Phase Variant Analysis Algorithm for Azimuth Ambiguity Detection

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***Abstract*—An innovative algorithm to detect the azimuth ambiguities is presented. The proposed algorithm is completely model independent and can work in every conditions, being very sensitive and efficient. A dedicated filtering process increases the sensitivity to detect small and weak ambiguities and decreases the false alarm occurrence.**

***Index Terms*—Azimuth Ambiguity detection, Synthetic Aperture Radar, phase derivative**

I. Introduction

Synthetic Aperture Radar (SAR) data contain a very high level of informative content that allows the application to be used in many domains. Image quality is affected by various artifacts that can limit their use. One important class of artifacts are azimuth ambiguities. They are caused by finite sampling and sidelobe backscattering contamination from adjacent pulses. This is because the SAR spectrum is not strictly band limited, and the signal band is contaminated by ambiguous signals from adjacent spectra. The azimuth ambiguities affect both the amplitude and phase information of the SAR data, making their exploitation challenging. It appears clear that it is very important to detect this type of artifact for data quality assessment to define where the useful information is corrupted. An innovative technique to detect the ambiguities using the phase information is proposed in this paper.

The paper is organized as followed. Section II introduces the ambiguity issue, section III describes the developed algorithm for azimuth ambiguity detection, section IV shows the results obtained and the performance metrics of the algorithm and section V concludes the paper and describes the advantages and limitations of the algorithm.

II. Azimuth ambiguity artifacts

There are many contributions to the occurrence of azimuth ambiguities: the antenna pattern, the Range Migration Compensation (RMC) performed in the band [-PRF/2,+PRF/2], where PRF is the Pulse Repetition Frequency, and the errors in the Doppler centroid estimation. SAR processing focuses the energy coming from the mainlobe of the radiation pattern. Residual energy is captured from all directions by the sidelobes of the antenna pattern which contribute to ambiguities. If the spectral signature of a target exceeds the azimuth bandwidth defined by the PRF, then aliasing wraps the portions of spectrum outside the PRF into the useful bandwidth. To understand how the azimuth ambiguities are generated we have to consider how the data is processed. During processing, Range Migration Compensation (RMC) plays a major role in ambiguity generation. Because the slant range changes during the integration time, the resulting range migration must be compensated for:

$$R(f_D) = R_0 / D(f_D, V_r) \tag{1}$$

with D migration factor:

$$D(f_D, V_r) = \sqrt{(1 - (\lambda^2 f_D^2)/(4V_r^2))} \tag{2}$$

where f_D is the Doppler frequency, R_0 is the slant range at the zero Doppler, V_r is the relative velocity between antenna and target and λ is the wavelength. After RMC, the portions of energy that fall into the azimuth bandwidth are not well compensated and produce the unfocused ambiguities in the final image.

