A TerraSAR-X Experiment for Validation of Nadir Echo Suppression through Waveform Encoding and Dual-Focus Post-Processing

Se-Yeon Jeon, Ulrich Steinbrecher, Michelangelo Villano, and Gerhard Krieger
German Aerospace Center (DLR), Microwaves and Radar Institute, Wessling, Germany

Abstract

Synthetic aperture radar (SAR) is a powerful remote sensing technique providing high-resolution images of Earth's surface. The pulsed operation of SAR may cause nadir echoes in SAR images which significantly affect the image quality. The selection of pulse repetition frequency (PRF) in the design of conventional spaceborne SAR systems is constrained to avoid the nadir interference. As this leads to the limitation of SAR performances such as the swath width and the ambiguities, a novel concept for nadir echo suppression using waveform encoding and dual-focus post-processing has been proposed to alleviate the constraint in PRF selection. This technique improves the image quality and the flexibility of SAR system design. This work analyses this concept with more realistic simulation and validates it with a TerraSAR-X experiment.

1 Introduction

Synthetic aperture radar (SAR) is a technique that provides high resolution images for remote sensing regardless of sunlight and weather conditions.

The pulsed operation of SAR leads to the simultaneous return of the echoes reflected from the point with shortest range from the radar and the echoes from the desired scene by transmission of subsequent pulses. The nadir echo may significantly affect the SAR image quality with the stronger intensity than desired, because of the short distance and specular reflection. The nadir echo is typically seen as a bright stripe in the SAR image as shown in Figure 1.

The nadir interference in SAR images is avoided by proper selection of the pulse repetition frequency (PRF) in the design of conventional spaceborne SAR systems. The timing diagram of a SAR system for PRF selection is shown in Figure 2. The blue areas represent the blind ground ranges which cannot be imaged due to the transmit interference, while the green areas represent ground ranges where nadir interference is present in the imaged scene. The imaged swath are determined corresponding to the given PRF as the red lines shown in Figure 2 to avoid the transmit and nadir interferences. The PRF is therefore selected for the desired range swath to be imaged without transmit and nadir interferences.

The constraint on the PRF selection additionally imposed by the nadir echoes limits the SAR system performances in both swath width and the ambiguities. Therefore, nadir echo suppression can alleviate the constraint on the PRF selection so that given requirements can be achieved without increasing the system complexity or the size of the antenna.

To relieve the constraint on the PRF selection imposed by the nadir interference, an innovative concept using waveform-encoding and dual-focus post-processing for nadir echo suppression was proposed in [1]. This method exploits pulse-to-pulse waveform variation on transmit, and different matched filters in post-processing for nadir echo removal. This idea can be also exploited for range ambiguity suppression [2], [3].

This paper presents more realistic simulation of the proposed concept and a validation using a TerraSAR-X experiment. The nadir echo appearing in the acquired SAR image can be in fact suppressed through waveform encoding and dual-focus post-processing.

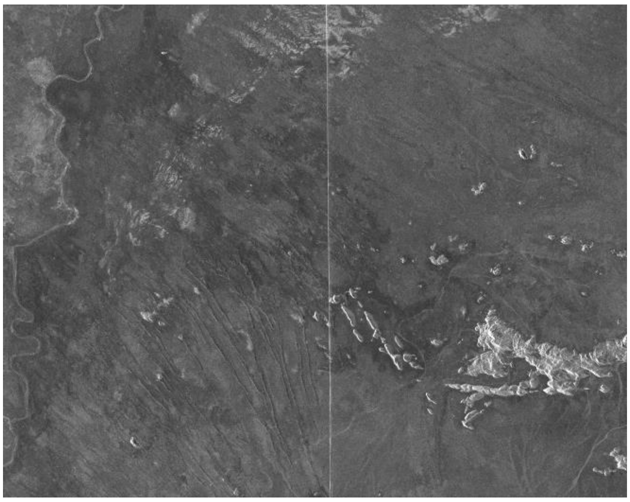

Figure 1 TerraSAR-X image over Australia as an example of nadir echo in a SAR image, where the horizontal and vertical axes represent slant range and azimuth, respectively. The nadir echo, a bright vertical line, appears in the middle of the image.

