Intra-Pulse Effect Compensation Method for SAR Systems with Up- and Down-Chirp Modulation

Nida Sakar, Pau Prats-Iraola, *Fellow, IEEE,* and Marc Rodriguez-Cassola

***Abstract*—The motion of the SAR sensor during the transmit and receive events introduces a space-invariant polychromatic phase, known as intra-pulse (IP) effect, which may degrade the impulse response function if left uncorrected. A straightforward solution is already available in the literature to compensate for this effect for conventional SAR systems using a single waveform during the acquisition. However, there is currently no solution in the case the SAR system transmits an interleaved up/down sequence. If left uncorrected, besides the impulse response degradation in terms of azimuth and range resolution loss, additional azimuth ambiguities will appear. This paper proposes an azimuth-reconstruction based approach to mitigate the IP effect for both single- and multi-receiver SAR systems with up- and down-chirp (UDC) modulation. The performance of the approach is demonstrated with point target simulations.**

***Index Terms*—Intra-Pulse effect, up- and down-chirp modulation, azimuth reconstruction, multi-channel SAR.**

I. INTRODUCTION

DESPITE being a well-proven imaging technique, conventional Synthetic Aperture Radar (SAR) systems cannot be easily upgraded to accommodate the increasing demands for higher spatial resolution and wider swath width. Using different modulated waveforms, i.e., alternating up- and down-chirp (UDC) in each transmit event, is one way of improving the performance of conventional SAR systems, e.g., in terms of range ambiguity or nadir echo suppression [1], [2], [3], [4]. With this method, each pulse is compressed with its corresponding matched filter. Therefore, the range ambiguity suppression of prominent scatterers is naturally achieved -for the odd ambiguities, where the first one is usually the strongest-, since the ambiguous signal compressed with the wrong matched filter becomes smeared along the range dimension. Another way towards acquiring high-resolution wide-swath (HRWS) imaging is to make use of several receive channels while reducing the system PRF [5]. Multiple receive channels can be acquired by splitting the antenna in the azimuth direction, i.e., multi-channel SAR, or by employing multiple receive-only satellites in a SAR constellation with one transmitter, i.e., multi-static SAR. Moreover, both approaches can be utilized for a multi-receiver SAR system with up- and down-chirp modulation [4].

Typical spaceborne SAR processing approaches assume that the platform is stationary during transmit and receive events, and starts moving again when these events are complete. This assumption is usually referred to as the 'stop-and-go' or 'start-stop' approximation. However, the platform actually moves during the transmission/reception of the pulse, which introduces a Doppler- and range-frequency-dependent space-invariant phase. The TerraSAR-X satellite ($v_s = 7600$ m/s) moves 40 cm during 50 μs of chirp duration, while the ROSE-L satellite ($v_s = 7560$ m/s) moves 37 cm during 48.61 μs of chirp duration. The system parameters of the sensors are given in Table I (TerraSAR-X) and Table II (ROSE-L). This effect is referred in the literature as the intra-pulse (IP) effect. It can result in a loss of resolution in the azimuth and range dimensions for high resolution systems without alternating waveforms [6]. When UDC modulation is used, the intra-pulse effect results in additional azimuth ambiguities. A solution for the single waveform case is already provided in [6].

This paper proposes two methods for the compensation of the IP effect for single and multi-receiver SAR systems with UDC modulation. Both solutions exploit the same idea, namely the use of an azimuth reconstruction approach to correct for the IP effect, which is originally proposed to resolve the azimuth ambiguities in case of undersampled multi-receiver SAR systems. Section 2 presents the data model, introduces the IP effect compensation methods and demonstrates their performance with the point target simulations, while Section 3 concludes the paper with a discussion.

II. INTRA-PULSE EFFECT COMPENSATION

A. Signal Model

The top plots of Figure 1 illustrate the observation geometry of a monostatic SAR (left) and an along-track multistatic SAR constellation (right). The bottom plots show the data matrices where the up- and down-chirps are represented with yellow and green colours, respectively. Note that the multi-receiver SAR system case (multi-channel and multistatic) is a particular case of a multistatic SAR system, since the processing approach for a multistatic SAR system represents a generalized solution for the multi-receiver case.
The movement of the platform during the transmission and the reception of the chirp signal introduces a space-invariant polychromatic phase, i.e., the intra-pulse (IP) effect, that can be expressed in the wavenumber domain as [6]

$$H_{IP,up}(f_r, f_a) = \exp\left[\mathrm{j} \cdot 2\pi \cdot \frac{f_a}{|K|} \cdot f_r\right], \tag{1}$$