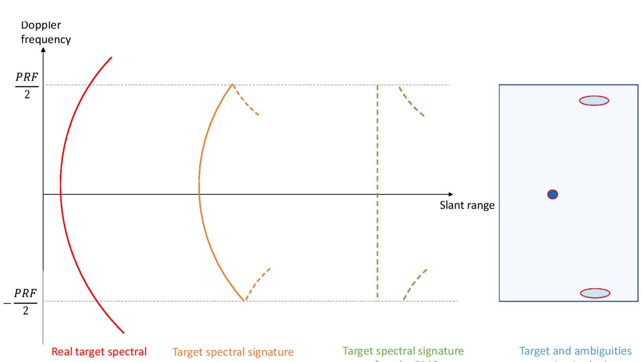

Fig. 1. Range migration compensation and ambiguity generation

The first approach to reduce the azimuth ambiguities is to design the SAR system by selecting the antenna size and the PRF accordingly. During the phase of antenna design the azimuth ambiguity issue can be mitigated by setting properly the PRF depending on the antenna length [1], considering that an increase of the PRF reduces their occurrence. However, an increase of the PRF causes an increase in the range ambiguity occurrence, and a balance between the two types of ambiguities must be found. Unfortunately, the proper design may not be in line with the requirements of modern micro-SAR platforms. New SAR satellite constellations are equipped with smaller antennas compared to their predecessors, imposing constraints that restrict conventional suppression of the ambiguities. Theses design constraints make the acquisitions particularly prone to generate ambiguities. The typical approaches to detect the ambiguities are based in dedicated post-processing techniques. Several algorithms have been proposed to estimate the local azimuth ambiguity-to-signal ratio (AASR). A proposed technique for azimuth ambiguity detection is based on the use of independent range sub-apertures to detect the ambiguities, considering the wavelength dependence of the ambiguity that caused the wrong co-location in different looks [2]. Another method is based on the raw data analysis to discriminate the main signal from the ambiguity in the local Doppler power spectrum [3]. Most of the existing algorithms for AASR estimation and suppression are based on the assumption that the ambiguous signals are located in specific areas of the signal spectrum depending on the antenna pattern [4] [5] [6]. In these proposed techniques the Wiener filters built from the antenna pattern model are used to discriminate the ambiguous spectrum, allowing the detection of the ambiguities. The limitation of these methods is the low sensitivity to weak and small ambiguities and the ineffectiveness when the ambiguity spectral signature covers also the central area of the Doppler spectrum.
A new algorithm for ambiguity map detection is here proposed, exploiting the phase information to decouple the main signal from the ambiguous signal.

III. Ambiguity detection

A. Ambiguity contribution to the signal phase

The SAR data affected by azimuth ambiguities are the sum of the main signal and the signal generated by the ambiguities:

$$\zeta(s,t) = M(s,t) + A(s,t) \tag{3}$$

where M is the ambiguity-free signal, A is the ambiguity signal and s and t are respectively the azimuth and the range time. The main signal after compression is:

$$M(s,t) = p_{rg}(t)p_{az}(s)e^{-j\frac{4\pi}{\lambda}R_0}e^{j2\pi f_{dc}s} \tag{4}$$

where P_{rg} and P_{az} are the sinc-like amplitudes of the impulse response function in range and azimuth, and f_{dc} is the Doppler centroid. The phase of M is composed by a linear term, that represents the residual phase due to the non-zero Doppler centroid, and by a constant phase due to the target position.

$$\angle M(s,t) = 2\pi f_{dc}s - \frac{4\pi}{\lambda}R_0 \tag{5}$$

In the ambiguity signal an additional phase term Φ appears. In case of range ambiguity Φ depends only on the azimuth time, while in case of azimuth ambiguity it depends on range and azimuth time.

$$\angle A(s,t) = 2\pi f_{dc}s - \frac{4\pi}{\lambda}R_0 + \Phi(s,t) \tag{6}$$

The derivative of the phase for the main signal and the ambiguity signal are:

$$\angle M(s,t) : \begin{cases} \frac{\partial \angle M(s,t)}{\partial s} = 2\pi f_{dc} \\ \frac{\partial \angle M(s,t)}{\partial t} = 0 \end{cases} \tag{7}$$

$$\angle A(s,t) : \begin{cases} \frac{\partial \angle A(s,t)}{\partial s} = 2\pi f_{dc} + \frac{\partial \Phi(s,t)}{\partial s} \\ \frac{\partial \angle A(s,t)}{\partial t} = \frac{\partial \Phi(s,t)}{\partial t} \end{cases} \tag{8}$$

The derivative of the main signal in azimuth and range is respectively a constant and zero, while the ambiguity phase is azimuth and range variant.

B. Phase analysis for ambiguity detection

The analysis of the phase variance allows to detect all the ambiguities and to discriminate the azimuth ambiguity from the dependence of the phase. In fact, the ambiguities present a phase derivative different from zero, while the phase derivative of the main signal is close to zero. Equations 7 and 8 are calculated on the data using the Phase Derivative Value (PDV), that allows to decouple the main signal from the ambiguous signal for every pixel. Unfortunately, other contributions interfere with the signal phase, and many false alarms can be raised. In fact, the target motion contribute to the phase, and this can result in the false detection of moving targets, as ships, and of moving surfaces, as the sea surface in presence of wind and waves. Also the non proper focusing of the target introduces an offset in the phase. Finally, the PDV results sensitive to the Impulse Response Function (IRF) sidelobes of strong targets.

