Second Order Motion Compensation for Squinted Spotlight Synthetic Aperture Radar

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Abstract—This paper presents a 2nd order motion compensation (MoCom) algorithm for squinted spotlight synthetic aperture radar (SAR). A precise compensation of the range-dependent components of the motion error is indispensable for high-resolution SAR systems. Besides, the MoCom has to be compatible with an accurate focusing technique – the Omega-K algorithm in this case. After a proper bulk MoCom and a range cell migration correction, the proposed MoCom accomplishes a phase error compensation considered for every position in the spot. For pulsed SAR with a squint angle of 20° and a depression angle of 20°, the proposed algorithm compensates residual phase errors greater than \([-\pi, +\pi]\) radian and obtains significant image quality enhancement. The distinctive feature of the proposed approach is its capability to compensate residual motion errors in the presence of a large squint angle.

I. INTRODUCTION

Airborne SAR systems are disturbed by motion errors, which – if not corrected – lead to image quality degradation. The main effects observed are the loss of geometric resolution and radiometric accuracy, reduction of image contrast, increase of sidelobes and strong phase distortions [1]. By recording the relevant motion parameters with an onboard GPS/IMU system, the real movement of the sensor can be taken into account by advanced SAR imaging.

Several approaches have been used for the processing of airborne SAR data. Time-domain approaches are able to accurately consider non-linear movement of the sensor [2]. However, they have very high computational complexity and are at the moment not yet applicable for realtime onboard processing. Out of all frequency-domain approaches, the Omega-K algorithm provides an ideal solution of the SAR imaging [3]. Due to its computational efficiency, the Omega-K algorithm can be run in realtime [4] [5]. The main drawback of this algorithm is the requirement of a straight flight path and constant velocity of the sensor. If not held, the ideal flight path has to be restored by motion compensation (MoCom) techniques. Common MoCom procedure consists of a bulk (1st order) MoCom and a residual (2nd order) MoCom. Reigber et al. developed an extended Omega-K algorithm with an integrated MoCom [1]. This approach provides good results for broadside SAR with small squint angle.

This paper presents a 2nd order MoCom approach for squinted SAR, which is both compatible with and independent of the Omega-K algorithm. The proposed MoCom calculates and compensates the residual motion errors in the presence of the squint angle. The correction is done in the direction that is perpendicular to the direction of wave propagation. Therefore, a modified range cell migration correction (modRCMC) has to be realized first. The phase error induced by residual motion errors will be calculated for each position in the spot dependent on the squint and depression angle. After phase error correction the modRCMC will be inverted to retain the range compressed SAR data for the subsequent Omega-K processing.

This paper is organized as follows: In the next section the procedure for squinted spotlight SAR focusing is explained. The center beam approximation and 1st order MoCom will be described in section 3. Afterwards, section 4 analyzes the residual motion error in squinted SAR geometry and presents the proposed 2nd order MoCom approach. Results and discussions are presented in section 5.

II. SQUINTED SPOTLIGHT SAR IMAGING

While the platform moves with a constant velocity \(v\) along azimuth (the \(x\)-axis), the radar illuminates the ground within \([-L/2, L/2]\), see Fig. 1. The slant range \(z\) is perpendicular to the \(x\)-axis. In the presence of the squint angle \(\theta_s\), the wave propagation direction \(r\) is rotated by \(\theta_s\) from the slant range \(z\). The direction perpendicular to \(r\) is called “squinted azimuth”. The \(y\)-axis is called ground range, the \(h\)-axis denotes the height and \(\theta_0\) the depression angle. All scatterers are located within the spot on the flat ground surface.

The acquired SAR raw data is fed into the SAR processor shown in Fig. 2. Range compression is realized by a matched
The offtrack error induces a shift in range and a phase error of
\[ \phi_e = \exp \left\{ j2\pi \frac{2f_c}{c} \Delta z \cos \theta_S \right\}, \]  
where \( f_c \) is the carrier frequency and \( c \) velocity of light.

The 1st order MoCom [7] compensates the shift in range, the phase error given in (2) and the azimuth deviation in the listed order.

IV. PROPOSED SECOND ORDER MoCom

The 1st order MoCom [7] takes the squint angle \( \theta_S \) into account and exactly compensates the position errors for the spot center with the adjusted depression angle \( \theta_D \). Since the offtrack error depends on the depression angle \( \theta_D \), the calculation of \( \Delta z \) in (1) is only valid for the center range corresponding to \( \theta_D \). A target \( p \) at other range is afflicted with a range dependent offtrack error expressed as
\[ \Delta z_p = \Delta y \cdot \cos \theta_D - \Delta h \cdot \sin \theta_D. \]

For this target \( p \) a residual error of \( \Delta z_p - \Delta z \) is left after the 1st order MoCom. Focusing result degradation is expected for higher order residual phase error greater than \( \pi/4 \) [10]. I.e. for a X-band system with a wavenumber \( \lambda = 3 \) cm, a 2nd order MoCom is needed if the residual offtrack errors are greater than 2 nm.

The aim of the proposed 2nd order MoCom is to compensate the residual offtrack error \( \Delta z_p - \Delta z \) for every point target \( p \) in the spot. It is assumed that the residual offtrack error is small enough to be considered as phase error [1]. Each target in the spot is associated with an individual depression angle \( \theta_{DP} \). Common methods calculate the phase error in dependence of \( \theta_{DP} \). Targets located on a perpendicular line to the z-axis have the same \( \theta_{DP} \) (dashed line parallel to azimuth in Fig. 3) and so the same offtrack error \( \Delta z_p \). These methods are valid for broadside SAR with a small squint angle \( \theta_S \).

