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 (1^{st} order) MoCom and a residual (2^{nd} 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 2^{nd} 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 1^{st} order MoCom will be described in section 3. Afterwards, section 4 analyzes the residual motion error in squinted SAR geometry and presents the proposed 2^{nd} 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 θ_S, the wave propagation direction r is rotated by θ_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 θ_D 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

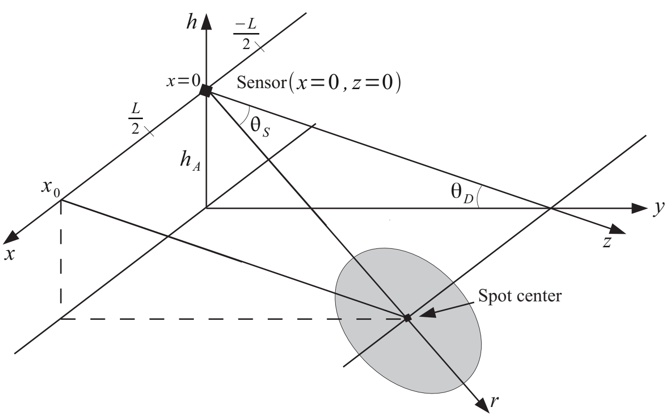


Fig. 1: SAR geometry in squinted spotlight mode

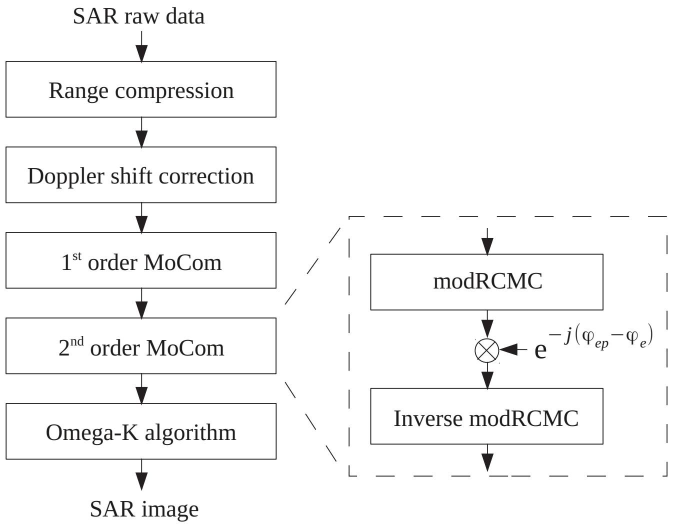


Fig. 2: Squinted spotlight SAR focusing with the proposed MoCom and Omega-K algorithm

filter. The squint angle evokes a shift of the Doppler center frequency which has to be compensated. After Doppler shift correction, a 1st order MoCom, which considers the squint angle [7], is carried out. The 1st order MoCom makes use of the center beam approximation [8] and fully compensates motion error for the spot center. All other targets within the spot are afflicted with a residual motion error. The 2nd order MoCom compensates the locally dependent residual motion errors by phase error compensation before Omega-K processing [9].

III. First Order MoCom with Center Beam Approximation

Fig. 3 shows the position errors of the platform measured by the GPS/IMU system. The position errors can be divided into the azimuth position error Δx and the offtrack error. The azimuth deviation arises from a variable flight velocity and is corrected by resampling and interpolation to retrieve spatially equidistant sampling in the azimuth direction.

For broadside SAR the offtrack error can be calculated by using the center beam approximation [8] as

$$\Delta z = \Delta y \cdot \cos\theta_D - \Delta h \cdot \sin\theta_D. \quad (1)$$