C. Ambiguity detection: Phase Variant Analysis Algorithm

The proposed algorithm to detect the ambiguities is named Phase Variant Analysis (PVA). The PVA algorithm uses the combination between a dedicated filtering and the derivative phase information to decouple the ambiguity from the main signal reducing the limitations aforementioned. The decreasing of the IRF sidelobes could be easily performed with smoothing windows of the signal spectrum. The use of the smoothing windows is able to reduce the sidelobes, but at the same time reduces also the sensitivity to detect the ambiguous signals localized in the spectrum borders. A dedicated adaptive filtering is then used, to reduce the sidelobes preserving the spectrum frequencies in which the ambiguities are located. an adaptive weighting to preserve the portion of the spectrum that contains ambiguity. The PVA algorithm is divided in the following steps:

1) The data spectrum is shifted to the Doppler Centroid. This step allows to set $f_{dc} = 0$ in equations 7 and 8.
2) The data spectrum is filtered with a dedicated filter. The filter is constituted by a static contribution, given by the classical smoothing windowing functions like Hamming, Hanning and Kaiser, and by an adaptive contribution. The adaptive contribution is defined analysing the Doppler spectrum to detect the energy distribution. The spectrum profile is used to define a filter that preserves the Doppler frequencies with higher energy corresponding to the ambiguous signals and attenuate the other frequencies. The purpose is to reduce the IRF sidelobes and maintain high sensitivity to detect the ambiguities.
3) The azimuth derivative phase $\frac{\partial \angle A(s,t)}{\partial s}$ is calculated, allowing the detection of many features: azimuth ambiguities, range ambiguities, multiple-bound reflections (especially in urban environment) and moving targets moving in the azimuth direction.
4) The range derivative phase $\frac{\partial \angle A(s,t)}{\partial t}$ is calculated, allowing the detection of azimuth ambiguities and the moving targets moving in the range direction. As the azimuth dependence of the azimuth ambiguities is stronger than in range, the range derivative phase has less sensitivity and can be used particularly to filter out the range ambiguities.
5) The ambiguity map is obtained multiplying the azimuth derivative phase with the range ambiguity phase.

Figure 2 shows the different steps of the PVA algorithm.

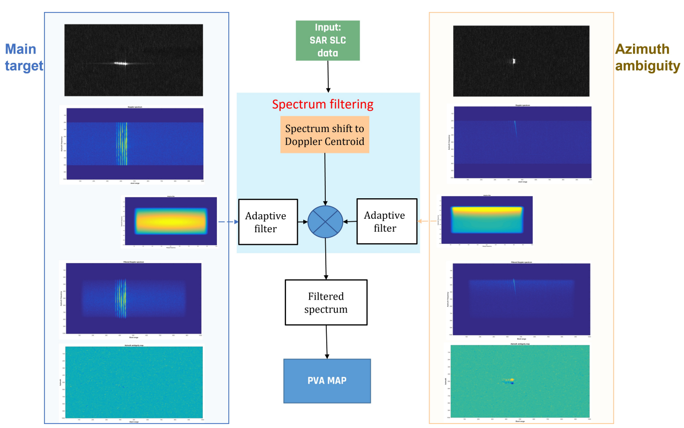

Fig. 2. PVA algorithm scheme

IV. Validation and Results

The PVA algorithm has been tested and validated by using simulated and real data. This section will show the performance metrics calculated on simulations and the results obtained on real data.

A. SAR data simulator

The SAR data simulator is a very important tool for recreation of on-demand realistic scenarios for generation of specific targets, needed for algorithm testing and validation. A dedicated SAR data simulator has been developed with the purpose of generating simulated ambiguities for algorithm validation. The SAR data simulator generates the raw data of targets using the full antenna pattern radiation, that includes the sidelobes that generate undesired received energy. The simulated data of the sidelobes are inserted in real scenarios following the processing steps:

- The SLC complex data are defocused in range and azimuth to generate the raw data.
- The simulated raw data of the ambiguities are summed to the real raw data according to the overlapping and sum principle.
- The data are focused in range and azimuth obtaining the simulated ambiguities in real data.

