# Mitigation of Azimuth Ambiguities in Spaceborne Stripmap SAR Images Using Selective Restoration

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*Abstract*—A novel framework is proposed for mitigating azimuth ambiguities in spaceborne stripmap synthetic aperture radar (SAR) images. The azimuth ambiguities in SAR images are localized by using a local mean SAR image, SAR system parameters, and a defined metric derived from azimuth antenna pattern. The defined metric helps isolate targets lying at locations of ambiguities. The mechanism for restoration of ambiguity regions is selected on the basis of size of ambiguity regions. A compressive imaging technique is employed to restore isolated ambiguity regions (smaller regions of interconnected pixels), whereas clustered regions (relatively bigger regions of interconnected pixels) are filled by using exemplar-based inpainting. The simulation results on a real TerraSAR-X data set demonstrated that the proposed scheme can effectively remove azimuth ambiguities and enhance SAR image quality.

*Index Terms*—Image processing, image restoration, synthetic aperture radar (SAR).

#### I. INTRODUCTION AND MOTIVATION

 ${f R}$  ECENT space missions have opened new horizons in the area of remote sensing [1]–[3]. The spaceborne synthetic aperture radar (SAR) systems have attracted special interest in remote sensing tasks such as surveillance, target and object detection, land classifications, disaster search and rescue, and homeland security [4], [5]. Recently, high-resolution SAR imagery has been employed for cyclone intensity estimation [6], ship classification [7], moving target detection [8], [9], oil field monitoring [10], 3-D building reconstruction [11], and feature detection [12]. The advanced and sophisticated applications also require high-quality SAR imagery free of artifacts. However, the spaceborne SAR imagery exhibits ambiguities which may lead to faulty interpretation of SAR imagery. The ambiguities are mainly divided into two categories, i.e., range ambiguities and azimuth ambiguities. Generally, range ambiguities are more likely shown as highly deformed images, resulting from mismatched Doppler rate. However, azimuth ambiguities are high-frequency spectral contributions, down

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converted by sampling having similar Doppler rate with respect to the ground targets illuminated by the antenna main lobe. Therefore, azimuth ambiguities lead to more apparent artifacts in SAR images, particularly in coastal areas, and will be addressed in this paper.

Finite sampling of azimuth Doppler signals introduces azimuth ambiguities in spaceborne SAR images. Aliased signals are produced due to folding of Doppler frequencies toward the central part of antenna pattern in Doppler frequency domain. The ambiguous signals will be displaced symmetrically in azimuth toward the right and left of the actual target position. Azimuth ambiguities cause decreased signal-to-noise ratio (SNR) and lead to unreliable visual quality of the SAR image. In particular, an extremely high intensity target may result in apparently strong false targets in low-intensity homogeneous background areas (e.g., sea surface) at locations displaced by both azimuth and range shifts.

The foremost way to reduce azimuth ambiguities is by increasing the pulse repetition frequency (PRF) of spaceborne SAR systems. However, the higher the PRF is, the smaller the swath width would be [13]. Normally, the azimuth-ambiguity-to-signal ratio (AASR) should be lower than -18 dB [14] according to past and current spaceborne SAR missions [15], [16]. The nominal AASR parameter of SAR is determined by averaging out the AASR over a significantly vast area, assuming that all regions are distributed homogeneous scatters. However, in practice, the local value of AASR varies in different types of regions, for instance, local AASR would be much higher than nominal AASR in coastal areas.

The postprocessing techniques to address azimuth ambiguities can be divided into two categories, i.e., based on bandpass filtering and in-phase cancellation. Bandpass filtering technique [17], [18] removes azimuth ambiguities by using bandpass filters (BPFs) to filter azimuth signals. The bandpass filtering technique is effective in suppressing azimuth ambiguities but results in lower SNR, decreased effective Doppler bandwidth, and additional speckle noise. Guarnieri [18] introduced an adaptive approach for filtering process to help lessen induced speckle noise at locations where ambiguous signals are small by employing an adaptive Wiener filter. The performance of the Wiener filter is very sensitive to SNR. However, precise SNR estimation would impose a challenge in adaptive Weiner filtering technique.