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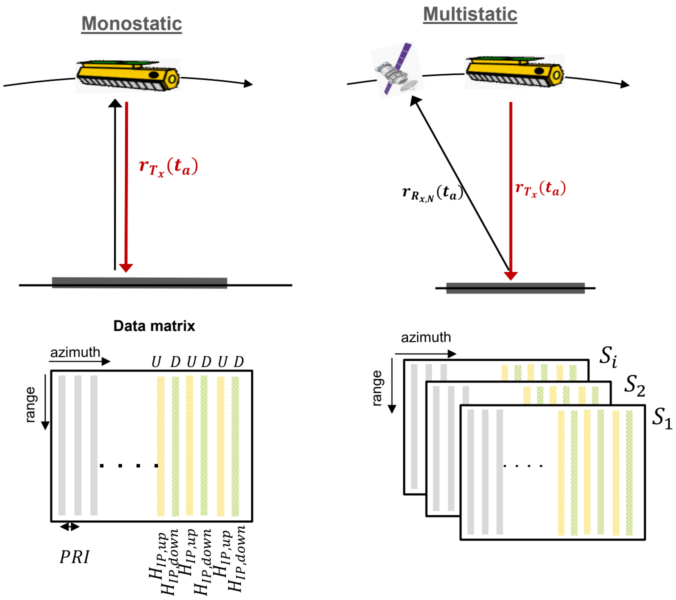

Fig. 1. Top: The observation geometry of a monostatic SAR system (left) and an along-track multistatic SAR constellation and the data matrices with the UDC modulation.

$$H_{IP,down}(f_r, f_a) = \exp\left[-\mathrm{j}\cdot 2\pi \cdot \frac{f_a}{|K|}\cdot f_r\right], \tag{2}$$

where f_r corresponds to the range-frequency, f_a to the Doppler frequency and $|K|$ is the absolute value of the chirp rate. For SAR systems without alternating transmitted signals, the IP effect may result in resolution loss both in azimuth and range dimensions, but it can be easily corrected with the complex conjugate of (1) or (2) depending on the transmitted waveform [6]. However, in case an up/down sequence is used, the intra-pulse effect shows itself as additional azimuth ambiguities if not properly accounted for. To date, no technique has been proposed in the literature to compensate for the intra-pulse effect in SAR systems with UDC modulation.

Figure 2 shows the impulse response function, where the azimuth ambiguities introduced by the uncompensated intra-pulse effect can be clearly observed, both for (top right) single channel and (bottom right) multichannel SAR systems with the UDC modulation. The simulation parameters are listed in Table I (single channel with TerraSAR-X parameters) and Table II (multi-channel with ROSE-L parameters). Figure 2 also shows as reference the impulse response of a system without UDC modulation and without any intra-pulse-effect (left column). As it can be clearly seen, the IP-related ambiguities in the single-channel system go as high as the ones due to the antenna pattern, while the ambiguities in the multi-channel system are much higher than the ones related to the antenna pattern. To put these results in numbers, the maximum Peak-to-Ambiguity-Ratio (PTAR) values in the single-channel system without UDC modulation and with IP effect are –30.60 dB and -33.16, where the total Azimuth-Ambiguity-to-Signal-Ratio (AASR) values are -20.42 dB and -23.69 dB, respectively. In the multi-channel case, the maximum PTAR values without UDC modulation and with IP effect are -59.51 dB and -38.92 dB, where the total AASR values are -40.13 dB and -29.50 dB, respectively.

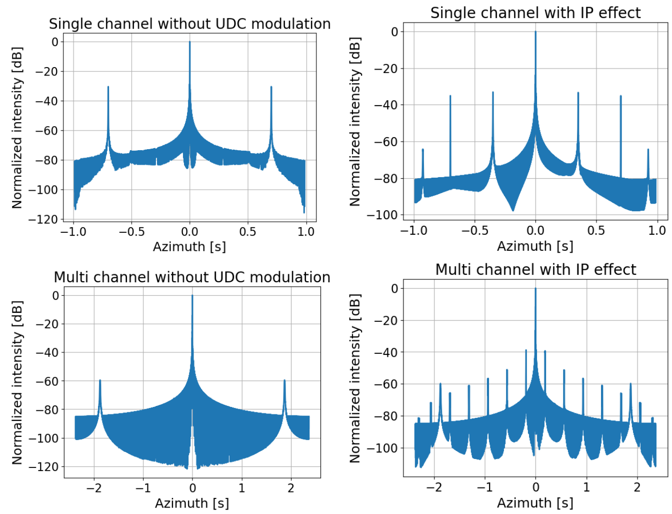

Fig. 2. Impulse response function (IRF) including the maximum of the azimuth ambiguity in all range bins. Top: single channel SAR system without UDC modulation (left) and with IP effect (right), and bottom: multi-channel SAR system without UDC modulation (left) and with IP effect (right).