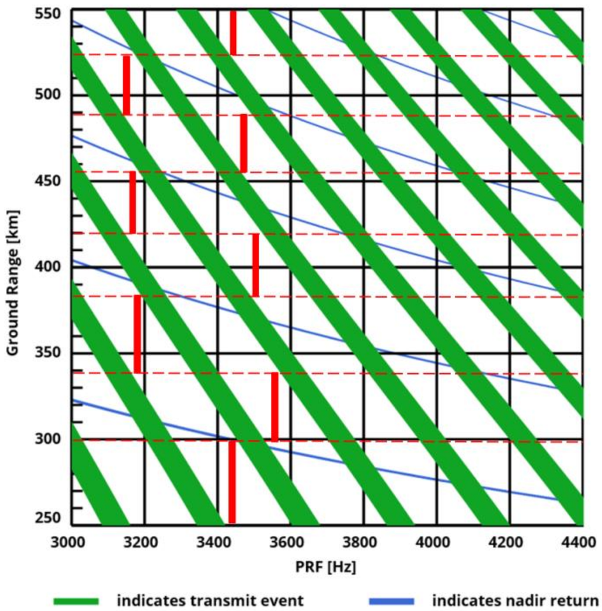

Figure 2 Timing diagram for PRF selection of conventional SAR. The green and blue areas are transmit and nadir interferences, respectively, while the red lines indicate possible swaths that avoid transmit and nadir interferences.

2 Waveform-Encoded SAR Concept

The nadir echo of a consecutive transmitted pulse can be smeared after operating the pulse or range compression if different "orthogonal" waveforms are used for the two transmitted pulses such as the up and down chirp alternation shown in [4].

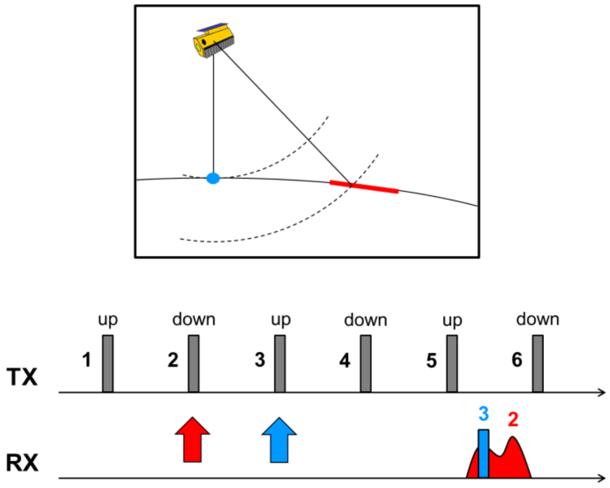

Figure 3 Waveform variation scheme, and superposition of nadir echo (blue) and useful signal (red) in the received signal.

The waveform variation scheme, the resulting nadir echo and the echo of interest are shown in Figure 3. The nadir echo is less visible, however, still appears as a background noise which may interfere with retrieving information from SAR images. By applying a further technique allowed by the waveform-encoding, i.e., the dual-focus post-processing, the nadir echo is not only smeared but can be removed.

The processing steps of a dual-focus post-processing for waveform-encoded SAR system to suppress the nadir echoes are shown as a block diagram in Figure 4. By applying a filter matched to the nadir echo on the SAR raw data, the nadir echoes are focused on a certain range while the useful signal is smear over the ranges. The focused nadir echo can be removed without significant degradation of the useful signal. The removal of the focused nadir echo is performed by simply replacing the pixel values into zeros. The location of nadir echo can be found either by determination from the PRF, the orbit information, and a digital elevation model (DEM) of the scene, or by application of an adaptive threshold. The data which nadir echoes have been removed are inverse focused back into raw data and then focused with a filter matched to the useful signal.