The second type of azimuth ambiguity mitigation techniques is called in-phase cancellation techniques [19], [20]. These techniques design a reference function that provides matched filtering of the desired signal and deconvolves the ambiguities. Moreira's design for signal-to-alias transfer function [19]



Fig. 1. SAR geometry for azimuth ambiguities.

corresponds to the concept of an ideal filter with undefined phase and fading of ambiguities, whereas Zhang and Wang [20] used three filters: a typical matched filter and other two filters matching the responses of ambiguities. The outputs of the ambiguity-matching filters are subtracted from the output of the matched filter to obtain an ambiguity-free image. The in-phase cancellation techniques are effective for SAR images having strong point targets but subject to poor performance for distributed targets, because high-frequency components of reflectivity spectra are unrecoverable.

In this paper, we propose a novel framework to mitigate azimuth ambiguities in spaceborne stripmap SAR images. The locations of azimuth ambiguities are determined by calculating both azimuth and range shifts. An ambiguity map is built by employing a local mean SAR image. A metric based on azimuth antenna pattern (AAP) is defined to isolate strong targets lying at ambiguity locations. All pixels at ambiguity locations are replaced with zeros, and these pixels are restored by employing emerging compressive sensing (CS) [21], [22] or exemplar-based inpainting [23] depending on the size of the ambiguity region. The proposed framework was tested on a real TerraSAR-X single-look complex (SLC) SAR image data set, and experimental results exhibit its superior performance in removing azimuth ambiguities.

The rest of this paper is organized as follows. A brief overview of azimuth ambiguities is given in Section II. The proposed framework for mitigation of azimuth ambiguity is described in Section III, and simulation results on the TerraSAR-X data set are given in Section IV. Finally, we conclude this paper in Section V.

#### **II.** AZIMUTH AMBIGUITIES

Consider a SAR system flying with velocity v and transmitting pulses after every  $1/f_p$  second, where  $f_p$  denotes the PRF, as shown in Fig. 1. Let  $(\tau, t)$  and (r, a) be representations of the SAR image in time and data domains, respectively.



Fig. 2. Azimuth two-way power antenna pattern of TerraSAR-X as a function of azimuth frequency. The sampling frequency of TerraSAR-X is 3.55 kHz.

Under ideal conditions, the echo signal for a target is given by [24]

$$S_0(\tau,t;r,a) = \sigma(\tau,t;r,a)G_r^2(\tau;r) \otimes_{(\tau,t)} h(\tau,t;r,a)$$
(1)

where  $\otimes_{(\tau,t)}$  represents 2-D convolution with respect to  $(\tau,t)$ .  $G_r^2(r;a)$  is the range antenna pattern,  $\sigma(\tau,t;r,a)$  is the backscatter coefficient for location (r,a), and

$$h(\tau, t; r, a) = G_a^2(t; a) \exp\left\{-j\frac{2\pi}{\lambda r_0}a^2\right\} \delta\left[r - r_1(x)\right] \quad (2)$$

where  $G_a^2(t; a)$  is the AAP,  $r_0$  is the minimum slant range,  $r_1 = r_0 + 0.5x^2/r_0$ , and  $h_s(\tau, t; r, a)$  is the impulse response of SAR for  $\sigma(\tau_0, t_0; r_0, a_0) = 1$  [19]. The AAP of spaceborne SAR as a function of azimuth Doppler frequency is shown in Fig. 2 (using TerraSAR-X as an example). The AAP is not finite in azimuth frequency domain. Fig. 2 shows the azimuth pattern in azimuth Doppler frequency domain at a reference time and one of its replicas shifted by PRF.

In Fig. 1, the desired target illuminated by the antenna main lobe is referred to as **O**, and two ambiguous targets which are illuminated by the antenna sidelobes are denoted as  $\mathbf{G}_R$  and  $\mathbf{G}_L$ . The contributions coming from targets  $\mathbf{G}_R$  and  $\mathbf{G}_L$  are displaced in azimuth by angles  $\Delta \varphi_R$  and  $\Delta \varphi_L$ , respectively. The corresponding Doppler centroid error for ambiguous signals can be found as

$$\Delta f_{d_{\wp}} = -\frac{2v}{\lambda} \Delta \varphi_{\wp} \tag{3}$$

where  $\wp$  would be R or L corresponding to ambiguous targets  $\mathbf{G}_R$  or  $\mathbf{G}_L$ , respectively. The signals from the main target and ambiguous targets are added coherently according to AAP. The contribution from the ambiguous targets becomes indistinguishable when the corresponding  $\Delta f_{d_{\wp}}$  is equal to a multiple of PRF. At each azimuth position, an infinite number of such ambiguous signals are received simultaneously. Taking into