TABLE I
SIMULATION PARAMETERS FOR THE SINGLE CHANNEL SIMULATION RESULTS SHOWN IN FIGURE 2 AND 5.

System parameters	
Orbit height	514 km
Center frequency	9.65 GHz
Chirp bandwidth	300 MHz
Chirp duration	50 μs
Processed Doppler bandwidth	2765 Hz
PRF	4174 Hz

B. IP Effect Compensation

The removal of the intra-pulse effect with UDC modulation differs for a single channel data sampled over the Nyquist frequency, and a multi-channel system operated with a PRF lower than the Nyquist criterion. Therefore, two different compensation techniques are proposed. The basic idea for both techniques is similar, namely, the removal of the phase deviation from both channels similarly as done when

TABLE II
SIMULATION PARAMETERS FOR THE SINGLE CHANNEL SIMULATION RESULTS SHOWN IN FIGURE 2 AND 6.

System parameters	
Orbit height	693 km
Center frequency	1.25 GHz
Chirp bandwidth	65.2 MHz
Chirp duration	48.61 μs
Processed Doppler bandwidth	2600 Hz
PRF	1378.18 Hz
Number of azimuth channels (N)	5

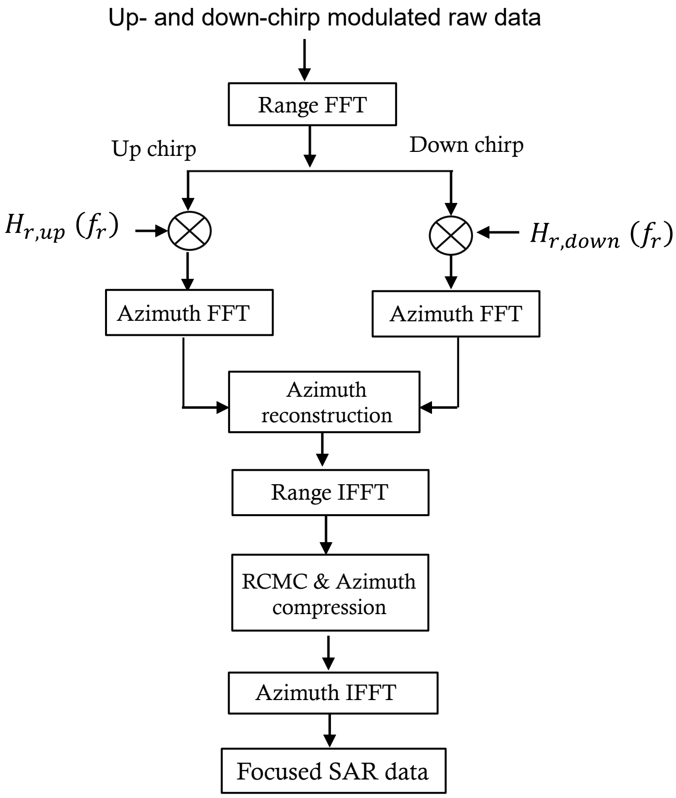

Fig. 3. Block diagram of the proposed reconstruction algorithm for single-channel SAR systems.

performing the azimuth reconstruction [5].

Figure 3 shows the block diagram of the processing approach for a single channel SAR system. The data are range compressed with the complex conjugate of the transmitted chirp via matched filtering with

$$H_{r,up}(f_r, f_a) = \mathrm{FT}\left\{\mathrm{rect}\left(\frac{t_r}{\tau_p}\right) \cdot \exp\left[-\mathrm{j} \cdot \pi \cdot |K| \cdot t_r^2\right]\right\}, \tag{3}$$

$$H_{r,down}(f_r, f_a) = \mathrm{FT}\left\{\mathrm{rect}\left(\frac{t_r}{\tau_p}\right) \cdot \exp\left[\mathrm{j} \cdot \pi \cdot |K| \cdot t_r^2\right]\right\}, \tag{4}$$

