Insights on Range Ambiguity Suppression based on Blind Source Separation in Multichannel SAR Systems

Ershad Junus Amin, Federica Bordoni, Gerhard Krieger, Marwan Younis, and Alberto Moreira
Deutsches Zentrum für Luft- und Raumfahrt (DLR), Münchener Str. 20, 82234 Wessling, Germany

Abstract

Addressing range ambiguity (RA) disturbance is crucial in high-resolution wide-swath spaceborne synthetic aperture radar (SAR) systems featuring multiple elevation beams. Recently, an innovative method to mitigate this issue using higher-order blind source separation (BSS), denoted as RABSS, has been proposed. In this paper, the advantages and drawbacks associated with RABSS are discussed in detail, providing further new insights on the method. The numerical analysis is based on realistic simulations employing TerraSAR-X image backscattering coefficients and incorporating the simulated antenna patterns of a large array-fed reflector antenna employing multiple elevation beams.

1 Introduction

In recent years, extensive research and development efforts have been dedicated to multichannel spaceborne synthetic aperture radar (SAR) systems equipped with digital beamforming (DBF) capabilities. This focus aims to resolve the trade-off between the extension of swath coverage and the spatial resolution encountered in traditional SAR systems. Noteworthy examples of these advanced high-resolution wide-swath (HRWS) SAR systems include the U.S.-Indian NISAR, scheduled for launch in 2024, and the highly innovative German mission proposal, Tandem-L (TDL) [1], [2]. Both of these systems employ an array-fed reflector antenna to enable a multi-beam operational mode: during transmission (Tx), a wide beam effectively illuminates a broad swath, operating at a high pulse repetition frequency (PRF). During reception (Rx), multiple narrow elevation beams, utilizing the scan-on-receive (SCORE) DBF technique [3], collect the useful signals.

A significant challenge associated with a multi-beam operational mode lies in the mitigation of range ambiguities (Fig. 1). In fact, the range ambiguities cannot be attenuated by the Tx pattern, as in a conventional case, since the useful signal for one Rx beam represents a range ambiguity for another beam [4]. In theory, a precise knowledge of the antenna pattern could enable the suppression of ambiguities. However, in practice, this proves to be a challenging task, especially for large reflector antennas, since the accurate calibration of the pattern on the ground may be impractical, as mechanical deformations and thermal instabilities can substantially distort the nominal antenna pattern. Additionally, errors stemming from the Tx and Rx channels, mispointing, and inaccuracies in topographic height may further deteriorate the accuracy of pattern estimation [5], [6].

In [4], for the first time, the issue of range ambiguity suppression in multi-beam SAR systems is formulated as a cocktail party problem. Specifically, the antenna pattern estimation is expressed as a mixing matrix estimation, and a solution based on the blind source separation (BSS) technique is proposed. Starting from this idea, the first result of a novel, data-based, method, relying on the higher-order (HO) BSS, was presented in [7], [8] to suppress the range ambiguities (RA). The approach, here denoted as RABSS, is extended and analyzed in detail in [9]. A remarkable aspect of the RABSS method is that it does not require any prior knowledge of the actual antenna pattern, i.e., it estimates the mixing matrix directly from the acquired SAR

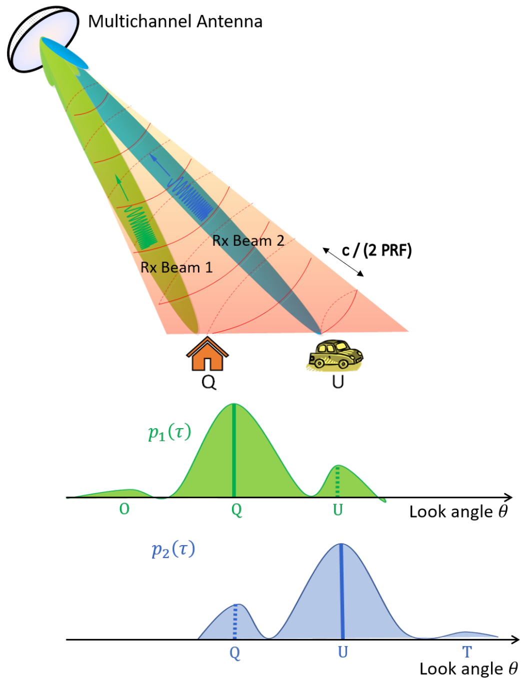

Figure 1 Zero-Doppler geometry. Two subswaths are imaged simultaneously by using a wide Tx beam and two narrow Rx beams, where $c/(2\,\mathrm{PRF})$ is the range ambiguity distance, c the speed of light.

data. Additionally, it does not affect the SAR instrument complexity, since it is applied on-ground to the downlinked data.