Fig. 3. Framework for removal of azimuth ambiguities using image selective restoration.

account these ambiguous signals, the received echo signal can be modified as [19]

$$S(\tau, t; r, a) = \sum_{i=-\infty}^{\infty} S_0(\tau, t; r, a) \exp\left\{j2\pi t f_p i\right\} \times \operatorname{rect}\left[\frac{\tau + \Delta \tau_i}{\tau_p}, \frac{t + \Delta t_i}{T_s}\right] \quad (4)$$

where  $T_s$  is the synthetic aperture time,  $V_g$  is the ground velocity of the platform,  $\Delta \tau_i = 2\Delta r_i/c$ , and  $\Delta t_i = 2\Delta a_i/V_g$ ( $\Delta r_i$  and  $\Delta a_i$  are the shifts in azimuth and range directions after image formation processing).

## III. PROPOSED AMBIGUITY REMOVAL FRAMEWORK

The proposed ambiguity removal framework is shown in Fig. 3. The SLC data of SAR are processed to find out locations of pixels which are dominated with ambiguous contributions. We classify azimuth ambiguities into two categories, namely, clustered ambiguities and isolated ambiguities. If ambiguity regions appear in the form of connected pixels of size greater than 50 pixels,<sup>1</sup> we name them as clustered ambiguities, with all other ambiguity regions termed as isolated ambiguities. The pixels in ambiguity regions in SLC data are assumed to be unknown, and selective restoration mechanism is used to find the values of these pixels. The pixels in isolated ambiguity regions are found out by employing a recently developed compressive

<sup>1</sup>The value is selected on the basis of experiments on SAR data sets.

imaging framework, whereas the pixels in clustered ambiguities are restored by using exemplar-based inpainting technique, as discussed in Section III-B.

Selective restoration strategy is adopted to achieve better restoration with computational efficiency. Compressive restoration is efficient but may result in poor restoration for clustered ambiguities. Therefore, exemplar-based inpainting, which is computationally inefficient, is employed to restore clustered ambiguities only.

#### A. Localization of Ambiguities

Each target in a spaceborne SAR image imparts its ghosts at azimuth frequencies that are integer multiples of PRF. A target O would impart I number of significant ambiguity image pairs on both the right and left sides. The *i*th ambiguous images on the right and left can be represented as  $\mathbf{G}_{R_i}$  and  $\mathbf{G}_{L_i}$ , respectively, shifted by  $\Delta a_i$  in azimuth direction and  $\Delta r_i$  in range direction, as shown in Fig. 1 (only the two most significant pairs of ambiguities are shown). The  $\Delta a_i$  and  $\Delta r_i$  are estimated by the following equations:

$$\Delta a_i = \frac{\Delta f_D}{f_r} V_g \tag{5}$$

$$\Delta r_i = \frac{\lambda}{2} \left( f_D + \frac{\Delta f_D}{2} \right) \frac{\Delta f_D}{f_r} \tag{6}$$

where  $f_D$  is the Doppler centroid in hertz,  $f_r$  is the Doppler rate in hertz per second,  $V_g$  is the ground velocity of the spaceborne vehicle, and  $\Delta f_D$  is the Doppler centroid frequency error for ambiguous signals. The Doppler centroid errors for ambiguous signals are given by

$$\Delta f_D = i f_p, \qquad i = \pm 1, \pm 2, \dots, \pm \infty \tag{7}$$

where *i* is the number of ambiguity images from the target either on the right or left. Any pixel value on the SAR image corresponds to the sum of the scatter energy from the target and the ambiguity scatter energy from locations at multiples of  $f_p/f_r$  (the ambiguity energy for the first ambiguity is shown as the shaded area in Fig. 2). Due to exponential decay of AAP envelop, about 85% of ambiguity energy is due to ambiguities at locations displaced in azimuth by  $\pm f_p/f_r$  [20]. Therefore, the scatter at any arbitrary location (r, a) can be estimated by using the following equation:

$$S(\tau,t;r,a) \approx \sum_{i=-1}^{1} S_0(\tau,t;r,a) \exp\{j2\pi t f_p i\}$$
$$\times \operatorname{rect}\left[\frac{\tau + \Delta \tau_i}{\tau_p}, \frac{t + \Delta t_i}{T_s}\right]$$
$$= S_0(\tau,t;r,a) + S_{L_1}(\tau,t;r,a) + S_{R_1}(\tau,t;r,a) \quad (8)$$

where  $S_0(r, a)$  is the scatter from the target by the antenna main lobe at an arbitrary location (r, a) and  $S_{L_1}(r, a)$  and  $S_{R_1}(r, a)$ are the most significant left and right ambiguous energies at i = -1 and i = 1, respectively. We assume that only one ambiguity either on the left  $(S_{L_1})$ or on the right  $(S_{R_1})$  is dominant at one pixel. For localization of ambiguity regions in a stripmap SAR image, a local mean SAR is employed along with approximated azimuth and range shifts of ambiguities given by (5) and (6), respectively. A local mean SAR image (denoted by  $S_{\mu}$ ) is obtained by convolving an SCL SAR image with an  $(m_a \times n_a)$  averaging kernel. The ambiguity map of the SLC SAR image is built by using

$$B(r,a) = \begin{cases} 1, & \text{if } |S_{\mu}(r,a)|^2 > \xi_i |S_{\mu}(r + \Delta r_i, a + \Delta a_i)|^2 \\ 0, & \text{if otherwise} \end{cases}$$
(9)

where  $\Delta a_i$  and  $\Delta r_i$  are given by (5) and (6), respectively, for  $i = \pm 1$ . The locations in ambiguity map **B** with zero values are treated as ambiguity regions. In (9), metric  $\xi_i$  is used to represent the contribution of the *i*th ambiguous signal at a certain location in the SAR image. The  $\xi_i$  is derived from AAP by using the following equation:

$$\xi_i = \frac{\int_{-f_p/2}^{f_p/2} |G(f_d)|^4 df_d}{\int_{if_p - f_p/2}^{if_p + f_p/2} |G(f_d)|^4 df_d}$$
(10)

where  $f_d$  denotes the azimuth Doppler frequency. The numerator in (10) denotes the energy of two-way AAP from  $-f_p/2$ to  $f_p/2$ , and the denominator is the ambiguous energy of the *i*th ambiguity, estimated by the energy of two-way AAP from  $if_p - f_p/2$  to  $if_p + f_p/2$ . The ambiguity map given by (9) is sensitive to the value of  $\xi_i$  and the size of averaging mask, which is used to obtain  $\mathbf{S}_{\mu}$ . Higher values of  $\xi_i$  may result in marking weak targets as ambiguities. On the other hand, lower values of  $\xi_i$  defined by (10) provides a realistic compromise for the construction of ambiguity map.

The local mean SAR image helps take into account the SAR parameter estimation error and defocusing phenomenon of distributed images. Moreover, many structures in populated areas behave as distributed/complex targets with several scattering centers. A distributed/complex target and its corresponding ambiguity image share similar structure but may differ in many details, as shown in Fig. 4. It can be observed that the ambiguity image is blurred in azimuth direction and has details that are also different compared to those of the actual target. The averaging filter makes ambiguity localization (9) insensitive to SAR parameter estimation and defocusing/blurring of ambiguous images. The suitable size of the averaging kernel is decided based on experimental results. In this paper, we take the average of 40 azimuth and 15 range samples to compute  $S_{\mu}$  (Fig. 5).

### B. Mitigation of Ambiguities

The selective restoration strategy is employed to mitigate ambiguities localized through (8). The isolated ambiguities are restored by applying a compressive imaging framework, whereas clustered ambiguities are found out by exemplar-based inpainting technique.

1) Removal of Isolated Ambiguities: Let S be an  $m \times n$  matrix representing the stripmap SAR image. If  $y_s$  is a vector



Fig. 4. Structure of ambiguities. (Left) TerraSAR-X image patch with distributed target and its ambiguities. (Right) Rescaled target and its ambiguous images. The target and its ambiguous image share the same structure but differ in details. The target is well focused, but its ambiguous image is blurred due to mismatched range cell migration corrections.