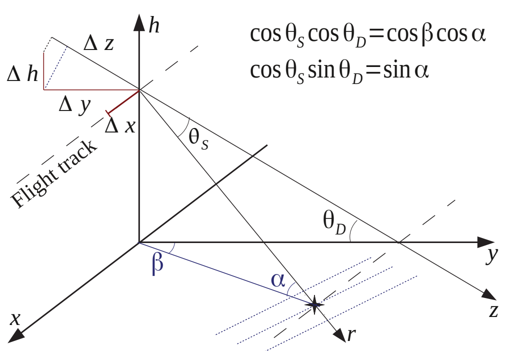


Fig. 3: Geometry of position errors and proposed MoCom

The offtrack error induces a shift in range and a phase error of

$$\phi_e = \exp\left\{ j2\pi \frac{2f_c}{c} \Delta z \cdot \cos\theta_S \right\}, \quad (2)$$

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 θ_S into account and exactly compensates the position errors for the spot center with the adjusted depression angle θ_D. Since the offtrack error depends on the depression angle θ_D, the calculation of Δz in (1) is only valid for the center range corresponding to θ_D. A target p at other range is afflicted with a range dependent offtrack error expressed as

$$\Delta z_p = \Delta y \cdot \cos\theta_{Dp} - \Delta h \cdot \sin\theta_{Dp}. \quad (3)$$

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 $\lambda = 3\,\text{cm}$, a 2nd order MoCom is needed if the residual offtrack errors are greater than 2 mm.

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 θ_{Dp}. Common methods calculate the phase error in dependence of θ_{Dp}: Targets located on a perpendicular line to the z-axis share the same θ_{Dp} (dashed line parallel to azimuth in Fig. 3) and so the same offtrack error Δz_p. These methods are valid for broadside SAR with a small squint angle θ_S.

However, if θ_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 β and α_p

$$\phi_{ep} = \exp\left\{ j\frac{4\pi f_c}{c} \left(\Delta y \cos\theta_{Dp} \cos\theta_S - \Delta h \sin\theta_{Dp} \cos\theta_S \right) \right\}$$
$$= \exp\left\{ j\frac{4\pi f_c}{c} \left(\Delta y \cos\beta \cos\alpha_p - \Delta h \sin\alpha_p \right) \right\}. \quad (4)$$

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.

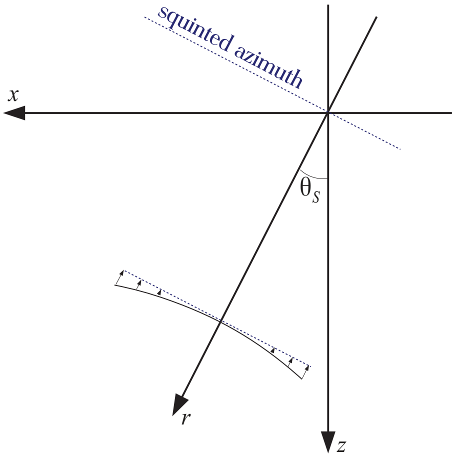


Fig. 4: Modified RCMC: the range migration is corrected to a straight line perpendicular to the wave propagation direction

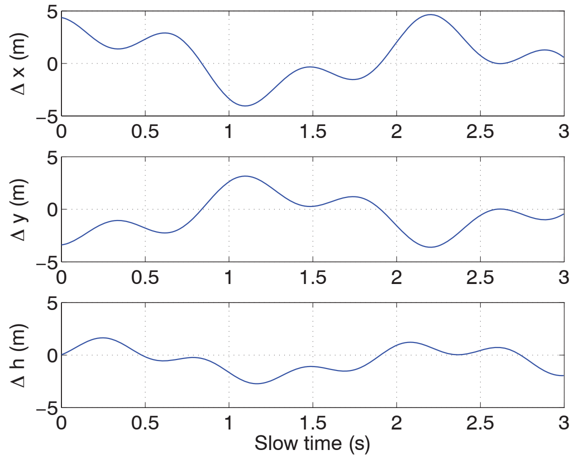


Fig. 5: Simulated motion errors in directions of azimuth, ground range and height