To date, the evaluation of the RABSS method [9] has primarily focused on a single scene, leaving uncertainty about its effectiveness across various scene types. This uncertainty stems from the inherent characteristics of the HO BSS technique, which performs optimally when handling signals with non-Gaussian statistics, as discussed in [10]. In this paper, the robustness of the RABSS method is assessed by exposing it to various scene types, offering new insights into its performance.

2 RABSS Method

Let's consider, without any loss of generality, the simplified scenario depicted in Fig. 1: A HRWS SAR system effectively covers the entire imaged swath at a high PRF using a broad Tx beam. On Rx, the system employs $N = 2$ narrow beams, applying the SCORE technique [1]-[3], to simultaneously gather echoes from N subswaths. Within the imaged surface, there are four distinct point-targets labeled as O, Q, U, and T, with separations corresponding to the range ambiguity distance. Specifically, Q and U are located in the first and second imaged subswaths, respectively, while O and T fall outside the imaged swath. Consequently, in the first beam, Q returns the signal of interest, while U generates a prominent range ambiguity. In the second beam, it is U that carries the useful signal, while Q produces a strong range ambiguity. O and T, on the other hand, produce weaker ambiguities. In this particular scenario, the instantaneous Rx signal can be expressed as follows [4] ,[8], [9]:

$$\mathbf{x}(\tau, f_t) = \mathbf{A}(\tau, f_t) \cdot \mathbf{s}(\tau, f_t) + \mathbf{s}_{WA}(\tau, f_t) + \mathbf{n}$$
$$\begin{bmatrix} x_1(\tau, f_t) \\ x_2(\tau, f_t) \end{bmatrix} = \begin{bmatrix} 1 & a_{12}(\tau, f_t) \\ a_{21}(\tau, f_t) & 1 \end{bmatrix} \cdot \begin{bmatrix} s_1(\tau, f_t) \\ s_2(\tau, f_t) \end{bmatrix} + \begin{bmatrix} s_{1,WA}(\tau, f_t) \\ s_{2,WA}(\tau, f_t) \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad (1)$$

where τ and f_t denote the range time and the azimuth frequency, respectively; $\mathbf{s}$ the useful signals; $\mathbf{s}_{WA}$ the weak ambiguity signals; $\mathbf{n}$ the additive noise; $\mathbf{A}$ the mixing matrix, with antidiagonal elements given by:

$$a_{12}(\tau, f_t) = \frac{p_1(\tau, f_t, \mathrm{U})}{p_2(\tau, f_t, \mathrm{U})}, \quad a_{21}(\tau, f_t) = \frac{p_2(\tau, f_t, \mathrm{Q})}{p_1(\tau, f_t, \mathrm{Q})}, \quad (2)$$

where p_j denotes the 2-way antenna pattern, used to image the j-th subswath ($j = 1, 2$), evaluated at the position of U or Q.

From (1) and (2), the useful signal can be estimated as:

$$\hat{\mathbf{s}} = \hat{\mathbf{B}}\mathbf{x}, \quad (3)$$

where $\hat{\mathbf{B}}$ denotes a proper estimate of the separation matrix, $\mathbf{B} \approx \mathbf{A}^{-1}$ the actual separation matrix, and the approximation is due to the presence of the weak ambiguities and the additive noise [4], [9].