Fig. 5. Ambiguity map for TerraSAR-X data set. (a) Ambiguity map obtained by using (9) with ambiguity regions shown by black and white patterns. (b) Classifications of ambiguity regions. The regions encircled in green are taken as isolated ambiguities, and ambiguity regions encircled by red are taken as clustered ambiguities.

containing M ambiguous pixels of isolated ambiguities in S, then, by using the compressive imaging framework, it can be written as

$$\mathbf{y}_s = \mathbf{\Phi} \mathbf{S} \tag{11}$$

where  $\Phi$  is an  $M \times N$  sampling matrix with  $N = m \times n$ . Each row of sampling matrix contains only one "1" corresponding to pixel location in the SAR image (arranged in a column). This sampling matrix would be equivalent to a point sampling matrix [25]. If  $S_w$  is the sparse representation in wavelet domain, (11) can be given as

$$\mathbf{y}_s = \mathbf{\Phi} \mathbf{\Psi}^T \mathbf{S}_w = \mathbf{\Theta} \mathbf{S}_w \tag{12}$$

where  $\Psi$  is the wavelet transform matrix.  $\Theta = \Phi \Psi^T$  is called the measurement matrix. The problem is to find  $\mathbf{S}_w$  from  $\mathbf{y}_s$ if the measurement matrix is known. Once  $\mathbf{S}_w$  is known,  $\mathbf{S}$ can be found by taking the inverse  $\Psi$  transform. The problem is highly underdetermined as the number of known elements is M and the number of unknowns is N with  $M \ll N$ . The



Fig. 6. Notation diagram for exemplar-based inpainting [23]. (a) Source and target regions. (b) Selection of candidate patches.

CS reconstruction requires that, in order to recover  $S_w$  in (12), the sampling matrix should be sufficiently incoherent to the basis matrix [21], [22]. For the coherence between sampling matrix  $\Phi$  and wavelet basis matrix  $\Psi$ , a blurring filter can be incorporated in the measurement process [25], so

$$\Theta = \Phi \Gamma^{-1} \Psi^T \tag{13}$$

where  $\Gamma^{-1}$  is the sharpening filter.  $\mathbf{S}_w$  can be reconstructed from measurement vector  $\mathbf{y}_s$  (12) by solving the following  $l_1$ optimization problem [21]:

$$\hat{\mathbf{S}}_w = \arg\min \|\mathbf{S}_w\|_1, \quad \text{subject to } \mathbf{y}_s = \mathbf{\Theta} \mathbf{S}_w.$$
 (14)

 $\hat{\mathbf{S}}_w$  is composed of wavelet coefficients of recovered SLC image  $\hat{\mathbf{S}}$ . The solution to (14) requires a backward measurement matrix  $\Theta^*$ , to remove the effect of  $\Theta$  (i.e.,  $\|\Theta^*\Theta \mathbf{v}\| \approx \|\mathbf{v}\|$ ) during the minimization process. The backward measurement matrix is defined as  $\Theta^* = \Psi \Gamma \Phi^T$  [25] (where  $\Gamma$  is the blurring filter). Once  $\hat{\mathbf{S}}_w$  is found by solving (14),  $\hat{\mathbf{S}}$  is found by taking the inverse wavelet transform and then applying the sharpening filter. The isolated ambiguities have been removed in  $\hat{\mathbf{S}}$ , but it still contains clustered ambiguities which are restored using exemplar-based inpainting technique.

2) Removal of Clustered Ambiguities: Let there be  $N_c$  ambiguous regions in SAR data. These ambiguities are removed sequentially starting from the top-left corner of  $\hat{S}$  by applying exemplar-based inpainting technique. Exemplar-based inpainting [23] employs a template window for filling the lost patches of images. The fill order is the core of exemplar-based inpainting. The algorithm by Criminisi *et al.* [23] starts from filling the front region pixels based on a defined priority parameter as defined hereinafter. The readers are referred to [23] for a detailed description of the technique.

Let  $\Omega$  be the region that we need to fill in an image  $\chi$ , and  $\Lambda = \chi - \Omega$  is the source region, as shown in Fig. 6. The front of the target region is the interface between the target and source regions, shown as  $\delta\Omega$  in Fig. 6(a). The target region is filled from outside to inward in concentric layers. The priorities of all pixels at the  $\delta\Omega$  are calculated, and these priorities are used to determine the order of filling pixels at the border of the target region. Given a patch  $\mathbf{P}_{\alpha}$  at point  $\alpha$  for  $\alpha$  ( $\alpha \in \delta\Omega$ ), its priority is given as [23]

$$R(\alpha) = C(\alpha)D(\alpha) \tag{15}$$



Fig. 7. Segmentation of TerraSAR-X image based on texturedness. The local variance is used as measure of image texture.