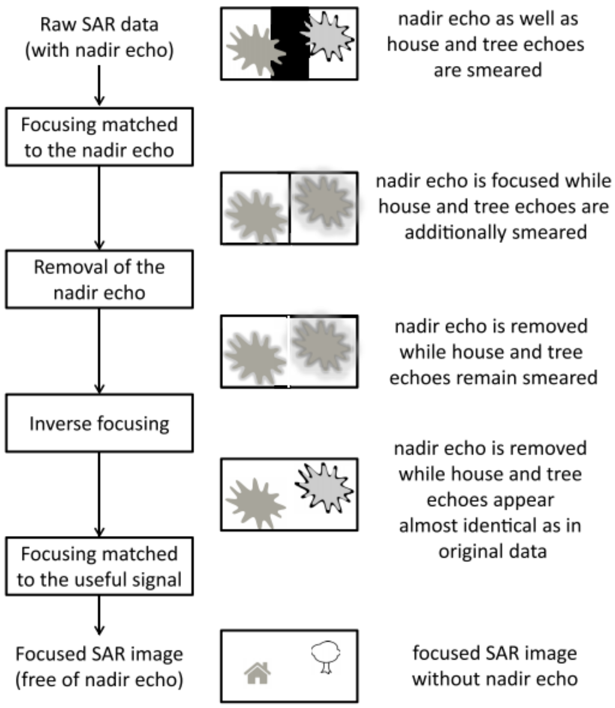

Figure 4 Block diagram of dual-focus post-processing steps of waveform-encoded SAR for nadir echo suppression.

2.1 Frequency-Dependent Non-Uniform Sampling Due to Up and Down Chirp Alternation

The up and down chirp alternation used for the waveform variation causes an additional frequency-dependent non-uniform sampling for every range frequency except for the center frequency as depicted in Figure 5. This leads to additional azimuth ambiguities as shown in Figure 6. Variable filters for each range frequency can be introduced to correct the non-uniform sampling in a similar way as the multichannel reconstruction (MCR) processing proposed in [5], [6]. The correction of non-uniform sampling is performed in two-dimentional (2D) frequency domain, while MCR is the usually applied in the range-Doppler domain, if the non-uniform sampling is not frequency-dependent.

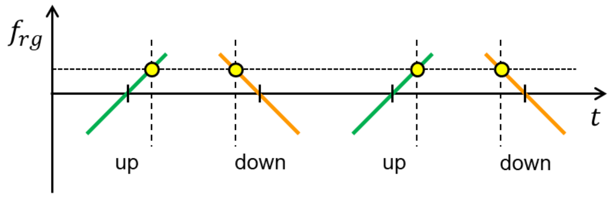

Figure 5 Non-uniform sampling caused by using up and down chirp alternation for waveform variation.

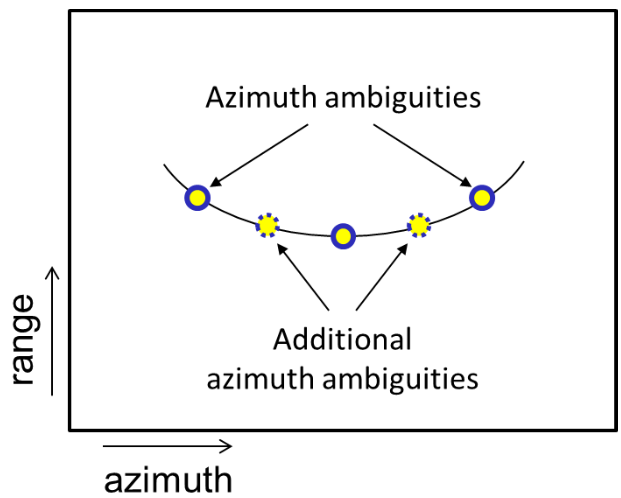

Figure 6 Additional azimuth ambiguities caused by frequency-dependent nonuniform sampling.