It is important to emphasize that the useful signal refers to the signal that is free from any range ambiguities. Consequently, it becomes evident that obtaining an accurate estimate of this useful signal is equivalent to effectively mitigating range ambiguities. Additionally, the mathematical model highlights the significance of the mixing matrix, denoted as $\mathbf{A}$, or equivalently, the antenna pattern: any inaccuracies in estimating this mixing matrix can lead to an incorrect retrieval of the unambiguous signal, resulting in suboptimal range ambiguity suppression.

The challenge of estimating the useful SAR signal bears similarity to the well-known "cocktail party problem" in signal processing [4], [8], [9]. To tackle this "SAR cocktail party problem," a method based on higher-order (HO) blind source separation (BSS), referred to as the RABSS method, was introduced and analyzed in [9]. The choice of employing a higher-order approach is justified by its robustness against noise when compared to the second-order (SO) approach [11], [12].

3 Numerical Analysis

A reference DBF HRWS L-band SAR system, based on an array-fed reflector antenna, is considered in the following. Its key parameters are provided in Table 1. The system implements a multi-beam operational mode: a broad Tx beam, obtained by activating simultaneously all the feed elements, illuminates a swath on the ground of approximately 300 km; a PRF of 2700 Hz is chosen to achieve an azimuth resolution of 6 m; five narrow SCORE Rx beams, formed by activating and combining consecutive sets of feed elements, simultaneously collect the echo from five, mutually range ambiguous, subswaths. Accordingly, during the imaging process, the system receives four strong ambiguous echoes for each subswath. Moreover, two weak ambiguities are considered, originating from the near and far range, respectively.

Table 1 Reference System Parameters.

Parameter	Value
Orbit height	628 km
No. channels in elevation	35
Elevation tilt angle w.r.t. nadir	36 deg
Center frequency	1.26 GHz
PRF	2700 Hz
Chirp bandwidth	38 MHz
Processed Doppler bandwidth	1348 Hz

In order to assess the robustness of the RABSS method against various types of backscattering surfaces, nine L-band SAR data sets are simulated, each characterized by a different degree of scene homogeneity. The corresponding focused SAR images are shown in Fig. 2. To ensure the realism of the simulation, the L-band data are generated by using the Tandem-L (TDL) antenna patterns [1] and the actual backscattering coefficient of real SAR images, acquired by TerraSAR-X (TSX) [13].

Figure 3 illustrates the performance of the RABSS method in terms of RASR when directly applied to the nine distinct datasets. The results indicate that the RABSS method

[1] There is no continuity between subswaths due to the limited number of simulated samples. Therefore, a brightness jump may occur, as for instance in the middle-right of image (6).

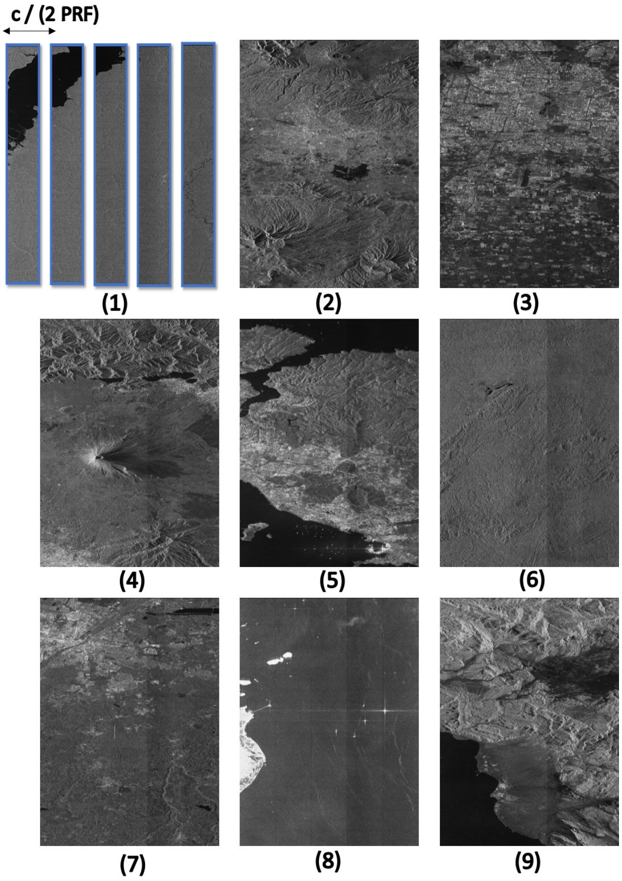

Figure 2 Simulated images for the large array-fed reflector SAR system, derived from a real TSX complex SAR image [13]. Each image is composed of five range-ambiguous subswaths[1], as highlighted in the scene (1). The horizontal axis represents the range direction, the vertical axis the azimuth direction.