B. PVA performance metric

The PVA algorithm allows the detection of azimuth ambiguity, generating ambiguity maps. Its performance have been measured using simulated data. The validation has been performed generating 50 simulated ambiguities of first order and 50 of second order and calculating the performance metrics shown in the next paragraphs. The position and the backscattering of the target are defined randomly by using an uniform distribution. Only stripmap acquisition mode was used for the calculation of the metrics.

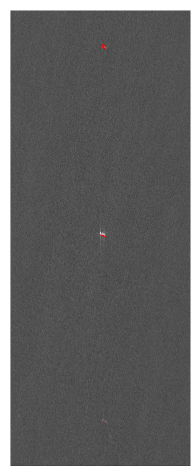

Fig. 3. Ambiguity of a simulated ship, both left an right ambiguities are detected

The ambiguity is considered successfully identified when a minimum cluster of n ambiguous pixels are detected as ambiguities, presenting a derivative phase higher than the threshold T. In our simulation we fixed n=15 pixels and T=0.6 radians based on empirical observations. An adaptive thresholding depending on the level of the signal energy could provide better results for weak ambiguities.

The missing detection of the algorithm is related to the level of ambiguous energy that has been simulated. If the energy

TABLE I
AMBIGUITY DETECTION PERFORMANCES OF THE PVA ALGORITHM

Ambiguity order	detection rate [%]
1	86
2	91.5
TOT	88.7

of the simulated target in the real background is too low, the ambiguity will be not visible and the algorithm could fail.

C. Results on real data

The PVA algorithm have been tested on real images. Figure 4 and Figure 5 show the results of the ambiguity detection on stripmap and spotlight images.

Fig. 4. Ambiguities detected in Stripmap

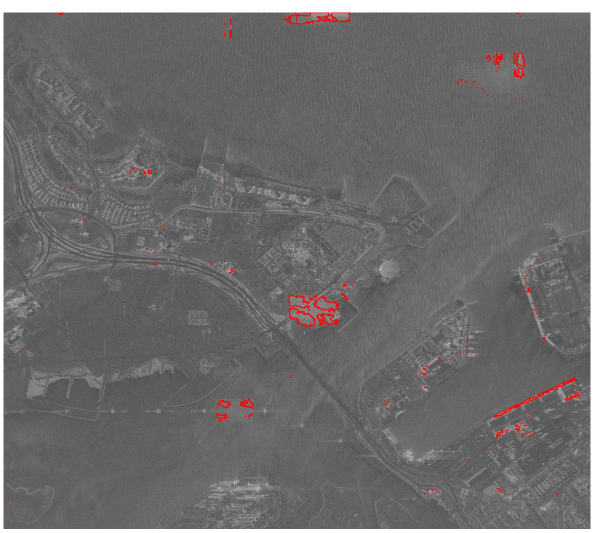

Fig. 5. Ambiguities detected in Spotlight

V. CONCLUSIONS

We presented a new algorithm to detect the azimuth ambiguities. The algorithm achieved very good results in simulated and real data (see figure 4 and 5) and is currently used in the quality processing chain of ICEYE. The implemented algorithm solves the problem of the ambiguity detection with a light and easy technique. The algorithm can work also when the ambiguous signature cannot be easily decoupled from the main signal. The advantages of the PVA algorithm are the processing speed and the independence on specific models, as the antenna pattern. Moreover, it can be used in parallel processing, speeding more the processing. The dedicated spectral filtering reduces the algorithm sensitivity to urban area's multi-paths that generate many false positives and the difficulty to separate azimuth and range ambiguities in presence of strong range ambiguities. The future step is to overpass these limitations implementing a dedicated algorithm for the range ambiguity detection. Finally, a dedicated adaptive thresholding could be applied to change the algorithm sensitivity depending on the energy level of the signal and to improve the performances with weak ambiguities.

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