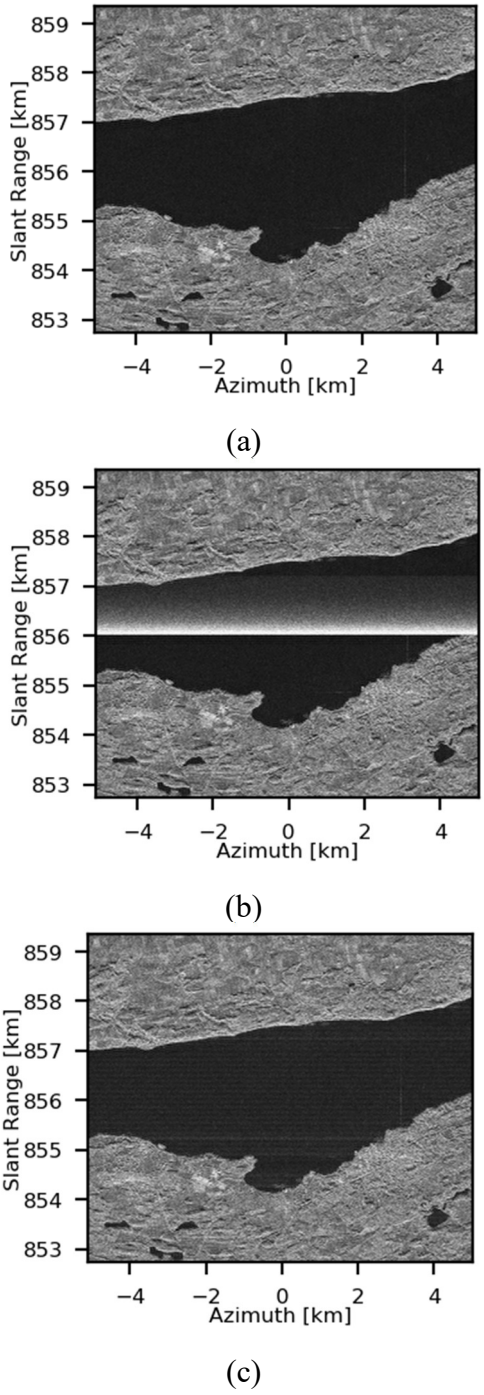


Figure 4 Focused images for a reference without nadir echo contribution (a), and for a constant PRI SAR (b) and a staggered SAR (c) with a strong nadir echo contribution (from [25]).

4 Hybrid quad-pol SAR and simultaneous single-/dual-pol and quad-pol imaging

The staggered SAR concept is compatible with quad-polarimetric (quad-pol) operation, although due to severe ambiguity constraints, the achievable swath in quad-pol mode is narrower than in single- (or dual-) pol mode.
As shown in [30], due to the continuous PRI variation staggered SAR cannot benefit of the cross-pol ambiguity cancellation that occurs for constant PRF system in case right and left circular polarizations are alternated on transmit (hybrid quad-pol SAR), therefore the alternation of linear horizontal and vertical transmit polarizations have to be preferred for quad-pol staggered SAR.
Furthermore, a novel SAR acquisition mode, based on pulse-to-pulse alternation of the antenna pattern on transmit is proposed in [31], that delivers at the same time single- (or dual-) pol data over a wider swath and quad-pol data over a narrower swath at the expense of an acceptable degradation of the ambiguity performance. A schematic representation is shown in **Figure 5**.

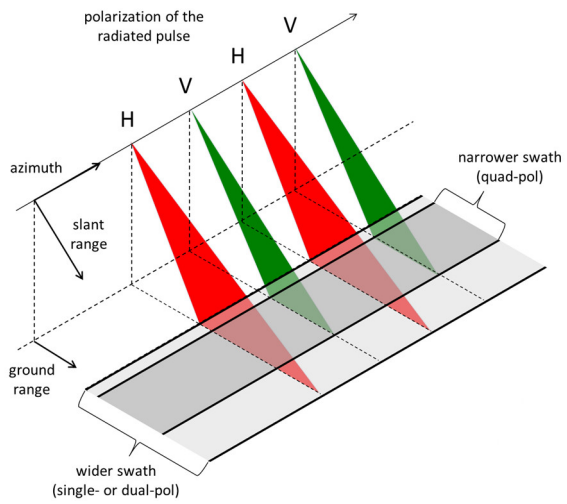


Figure 5 Schematic representation of the novel imaging mode, which allows simultaneous single- (or dual-) pol and quad-pol SAR imaging over swaths of different widths by alternating from pulse to pulse not only the polarization of the radiated pulse, but also the antenna pattern on transmit (from [31]).

5 Conclusion

This paper reviews the recent advances concerning ambiguities and nadir echoes, option for onboard and on-ground processing that offer the system designer multiple implementation options for staggered SAR. Some design trade-offs are discussed to help understanding which implementation has to be preferred in different scenarios. Finally, the considerations drawn in this paper suggest that even conventional SAR systems without digital beamforming could benefit from a (slight) PRI variation

to better mitigate the effects of ambiguities. This is particularly relevant, if the systems are exploited for interferometric applications.

6 Literature

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