does not consistently yield superior RASR suppression performance. Notably, in high homogeneous scenes (1) and (6), the RASR is actually worse after applying the RABSS method compared to the RASR before applying the RABSS method. This highlights a limitation of the RABSS method, where its effectiveness is restricted to specific scene types. On the contrary, when dealing with a heterogeneous scene, such as scenes (3) and (5), the method effectively suppresses range ambiguities. Specifcally, a range ambiguity suppression up to 16 dB is achieved for scene (5).

As expressed in (3), the good estimation of the useful signal heavily depends on the accurate estimation of the separation matrix. Fig. 4 presents a plot that numerically justifies the relationship between the average RASR [9] and the mixing matrix correlation coefficient, given by:

$$r = \frac{\sum_{j=1}^{N} \sum_{k=1}^{N_a} r_{j,k}}{N \times N_a} \tag{4}$$

where N_a denotes number of azimuth samples in Doppler domain; N the number of subswaths, and

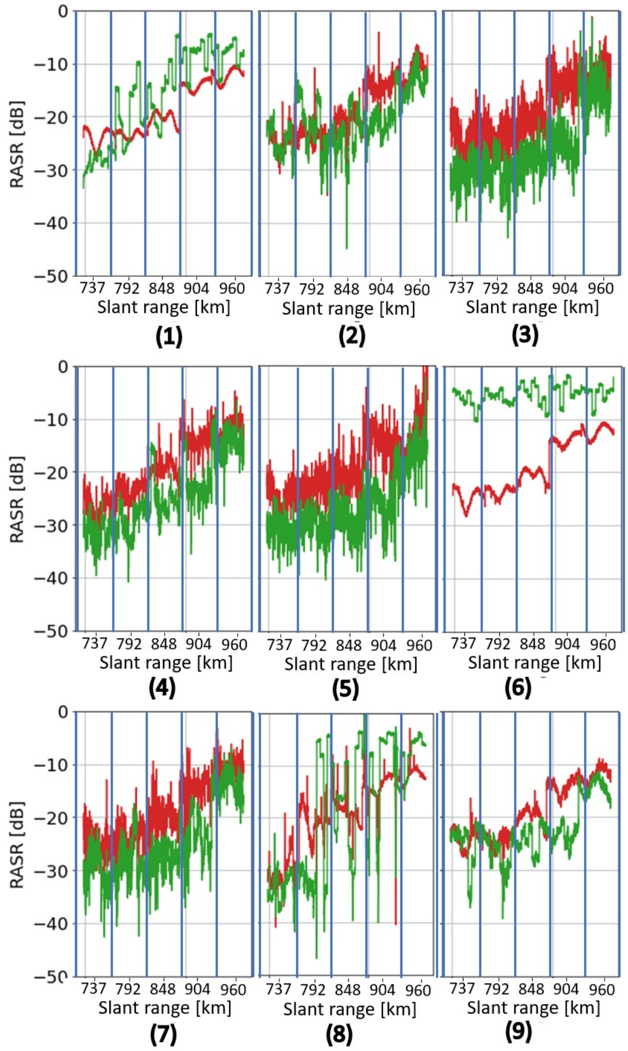

Figure 3 RASR performance for the nine scenes in Fig. 2: after the RABSS method (green), initial (red). The blue vertical lines indicate the boundary between the simulated swath segments. The number refers to the scene.

$$r_{j,k} = \frac{\left| \sum_{i=1}^{N_r} \left(\hat{a}_i - \bar{\hat{a}}\right)\left(a_i - \bar{a}\right) \right|}{\sqrt{\sum_{i=1}^{N_r} \left(\hat{a}_i - \bar{\hat{a}}\right)^2} \sqrt{\sum_{i=1}^{N_r} \left(a_i - \bar{a}\right)^2}} \tag{5}$$

where $\hat{a}$ and a denote the estimated and actual element of mixing matrix $\mathbf{A}$. The mixing matrix $\mathbf{A}$ has a size of N_r (number of range samples), N_a (number of azimuth samples in Doppler domain), and N (number of subswaths). Indices i, j, k refer to the indices of range samples, azimuth samples, and sub-swaths, respectively. The mixing matrix correlation coefficient's value ranges between 0 (indicating the worst similarity) and 1 (representing the best similarity).