where t_r is the range time (fast time) and τ_P is the chirp duration, such that two independent channels are obtained: one for the up-chirp and one for the down-chirp. Then, the azimuth reconstruction with the inverse filter takes place in the wavenumber domain since the phase deviation due to the IP effect is space invariant, but range- and Doppler-frequency dependent. The transfer function of the IP effect is defined with a 2x2 matrix as

$$H(f_a) = \begin{bmatrix} H_{IP,up}(f_a) & H_{IP,down}(f_a) \\ H_{IP,up}(f_a + PRF) & H_{IP,down}(f_a + PRF) \end{bmatrix}. \tag{5}$$

where $H_{IP,up}(f_a)$ and $H_{IP,down}(f_a)$ represent the intra-pulse effect for up- and down-chirp respectively (see (1) and (2)), and PRF is the half of the operational PRF (PRF_{op}). The reconstruction filters may be computed by various different methods that can be found in the literature [5], [7], [8], [9], [10]. The choice of the reconstruction filter computation method highly depends on the considered system. For the single-platform system, the inverse filter (nulling approach) is the most convenient due to its simplicity and the fact that the displaced phase center antenna (DPCA) condition is met, hence ensuring a well-conditioned inversion. The reconstruction filters are computed with the inverse of the transfer functions as [5]

$$P(f_r, f_a) = H^{-1}(f_r, f_a). \tag{6}$$

Note, however, that since the transfer function of a single channel system is a 2x2 matrix for each range and azimuth frequency, the inversion can be computed analytically with the elements of the impulse response matrix (5) as

$$P(f_a) = \frac{1}{H_{11} \cdot H_{22} - H_{12} \cdot H_{21}} \begin{bmatrix} H_{22} & -H_{12} \\ -H_{12} & H_{11} \end{bmatrix} \tag{7}$$

which reduces the computational complexity considerable since the matrix inversion does not need to be performed. After the azimuth reconstruction is finalized, the remaining processing steps (RCMC and azimuth compression) can be applied in a conventional manner.

In the case of a multi-channel SAR system, the compensation approach becomes more complicated since the azimuth reconstruction has to consider the phase deviations caused by the geometrical differences of the multi-channel operation itself, as well as the intra-pulse effect. This implies that the complete transfer function depends on range time, as well as on the range and Doppler frequencies. This can be expressed as

$$\begin{aligned} H_{i,up}(f_a, f_r; r_0) = {} & \exp\left[-\mathrm{j} \cdot \Delta\phi_{geo,i}(f_r, f_a; r_0)\right] \cdot \\ & H_{IP,up}(f_a, f_r), \end{aligned} \tag{8}$$

$$\begin{aligned} H_{i,down}(f_a, f_r; r_0) = {} & \exp\left[-\mathrm{j} \cdot \Delta\phi_{geo,i}(f_r, f_a; r_0)\right] \cdot \\ & H_{IP,down}(f_a, f_r), \end{aligned} \tag{9}$$

where the first term of each equation is the phase deviation due to the geometrical difference of the receiver i with respect to the reference channel, and the second term is due to the intra-pulse effect. The phase of the geometrical difference can be expressed as

$$\Delta\phi_{geo,i} = 2\pi \cdot \left(\frac{f_0 + f_r}{f_a} \cdot C_0 + C_1 \cdot f_a + \frac{c \cdot C_2}{f_0 + f_r} \cdot f_a^2\right), \tag{10}$$

where c is the speed of light and the coefficients C_i are functions depending on range, baseline, wavelength, Doppler centroid and Doppler rate as shown in [11].