3 Simulation Analysis

A preliminary analysis of the technique is made with simulated SAR data prior to the experiment. A TerraSAR-X image is used as the complex backscatter map to generate raw data. The raw data for both the cases without and with waveform variation are generated as if they were acquired by a SAR system with the parameters listed in Table 1. The raw data and the focused images will be shown in the final paper.

Nadir echo is then introduced to the SAR images using a nadir echo model derived from real TerraSAR-X data [Maxwell's]. Nadir echoes are smeared in the focused image of waveform-encoded SAR, and are further suppressed through the dual-focus post-processing.
The frequency-dependent MCR correction is applied in the 2D frequency domain to correct the additional azimuth ambiguities before performing the dual-focus post-processing.

4 TerraSAR-X Experiments

4.1 Experimental Setup

An experiment was executed to validate the proposed technique by operating TerraSAR-X to acquire real SAR data. The scene was selected considering the scenario in which the nadir echo appears in the image to show that nadir echoes can be suppressed through waveform-encoding and dual-focus post-processing. The scene includes nadir on calm water surface and strong scatters such as town in the swath as illustrated in **Figure 7**. TerraSAR-X data was acquired over an area that satisfies this property, Tianjin, China, on 20th July, 2019. The detailed geometry of SAR data acquisition is described in **Figure 8**. The red line indicates the imaged ground swath ranging from 207 km to 224 km.

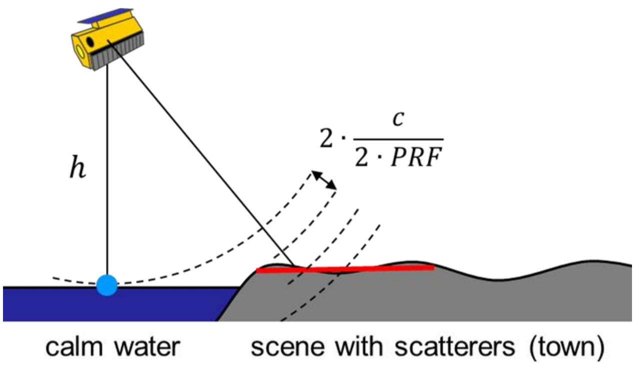

Figure 7 Properties of the selected scene.

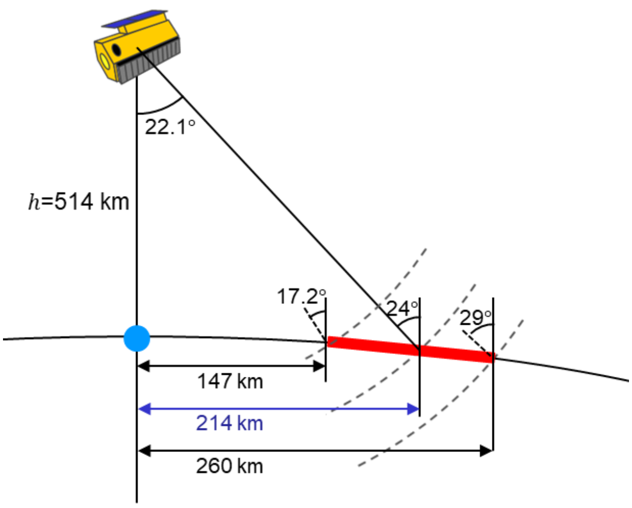

Figure 8 Geometry of SAR image acquisition.

The system parameters of TerraSAR-X for the experiment are provided in Table 1. The waveform variation during the experiment was arranged as shown in Figure 9, i.e., alternatively three up chirps and a down chirp, to acquire an interleaved reference image with the same parameter, geometry, and scene to the waveform-encoded SAR image for comparison. The PRF of TerraSAR-X is therefore twice the PRF of each image to be processed.