The accurate estimation of the mixing matrix, shown by a high correlation coefficient, for instance, in scene (5), leads to good range ambiguity suppression, as indicated by a low average RASR value. On the other hand, the poor estimation of the mixing matrix, shown by a low correlation coefficient, for instance, in scene (6), leads to poor range ambiguity suppression, as indicated by a high average RASR value. Despite the general trend, Fig. 4 reveals a perculiarity for scene (8), where a moderate estimation of the mixing matrix leads to relatively good RASR performance. This is attributed to the good RASR performance at low backscattering levels in the near range (around 792 km slant range), where even a moderate estimation of the mixing matrix yields satisfactory results due to ambiguities arising from strong backscattering levels.

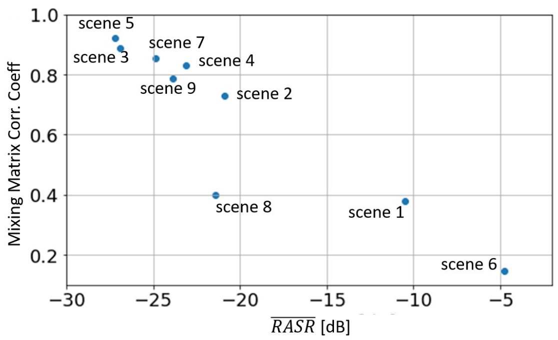

Figure 4 The relationship between average RASR and mixing matrix correlation coefficient

Fig. 5 shows the zero-Doppler actual and the estimated complex mixing matrix of the third beam, for the heterogeneous scene (5) and the homogeneous scene (6). The comparison between the results obtained for the two scenes clearly highlights that an accurate estimation, both in amplitude and phase, is achieved only for the heterogeneous scene. Additionally, it is observed that the areas with constant mixing matrix values correspond to the off-diagonal elements of the mixing matrix. These values represent the normalized value of the mainlobe of the third beam.

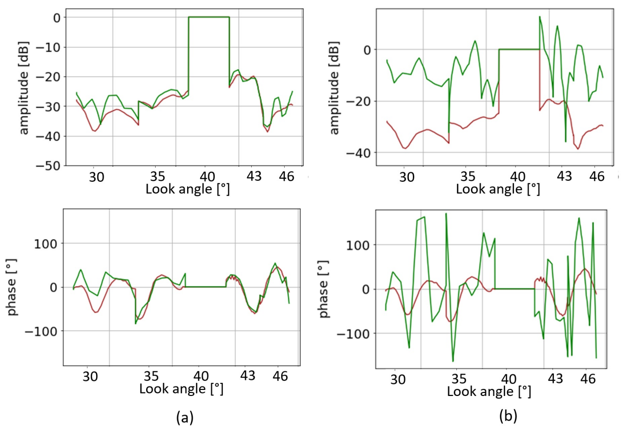

Figure 5 Amplitude (top) and phase (bottom) of the zero-Doppler actual (red curve) and estimated mixing matrix (green curve) of the third beam, obtained by the RABSS method [9], versus off-nadir angle. Two SAR acquisition scenes are considered: (a) the heterogeneous scene in Fig. 2 (5); (b) the homogeneous scene in Fig. 2 (6). The spatial separation between the subswaths is here not visualized.