TABLE I PARAMETERS OF TERRASAR-X FOR LOCALIZATION OF AZIMUTH AMBIGUITIES

Parameter	Value	Remarks
Doppler velocity (m/s)	7088.791	
Frequency (GHz)	9.65	
PRF (Hz)	3551.128	
Antenna Length (m)	4.8	
Doppler Centroid (Hz)	10.144	at azimuth/range center
Doppler Rate (Hz/s)	5704.122	
Azimuth resolution (m)	3.3	
Ground range resolution (m)	2.0	

where  $C(\alpha)$  and  $D(\alpha)$  are the confidence term and data term, respectively, defined as [23]

$$C(\alpha) = \frac{\sum_{\beta \in \mathbf{P}_{\alpha} \cap \bar{\Omega}} C(\beta)}{|\mathbf{P}_{\alpha}|}$$
(16a)

$$D(\alpha) = \frac{|I_{\alpha} \cdot \mathbf{n}_{\alpha}|}{\kappa} \tag{16b}$$

where  $|\mathbf{P}_{\alpha}|$  is the area of  $\mathbf{P}_{\alpha}$ ,  $\kappa$  is a normalization factor (e.g.,  $2^8 - 1$  for an 8-b image),  $\mathbf{n}_{\alpha}$  is a unit vector orthogonal to the front  $\delta\Omega$  in the point  $\alpha$ , and  $I_{\alpha}$  is the isophote (direction and intensity) at point  $\alpha$ . The distinct patches are selected for each pixel on the boundary of the target region, and priority is computed for these patches. The initial values of  $C(\alpha)$  are set to  $C(\alpha) = 0 \forall \alpha \in \Omega$  and  $C(\alpha) = 1 \forall \alpha \in \chi - \Omega$ . The confidence term  $C(\alpha)$  leads to filling of those patches first that have more of their pixels already filled. The data term  $D(\alpha)$  determines the strength of isophotes hitting the front  $\delta\Omega$  and hence ensures that linear structure will be synthesized first [23].

The patch on front  $\delta\Omega$  with the highest priority is filled first. For patch  $\mathbf{P}_{\alpha}$ , a patch is searched in the source region which is the most similar to  $\mathbf{P}_{\alpha}$ . The similarity between the patches is measured by the sum of square distances of already filled pixels in the two patches [23].

In order to increase computational efficiency of filling clustered ambiguities, the SAR image can be divided into segments based on texturedness. The SAR image is quite uniform in the areas of forest and sea, whereas populated areas appear as textures. A typical segmentation of a SAR image is shown in Fig. 7, where significant segments in a SAR image are numbered. Let  $N_r$  be the number of segments in a SAR image



Fig. 8. Ambiguity results on TerraSAR-X data set. (a) Original TerraSAR-X image with ambiguities in azimuth direction including rectangular structure causing ambiguity on both left and right sides. (b) Ambiguity map. (c) Restored image using BPF centered at azimuth sampling frequency. (d) Removal of azimuth ambiguities using proposed framework.

based on texturedness, and let  $\Omega_c^k$   $(k \in 1, 2, ..., n_c)$  be the number of clustered ambiguities. If the *k*th ambiguity  $\Omega_c^k$  lies in the *l*th segment  $\eta_l$  of the SAR image, the corresponding source region  $\Lambda_c^k$  can be given as

$$\Lambda_c^k = \eta_l - \Omega_c^k - \sum_{k'} \Omega_c^{k'} \tag{17}$$

where  $\Omega_c^{k'}$  represents cluster ambiguities other than the ambiguity under consideration lying in segment  $\eta_l$ . In order to avoid the possibility of introduction of false targets in the filled region, strong point targets in uniform segments such as  $\eta_1$  in Fig. 7 should not be included in the source region when applying exemplar-based inpainting. Therefore, (17) can be modified for uniform regions

$$\Lambda_c^k = \eta_l - \Omega_c^k - \sum_{i=1}^{k'} \Omega_c^i - \sum_{j \in p} P^l$$
(18)

where  $P^l$  represents strong point targets in uniform region segment  $\eta_l$ . For each patch to be filled at the region front, a patch is found out in the source region that is the most similar to the patch at the region front. Having found the best patch in the source region with minimum distance to the patch to be filled on boundary, the value of each pixel to be filled is copied from its corresponding position inside the patch to be filled [23].