As mentioned before, the dependencies of the phase deviation

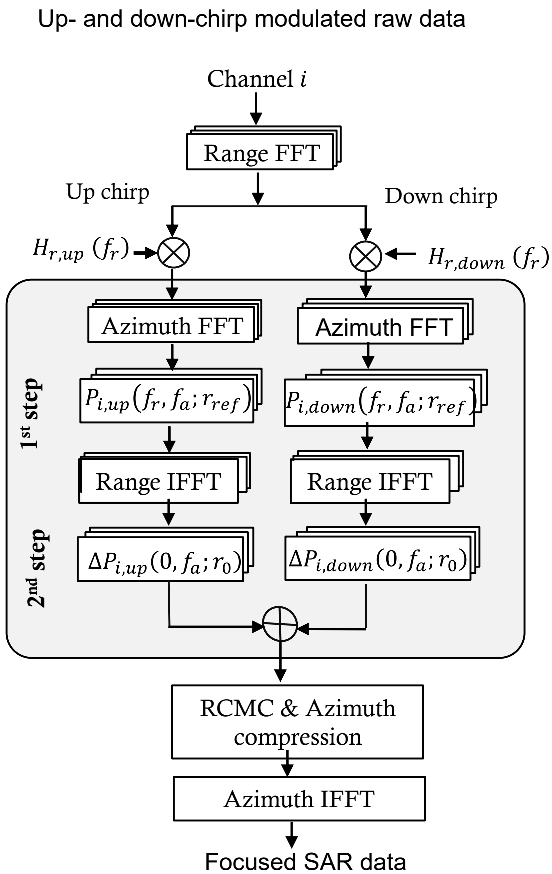

Fig. 4. Block diagram of the proposed reconstruction algorithm for single-channel SAR systems.

require a more elaborate compensation technique. Figure 4 shows the block diagram of the processing approach for multichannel systems. After the range compression and the separation of the up and down chirps in different data matrices, the number of channels doubles and the PRF becomes half of the operational PRF. Consequently, the reconstruction filter computation is done by solving the following system of linear equations [12]

$$H(f_r, f_a; r_0) = \begin{bmatrix} H_{1,up}(f_r, f_a; r_0) & H_{N,down}(f_r, f_a; r_0) \\ H_{1,up}(f_r, f_a + (2 \cdot N - 1) \cdot PRF; r_0) & H_{N,down}(f_r, f_a + (2 \cdot N - 1) \cdot PRF; r_0) \end{bmatrix} \tag{11}$$

$$P(f_r, f_a; r_0) = H^{-1}(f_r, f_a; r_0). \tag{12}$$

$$P_i(f_r, f_a; r_0) = P_i(f_r, f_a; r_{ref}) \cdot \Delta P_i(0, f_a; r_0(f_a)). \tag{13}$$

The first step of the azimuth reconstruction is to compute the filters in the wavenumber domain for a reference range bin ($P_i(f_r, f_a; r_{ref})$) and multiply the data with these filters without adding them together. After the data are brought back to the range-Doppler domain, the second step of the reconstruction takes place, which is the computation of the range- and Doppler-frequency-dependent residual filter as [12]

$$\Delta P_i(0, f_a; r_0) \approx \left| \frac{P_i(r_0, f_a)}{P_i(r_{ref}, f_a)} \right| \cdot \exp\left\{ \mathrm{j} \cdot \Delta\varphi_i(r_0, f_a) \right\}, \tag{14}$$

where the phase of the differential reconstruction filter is defined as [12]

$$\Delta\varphi_i(0, f_a; r_0) \approx \left[\varphi_i(0, f_a; r_0) - \varphi_i(0, f_a; r_{ref}) \right] \tag{15}$$

where $\varphi(.)$ is the phase of reconstruction filter $P_i(.)$. After the data are multiplied with (13) and summed up, the Doppler spectrum is recovered and the IP effect is compensated. As in the single channel case, the reconstructed data then go through the conventional SAR processing chain (RCMC and azimuth compression steps).

As hinted in the previous sub-section, this approach is a generalized solution for the multi-receiver system case. On the other hand, the computational complexity of the two-step reconstruction might be reduced for the multi-channel systems by isolating the compensation of intra-pulse effect and the geometry related deviations. It is already shown in [11] that the range-frequency dependence of $\Delta\phi_{geo}(.)$ can be neglected for the multi-channel SAR systems. Therefore, the first step of the reconstruction can be limited to the compensation of the intra-pulse effect, where the computation of the reconstruction filter becomes the inversion of a 2x2 matrix. Then, the second step can remove the geometry related phase deviation in the range-Doppler domain.

Note that should the orthogonal waveforms such as short-term-shift-orthogonal waveforms [13] be used instead of a UDC modulation scheme, the same reconstruction strategy could be applied to compensate the IP effect by modifying the transfer functions in (8) and (9) for each waveform accordingly.