However, if \( \theta_S \) is large, the direction of wave propagation \( r \) deviates from the slant range \( z \) and the target-dependent error has to be calculated with respect to lines perpendicular to the \( r \)-axis (dotted lines parallel to squinted azimuth in Fig. 3 and Fig. 4) [6]. Therefore, the proposed algorithm first performs a modRCMC realized by local linearization, see Fig. 4. The modRCMC is carried out with respect to the squinted azimuth direction (and not to the azimuth axis like common RCMC). The resulted range migration is perpendicular to the wave propagation direction.

The phase error is calculated and corrected for every target depending on \( \beta \) and \( \alpha_p \)
\[ \phi_{ep} = \exp \left\{ j4\pi f_c \left( \Delta y \cos \theta_{DP} \cos \theta_S - \Delta h \sin \theta_{DP} \cos \theta_S \right) \right\} \]
\[ = \exp \left\{ j4\pi f_c \left( \Delta y \cos \beta \cos \alpha_p - \Delta h \sin \alpha_p \right) \right\}. \]

Subsequent to the residual phase error compensation by using \( \phi_{ep} - \phi_e \), the modRCMC is inverted and finally an Omega-K algorithm for squinted SAR [9] is carried out yielding the desired SAR image.
Fig. 4: Modified RCMC: the range migration is corrected to a straight line perpendicular to the wave propagation direction.

It has to be noted that the efficiency of the proposed algorithm depends on both the squint angle and the depression angle. The calculation of $\phi_{ep}$ in (4) is also valid for the broadside case. For $\theta_S = 0$, $\alpha_p$ is identical with $\theta_{DP}$.

V. Results

Fig. 7 presents the results of an airborne X-band SAR simulation with parameters shown in Table I. Five targets are distributed in a square region of the size 500 m $\times$ 500 m with reference range $R_0 = 16$ km, squint angle $\theta_S = 20^\circ$ and depression angle $\theta_D = 20^\circ$. SAR raw data from the five targets were simulated with significant motion errors. The deviations from the ideal flight track in azimuth, ground range and height were set to vary between $\pm 5$ m, see Fig. 5. The resolution cell is 1 m $\times$ 1 m.

The simulated SAR raw data is first processed with 1st order MoCom. By applying the center beam approximation, $\Delta z$ is calculated with equation (1). The results of the 1st order MoCom are shown in Fig. 7 (b) and (c). For the target at spot center, motion errors have been completely compensated. For the bottom target, residual offtrack error suppresses the main lobe level by $-10$ dB and produces a smearing in squinted azimuth.

The accuracy of the 2nd order MoCom depends on the ground range distance from the point target to the spot center. Thus, the bottom and top target are chosen to demonstrate the efficiency of the proposed MoCom.

For the bottom point target, the residual phase error $\Delta \phi_y = \phi_{ep} - \phi_y$ is calculated (see Fig. 6) and compensated in the direction of squinted azimuth. Comparing the results of the image reconstruction without (in Fig. 7 (c)) and with 2nd order MoCom (in Fig. 7 (f)), we can see that the great part of motion errors are compensated. The focusing result of the top target in Fig. 7 (d) demonstrates the fact that the nearer a target is to the spot center, the better is the focusing result. The focusing quality of the center target remains as expected the same, see Fig. 7 (e).

Table II shows one-dimensional integrated sidelobe ratios (ISLR) calculated for the top, center and bottom point target as

$$\text{ISLR} = 10 \log_{10} \left\{ \frac{P_{\text{total}} - P_{\text{main}}}{P_{\text{main}}} \right\}. \quad (5)$$

$P_{\text{main}}$ is the power of the main lobe within twice the impulse response width. Thus, the numerator of (5) is the total power of the sidelobes within twenty times the impulse response width. The ISLR of the center target is in both cases close to the ideal value of $-9.8$ dB of an ideal sinc-function since no window is used for sidelobe suppression. For the top and bottom target, the 2nd order MoCom improves their ISLR significantly.

<table>
<thead>
<tr>
<th>TABLE I: Simulation parameters</th>
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<tr>
<td>Carrier frequency $f_c$</td>
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<td>Pulse bandwidth $B_p$</td>
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<tr>
<td>Pulse duration $T$</td>
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<tr>
<td>Sample frequency</td>
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<td>Platform velocity $v$</td>
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<td>Synthetic aperture length</td>
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<td>Pulse repetition frequency</td>
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<th>TABLE II: ISLR measured in the squinted azimuth direction</th>
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<td>Top target</td>
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<tr>
<td>after 1st order MoCom</td>
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<td>after 2nd order MoCom</td>
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Fig. 7: Simulation results for point targets in the spot: after 1st order MoCom in (b), (c) and after 2nd order MoCom in (d)–(f). Coloured contour lines given in dB.

VI. CONCLUSIONS

A 2nd order MoCom for squinted SAR imaging is presented in this paper. It is shown that the residual phase error has to be calculated and compensated in the squinted azimuth direction, which is perpendicular to the wave propagation direction. The performance and accuracy of the proposed approach has been demonstrated with simulated raw data in X-band. It is shown that residual phase error in the size of \([-\pi, +\pi]\) radian is mostly compensated for a squint angle of 20°.

The advantage of the presented approach is its independence of the subsequent SAR processor. Thus, it can be easily used together with a realtime Omega-K algorithm for onboard SAR processing.

For SAR geometries where the range migration is well approximated by the range walk, the modRCMC and Inverse modRCMC steps can be skipped. In those cases the 2nd order MoCom becomes very efficient since it consists of only a phase error calculation and compensation.

The proposed algorithm is a generalization for variable squint angle and is also valid for SAR broadside mode. So far this approach has been tested on X-band SAR data focused with Omega-K algorithm and needs further investigations on different settings to find its accuracy limitations.

REFERENCES