Improved SAR Motion Compensation without Interpolation

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Abstract

Motion compensation is an important part of SAR processing for high resolution airborne sensors, such as those flown on UAS's. The non-ideal motion of the platform results in degraded image quality, but for known motion, corrections can be made. Traditional motion compensation requires a computationally costly interpolation step to correct translational motion greater than a single range bin. This paper presents an efficient new motion compensation algorithm that corrects this range shift without interpolation. The new method is verified with simulated SAR data and data collected with the NuSAR.

1 Introduction

Motion compensation for airborne synthetic aperture radar (SAR) has always been important for high precision image formation. With high resolution SAR systems now operating on small aircraft and Unmanned Aircraft Systems (UAS's) [1]-[2], which are more susceptible to atmospheric turbulence, motion compensation is receiving renewed attention [3]-[5].

This paper develops a new motion compensation scheme for pulsed SAR systems. Conventional methods treat motion compensation as a phase correction problem, applying a bulk phase correction to the raw data to correct for a reference range followed by a differential phase correction applied after range compression to account for the range dependence of the motion correction.

This method fails to account for the source of the phase errors, the range shift due to the motion. This is a significant problem when the magnitude of the translational motion is greater than a range bin [6]. Interpolation is sometimes used to address this issue; however, it adds an additional computational burden. This is not acceptable for a high resolution SAR system designed to operate from a UAS and process the data in real-time.

The Naval Research Laboratory UAS SAR (NuSAR) is such a system. The NuSAR was developed as part of the U.S. Naval Research Laboratory's (NRL) DUSTER program in a team effort with Brigham Young University (BYU), ARTEMIS Inc., Space Dynamics Laboratory (SDL), and NRL. The NuSAR is one component of an integrated Longwave Infrared (LWIR), Visible Near-Infrared (VNIR), and SAR Imaging System.

The new motion compensation method presented in this paper uses chirp scaling principles to correct the range shift and phase variations caused by translational motion. Section 2 presents the errors caused by translation motion and the traditional two-step motion compensation algorithm. The new compensation algorithm is developed in Section 3. Section 4 presents simulation results comparing the proposed algorithm to the traditional method and also presents NuSAR data which is used to verify the new method.

2 Translational Motion Errors

Basic SAR processing assumes that the platform moves in a straight line. In any actual data collection this is not the case, as the platform experiences a variety of deviations from the ideal path. These deviations introduce errors in the collected data which degrade the SAR image.

Translational motion causes platform displacement from the nominal, ideal path. This results in the target scene changing in range during data collection. This range shift also causes inconsistencies in the target phase history [7]. A target at range R is measured at range $R + \Delta R$ which introduces a phase shift of

$$\phi_{\mathrm{m}} = \frac{-2\Delta R \cdot 2\pi}{\lambda} \tag{1}$$

in the data. Fortunately, if the motion in known (usually from an on-board INS/GPS sensor), then the motion errors can be corrected.

The common method for compensating for the non-ideal motion involves two steps. First, the corrections are calculated for a reference range, R_{ref}, usually in the center of the swath. The phase correction

$$H_{\mathrm{mc1}} = \exp\left(j\frac{4\pi\Delta R_{\mathrm{ref}}}{\lambda}\right) \tag{2}$$

is applied to the raw data.

The SAR data is range compressed. A second order correction is applied to each range according to the differential correction from the reference range. For each R, ΔR is calculated and the correction is formed,

$$H_{\mathrm{mc2}} = \exp\left(j\frac{4\pi\left(\Delta R - \Delta R_{\mathrm{ref}}\right)}{\lambda}\right). \tag{3}$$

At this point the motion-induced range shift can be removed through a computationally taxing interpolation. This method is commonly used in range-Doppler (RDA) processing and chirp-scaling (CSA) for SAR image generation.

3 New Motion Compensation

To formulate a new motion compensation scheme we start with the exponential terms of the demodulated SAR signal, as defined in [8],

$$s_0(\tau,\eta) = e^{(-j4\pi f_0 R(\eta)/c)} \cdot e^{\left(j\pi K_r(\tau-2R(\eta)/c)^2\right)} \quad (4)$$

where τ is fast (range) time, η is slow (along-track) time, f_0 is the center frequency, $R(\eta)$ is the range to target, c is the speed of light, and K_r is the chirp rate.