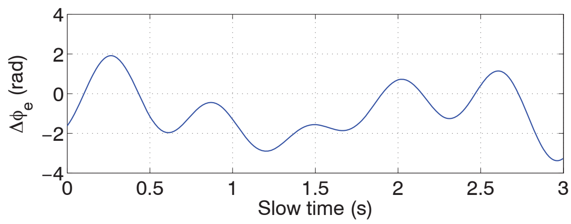


Fig. 6: Calculated residual phase error for bottom target

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 ϕ_{ep} in (4) is also valid for the broadside case. For $\theta_S = 0$, α_p is identical with θ_{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 $500\,\text{m} \times 500\,\text{m}$ with reference range $R_0 = 16\,\text{km}$, squint angle $\theta_S = 20°$ and depression angle $\theta_D = 20°$. 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 $\pm 5\,\text{m}$, see Fig. 5. The resolution cell is $1\,\text{m} \times 1\,\text{m}$.

The simulated SAR raw data is first processed with 1st order MoCom. By applying the center beam approximation, Δz 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 $-10\,\text{dB}$ 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 $\Delta\phi_e = \phi_{ep} - \phi_e$ 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

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

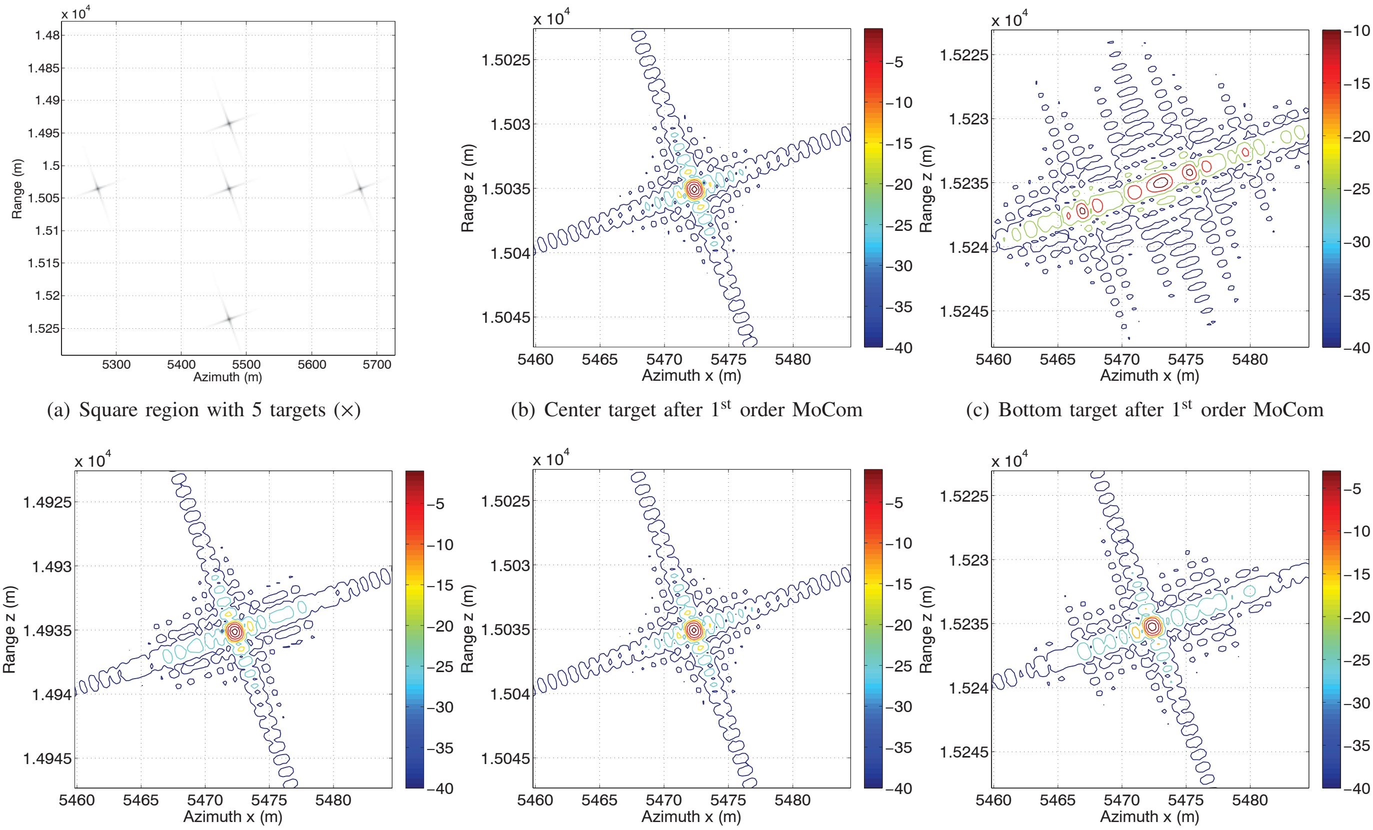
P_{main} is the power of the main lobe within twice the impulse response width. Thus, the numerator of (5) is the total power of the sidelobes within twenty times the impulse response width. The ISLR of the center target is in both cases close to the ideal value of $-9.8\,\text{dB}$ of an ideal sinc-function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