4 Discussion

While the RABSS method offers great performance for heterogeneous scenes by suppressing range ambiguities up to 16 dB (with an average 6 dB), Section 3 numerically demonstrates that RABSS performs poorly when dealing with homogeneous scenes. A possible solution to this issue is to apply to an homogeneous scene the estimated separation matrix, $\hat{\mathbf{B}}$, obtained from a heterogeneous scene, instead of computing it by means of the HO-BSS

$$\hat{\mathbf{s}}_{homo} = \hat{\mathbf{B}}_{hetero}\mathbf{x}_{homo} \tag{6}$$

Here, $\hat{\mathbf{B}}_{hetero}$ denotes the estimated separation matrix obtained from the heterogeneous scene, and $\mathbf{x}_{homo}$ represents the received signals of the homogeneous scene.

It is important to note that the heterogeneity of the scenes can be described and quantified by the Gaussianity level of the signals: non-Gaussian signals correspond to a heterogeneous scene, while a homogeneous signal corresponds to a homogeneous scene. Accordingly, the Gaussianity level, that can, for example, be measured by the kurtosis of the input SAR data can be used to improve the performance of the RABSS method as shown in Fig. 6. More in detail, the procedure in Fig. 6 is not supposed to be repetitively applied over short acquisition intervals but is a periodic calibration tool. In fact, the mixing matrix can be assumed to be stable during a few consecutive acquisitions. Moreover, sufficiently long data takes (data samples) are required by RABSS to accurately estimate the mixing matrix.

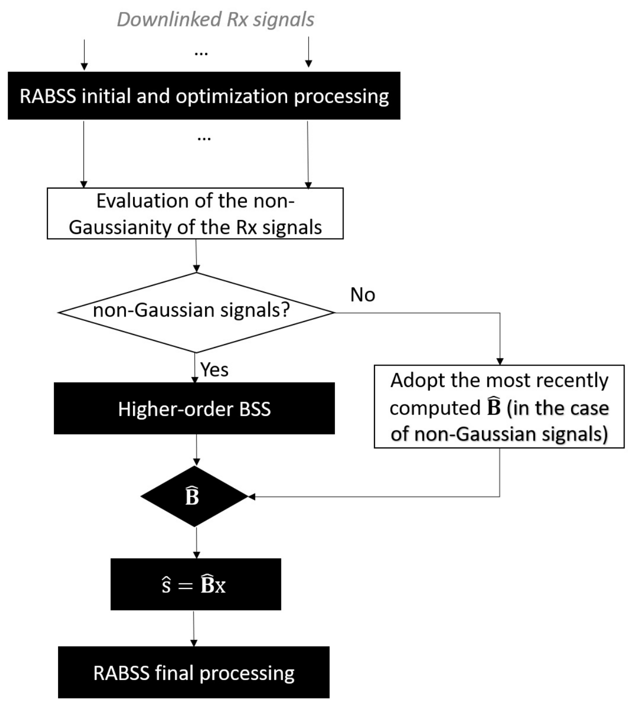

Figure 6 Flowchart illustrating a possible solution to improve the performance of the RABSS method. The black boxes denote the processing steps that are also performed by the basic RABSS method [9].

The solution in Fig. 6 requires a quantitative evaluation of the Gaussianity level of the input SAR data. When such a quantitative measure has been correctly proposed, it is expected that the solution can be successfully exploited to suppress the range ambiguities for different types of imaged surfaces, from heterogeneous to homogeneous surfaces. Solutions proposed in (6) and in Fig. 6 are investigated in very recent research and will be published soon as a journal paper [14].

5 Conclusion

The investigation of the range ambiguity suppression based on the blind source separation (RABSS) method involves various types of imaged surfaces. The results demonstrate effective range ambiguity suppression in heterogeneous scenes, achieving up to 16 dB (with an average of 6 dB). Conversely, the RABSS method exhibits poor performance in homogeneous scenes, indicating its limited applicability across all orbital positions for achieving range ambiguity suppression. Furthermore, the accurate estimation of the mixing matrix plays a crucial role in obtaining good range ambiguity suppression performance. Therefore, solutions, such as adopting the estimated mixing matrix from the heterogeneous scene and applying it to the homogeneous scenes, deserve attention when proposing possible enhancements to improve the performance of the RABSS method in the future. Such a solution is expected to address the issues in the basic RABSS method, thereby improving the performance of the range ambiguity suppression method when dealing with homogeneous scenes.

6 Literature

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