C. Results

Figures 5 and 6 show the IRF of a point target without (top) intra-pulse effect and (bottom) corrected intra-pulse effect with the azimuth reconstruction in single channel and multi-channel SAR systems, respectively. The responses without the correction are in Figure 2 on the right column. It is clear that the proposed approach mitigates significantly the azimuth ambiguities caused by the intra-pulse effect, such that they remain either less (single channel) or around the same level (multi channel) as the azimuth ambiguities related to the antenna pattern. The reason for not removing the IP effect completely is the impossibility to compensate the phase deviation in the frequency bins outside of the original signal spectrum ($[-N/2 \cdot PRF_{op}, N/2 \cdot PRF_{op}]$). The same limitation also applies to the traditional azimuth reconstruction, which only compensates for the geometry deviation within this same Doppler interval. Nevertheless, the proposed methods manage to keep the azimuth ambiguities within an acceptable level. Note that the intra-pulse effect and the geometric phase error correction are independent. Any performance degradation due to non-optimal sampling conditions or orbit knowledge errors will not affect the intra-pulse effect correction performance.

III. Conclusion

This paper has discussed the implications of the intra-pulse effect for UDC modulated SAR systems in both single and

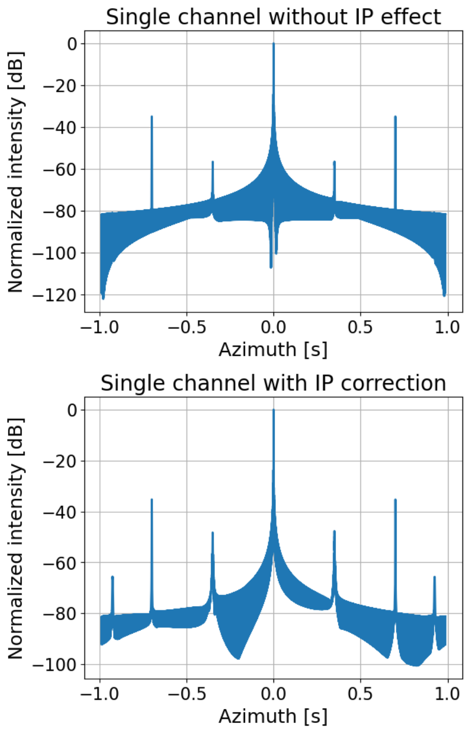

Fig. 5. Single channel: IRF of a point target including the maximum of the azimuth ambiguity in all range bins. Top: without IP effect (PTAR = -34.92 dB, AASR = -26.95 dB), bottom: after the IP correction (PTAR = -35.22 dB, AASR = -27.14 dB).

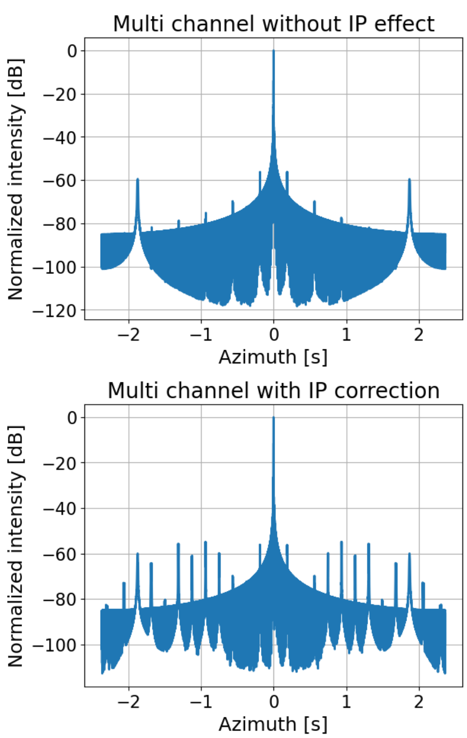

Fig. 6. Multichannel: IRF of a point target including the maximum of the azimuth ambiguity in all range bins. Top: without IP effect (PTAR = -56.23 dB, AASR = 39.52 dB), botom: after the IP correction (PTAR = -55.73 dB, AASR = -35.53 dB).

multi-receiver configurations. Although the IP effect is known and discussed in the literature for high-resolution single-platform SAR systems, it is not addressed for either wave modulated or multichannel SAR systems. The presented point-target simulations have shown that an uncompensated IP effect leads to additional azimuth ambiguities. We have proposed two different compensation approaches for single and multi-receiver systems based on an azimuth reconstruction processing scheme. For single-channel systems, the range-invariant polychromatic phase is corrected in the wavenumber domain, while for multi-receiver systems a two-step reconstruction method is required due to the time and frequency dependence of the azimuth reconstruction. The two proposed approaches have been validated with point target simulations, showing that the intra-pulse effect can be properly compensated and the additional azimuth ambiguities can be mitigated to an acceptable level.

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