## IV. IMPLEMENTATION AND EXPERIMENTAL RESULTS

### A. Experimental Results

The proposed azimuth ambiguity mitigation framework was tested on a TerraSAR-X data set. The parameters of TerraSAR-X used for localization of ambiguities are given in Table I. The TerraSAR-X image of Dubai coastal area (Jebel Ali port) with strong azimuth ambiguities is shown in Fig. 8(a). The ambiguities of a concrete/metallic rectangular structure can be seen on both the left and right sides in azimuth directions. The left ambiguity appears on uniform background, i.e., sea, whereas the right ambiguity appears on populated areas. This



Fig. 9. Ambiguity results on TerraSAR-X data set. (a) Original TerraSAR-X image of Dubai airport. (b) Restored TerraSAR-X image using BPF. (c) Restored TerraSAR-X image using proposed framework.

is an example of distributed targets producing ambiguities. The ambiguity map of the SAR image (9) is shown in Fig. 8(b). It can be seen that the ambiguity detection process is pragmatic and even small targets have not been marked as ambiguities. The results of ambiguity reduction by using a BPF are shown in Fig. 8(c). The increase in speckle noise due to BPF is obvious in Fig. 8(c), which would lead to lower SNR. Fig. 8(d) presents the ambiguity mitigation in the TerraSAR image obtained by employing the proposed framework, which shows significant enhancement in the SAR image.

The proposed framework was also used to mitigate ambiguities on the image of Palm Jumeirah resort in Dubai coastal area acquired by TerraSAR-X, as shown in Fig. 9(a). The restored image using BPF is shown in Fig. 9(b), whereas the image produced by using the proposed ambiguity removal framework is shown in Fig. 9(c). The zoomed patches of smooth areas are also shown in Figs. 8 and 9. Three important features of the proposed ambiguity mitigation framework can be observed in Figs. 8 and 9.

- 1) The filtering technique decreases SNR, whereas the proposed technique does not deteriorate signal quality.
- 2) The strong and distributed ambiguities are not removed completely using the BPF technique, as can be observed in Fig. 8, but the proposed framework can remove these ambiguities satisfactorily.
- The bandpass filtering technique results in blurring of the SAR image, whereas the proposed framework would not lose spatial resolution of the SAR image.

## B. Discussion

The metric defined by (10) helps targets not to be marked as ambiguities. However, if a scatter from a target is very weak and the ambiguous signal is quite strong, then (9) may mark this location as possible ambiguity, as scatter from weak targets may be less than the variation of parameter from actual AAP at the location. Thus, if a very weak target is fully corrupted by strong ambiguous signals, the whole target may be marked as an ambiguity region, and we may lose the target. However, if a very weak target is partially marked as ambiguity due to strong ambiguities, still, it can be reconstructed by using the framework.

Our proposed technique restores only ambiguous pixels within the SAR image. There is no change at all for all other locations. The filtering-based ambiguity reduction techniques lower the SNR in a SAR image. However, in the propped framework, SNR would be unchanged at the unambiguous locations.

The increased interest of research community in linear inverse problems would lead to highly efficient restoration algorithms in near future. We are confident that, exploiting latest research in these areas, the proposed framework would be a pragmatic and computationally efficient option for mitigation of azimuth ambiguities in spaceborne stripmap images.

## V. CONCLUSION

A novel framework based on selective restoration has been proposed for removal of azimuth ambiguities in spaceborne stripmap SAR images. The azimuth ambiguities in stripmap images are identified through a simple and effective technique by employing a metric derived from AAP. The ambiguous locations are predicted by selecting either compressive imaging or exemplar-based inpainting technique based on size of the ambiguous region. The experimental results on real SAR data have demonstrated that the proposed ambiguity mitigation framework is better compared to filtering-based reduction techniques.

The proposed framework will be extended for ambiguity mitigation in spaceborne high-resolution spotlight/slidingspotlight SAR images in the future. The azimuth ambiguity in spotlight/sliding-spotlight SAR exhibits different behavior compared to spaceborne stripmode SARs. Therefore, AASR in spotlight/sliding-spotlight SAR images varies as a function of azimuth position, and new formulation for localization of ambiguities would be required to deduce accordingly.