Parameter	Value
Frequency	9.65 GHz
Orbit height	513 km
Chirp bandwidth	100 MHz
Chirp duration	15 µs
PRF	6616 Hz
Incident angle	23.7° – 25.4°
Ground range of nadir echo	214 km

Table 1 Experimental parameters.

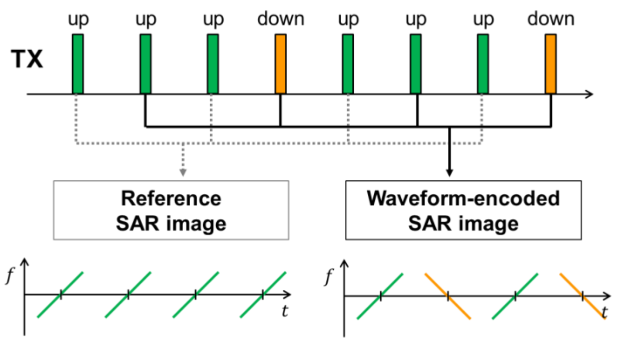

Figure 9 Waveform variation scheme for the experimental validation with TerraSAR-X.

4.2 Results

The acquired TerraSAR-X data with the parameters in Table 1 and their focused images are currently being processed. In particular, MCR correction and dual-focus post-processing will be applied. The results will be shown in the final paper.

5 Conclusion

The novel SAR technique using waveform-encoding and dual-focus post-processing for nadir echo suppression has been validated with a TerraSAR-X experiment. Through a preliminary analysis with simulated data and the results from TerraSAR-X data, it has been shown that the proposed technique can effectively suppresse the nadir echo. Moreover, the additional azimuth ambiguity caused by the non-uniform sampling when using up and down chirp alternation as waveform variation can be corrected by applying variable filters over range frequencies in the 2D frequency domain. The waveform-encoded dual-focus post-processing technique provides benefits to the SAR system design in terms of design flexibility with less limitation on PRF selection with a simple variation of transmitted waveforms.

6 Literature

[1] M. Villano, G. Krieger, and A. Moreira, “Nadir Echo Removal in Synthetic Aperture Radar via Waveform Diversity and Dual-Focus Postprocessing,” *IEEE Geosci. Remote Sens. Lett.*, vol. 15, no. 5, pp. 719–723, May 2018.

[2] M. Villano, G. Krieger, and A. Moreira, “Waveform-Encoded SAR: A Novel Concept for Nadir Echo and Range Ambiguity Suppression,” in *EUSAR 2018; 12th European Conference on Synthetic Aperture Radar*, 2018, pp. 1–6.

[3] L. Dell’Amore, M. Villano, and G. Krieger, “Assessment of Image Quality of Waveform-Encoded Synthetic Aperture Radar Using Real Satellite Data,” in *2019 20th International Radar Symposium (IRS)*, 2019, pp. 1–10.

[4] J. Mittermayer and J. M. Martinez, “Analysis of range ambiguity suppression in SAR by up and down chirp modulation for point and distributed targets,” in *IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings (IEEE Cat. No.03CH37477)*, 2003, vol. 6, pp. 4077–4079 vol.6.

[5] G. Krieger, N. Gebert, and A. Moreira, “Unambiguous SAR Signal Reconstruction From Nonuniform Displaced Phase Center Sampling,” *IEEE Geosci. Remote Sens. Lett.*, vol. 1, no. 4, pp. 260–264, Oct. 2004.

[6] G. Krieger, N. Gebert, and A. Moreira, “SAR signal reconstruction from non-uniform displaced phase centre sampling,” in *Proc. IEEE Int. Geosci. and Remote Sens. Symp. (IGARSS)*, Anchorage, AK, USA, 2004, vol. 3, pp. 1763–1766.