TABLE I: Simulation parameters

Carrier frequency f_c	10 GHz
Pulse bandwidth B_p	150 MHz
Pulse duration T	6 μs
Sample frequency	180 MHz
Platform velocity v	100 m/s
Synthetic aperture length	300 m
Pulse repetition frequency	400 Hz

TABLE II: ISLR measured in the squinted azimuth direction

	Top target	Center target	Bottom target
after 1st order MoCom	−1.58 dB	−9.87 dB	+7.44 dB
after 2nd order MoCom	−8.61 dB	−9.83 dB	−5.78 dB



(a) Square region with 5 targets (×)

(b) Center target after 1st order MoCom

(c) Bottom target after 1st order MoCom

(d) Top target after 2nd order MoCom

(e) Center target after 2nd order MoCom

(f) Bottom target after 2nd order MoCom

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

[1] A. Reigber, E. Alivizatos, A. Potsis and A. Moreira, "Extended wavenumber-domain synthetic aperture radar focusing with integrated motion compensation", IEE Proc.-Radar Sonar Navig., Vol. 153, No. 3, pp. 301–310, 2006.

[2] L. M. H Ulander, H. Hellsten and G. Stenstrom, "Synthetic aperture radar processing using fast factorized back-projection", IEEE Trans. Aerosp. Election. Syst., 2003, 39, (3), pp. 760–776.

[3] C. Cafforio, C. Prati and F. Rocca, "SAR data focusing using seismic migration techniques", IEEE Transaction on Aerospace and Electronic Systems, pp. 194-207, March 1991.

[4] C. Simon-Klar, M. Kirscht, S. Langemeyer, N. Nolte and P. Pirsch, "A flexible hardware architecture for real-time airborne Wavenumber Domain SAR processing", Proc. EUSAR 2012, Nuremberg, pp. 28–31, 2012.

[5] M. Pfitzner, F. Cholewa, P. Pirsch and H. Blume, "A flexible hardware architecture for real-time airborne Wavenumber Domain SAR processing", Proc. EUSAR 2012, Nuremberg, pp. 28–31, 2012.

[6] Fornaro, G. and Franceschetti, G. and Perna, S., "Motion compensation of squinted airborne SAR raw data: role of processing geometry", Proc. IGARSS'04, pp. 1518–1521, 2004.

[7] M. P. Nguyen, "Refined motion compensation for highly squinted spotlight synthetic aperture radar," Proc. EUSAR 2012, Nuremberg, pp. 738–741, 2012.

[8] G. Fornaro, G. Franceschetti and S. Perna, "On center-beam approximation in SAR motion compensation", IEEE Geoscience and Remote Sensing Letters, 3:22, pp. 276–280, 2006.

[9] M. P. Nguyen, "Omega-K algorithm – A generalization for highly squinted spotlight SAR imaging with dechirp-on-receive", Proc. APSAR 2011, Seoul, pp. 137–140, 2011.

[10] W. G. Carrara, R. S. Goodman and R. M. Majewski, "Spotlight synthetic aperture radar- Signal processing algorithms", Artech House, 1995.