With translational motion, the range $R(\eta)$ becomes $R(\eta) + \Delta R(\eta)$. We split the motion term into range-dependent, $\Delta R_{\text{diff}}(\eta)$, and range-independent, $\Delta R_{\text{ref}}(\eta)$, terms,

$$\Delta R(\eta) = \Delta R_{\text{ref}}(\eta) + \Delta R_{\text{diff}}(\eta), \quad (5)$$

which changes the demodulated signal, Eq. (4), to

$$s_m(\tau,\eta) = e^{\left(-j4\pi f_0 \frac{R(\eta)+\Delta R_{\text{ref}}(\eta)+\Delta R_{\text{diff}}(\eta)}{c}\right)} \cdot e^{\left(j\pi K_r\left(\tau-2\frac{R(\eta)+\Delta R_{\text{ref}}(\eta)+\Delta R_{\text{diff}}(\eta)}{c}\right)^2\right)} \quad (6)$$

which expands into

$$\begin{aligned} s_m(\tau,\eta) = \; & e^{(-j4\pi f_0 R(\eta)/c)} \cdot e^{\left(j\pi K_r(\tau-2R(\eta)/c)^2\right)} \\ & \cdot e^{\left(j4\pi K_r \frac{\Delta R_{\text{ref}}(\eta)^2}{c^2}\right)} \cdot e^{\left(-j4\pi f_0 \frac{\Delta R_{\text{ref}}(\eta)}{c}\right)} \\ & \cdot e^{(-j4\pi K_r \tau \Delta R_{\text{ref}}(\eta)/c)} \\ & \cdot e^{\left(j8\pi K_r \Delta R_{\text{ref}}(\eta)(\Delta R_{\text{diff}}(\eta)+R(\eta))/c^2\right)} \\ & \cdot e^{\left(j\frac{4\pi K_r \Delta R_{\text{diff}}(\eta)^2}{c^2}\right)} \cdot e^{\left(j\frac{8\pi K_r R(\eta)\Delta R_{\text{diff}}(\eta)}{c^2}\right)} \\ & \cdot e^{\left(-j4\pi f_0 \frac{\Delta R_{\text{diff}}(\eta)}{c}\right)} \cdot e^{\left(-j4\pi K_r \tau \frac{\Delta R_{\text{diff}}(\eta)}{c}\right)} \end{aligned} \quad (7)$$

where the first two terms are the desired signal, Eq. (4), the next three terms are the range-independent errors, and the last five terms are the range-dependent errors.

The proposed method also follows a two step scheme but eliminates the need for interpolation. The first correction is applied to the raw data.

$$M_1(\tau,\eta) = e^{\left(\frac{-j4\pi \Delta R_{\text{ref}}(\eta)\left(-f_0 c - K_r \tau c + K_r \Delta R_{\text{ref}}(\eta)\right)}{c^2}\right)}. \quad (8)$$

It cancels the range-independent errors and shifts the targets in range.

The data is then range compressed with a common algorithm (RDA or CSA). We simplify the next step by assuming that the range-dependent errors do not change during range compression. This introduces additional phase errors that we ignore, with future efforts planned to track the phase errors through the processing steps. The second motion correction is applied to the range compressed data, cancelling the range-dependent error terms,

$$\begin{aligned} M_2(R,\eta) = \; & e^{\left(-j8\pi K_r \Delta R_{\text{ref}}(\eta)(\Delta R_{\text{diff}}(\eta)+R(\eta))/c^2\right)} \\ & \cdot e^{\left(-j\frac{4\pi K_r \Delta R_{\text{diff}}(\eta)^2}{c^2} - j\frac{8\pi K_r R(\eta)\Delta R_{\text{diff}}(\eta)}{c^2}\right)} \\ & \cdot e^{\left(j4\pi f_0 \frac{\Delta R_{\text{diff}}(\eta)}{c}\right)} \cdot e^{\left(j4\pi K_r \tau \frac{\Delta R_{\text{diff}}(\eta)}{c}\right)} \end{aligned} \quad (9)$$

where $\tau = 2R/c$.

4 Results

SAR data, simulated with parameters matching the X-Band NuSAR described below, is used to verify the proposed motion compensation algorithm. In **Figure 1** a single point target is shown to have better range and azimuth resolution after applying the proposed motion compensation algorithm. **Figure 2** shows an array of point targets with the same motion as in **Figure 1**. The results of the proposed motion compensation algorithm are dramatically better for translational motion of larger magnitude, as is demonstrated in **Figure 3**.

The NuSAR is designed for UAS flight operating at L-Band or X-Band a 500 MHz bandwidth giving a 30 cm resolution. **Figure 4** shows an area imaged with the NuSAR and processed with the CSA. The application of the standard and proposed motion compensation algorithms is shown. Unfortunately the motion compensation in this example is limited by low quality motion data, nevertheless the image quality is enhanced by using the motion compensation algorithms. The improvements are most noticeable in the increased sharpness of the fine details. The processing time is virtually identical for the two motion compensation methods.

5 Conclusion

An improved motion compensation algorithm for pulsed SAR has been proposed and tested. The results show that it properly corrects the effects of non-ideal motion while offering some advantages. The proposed method can be implemented in place of the traditional method to improve processing efficiency and accuracy.

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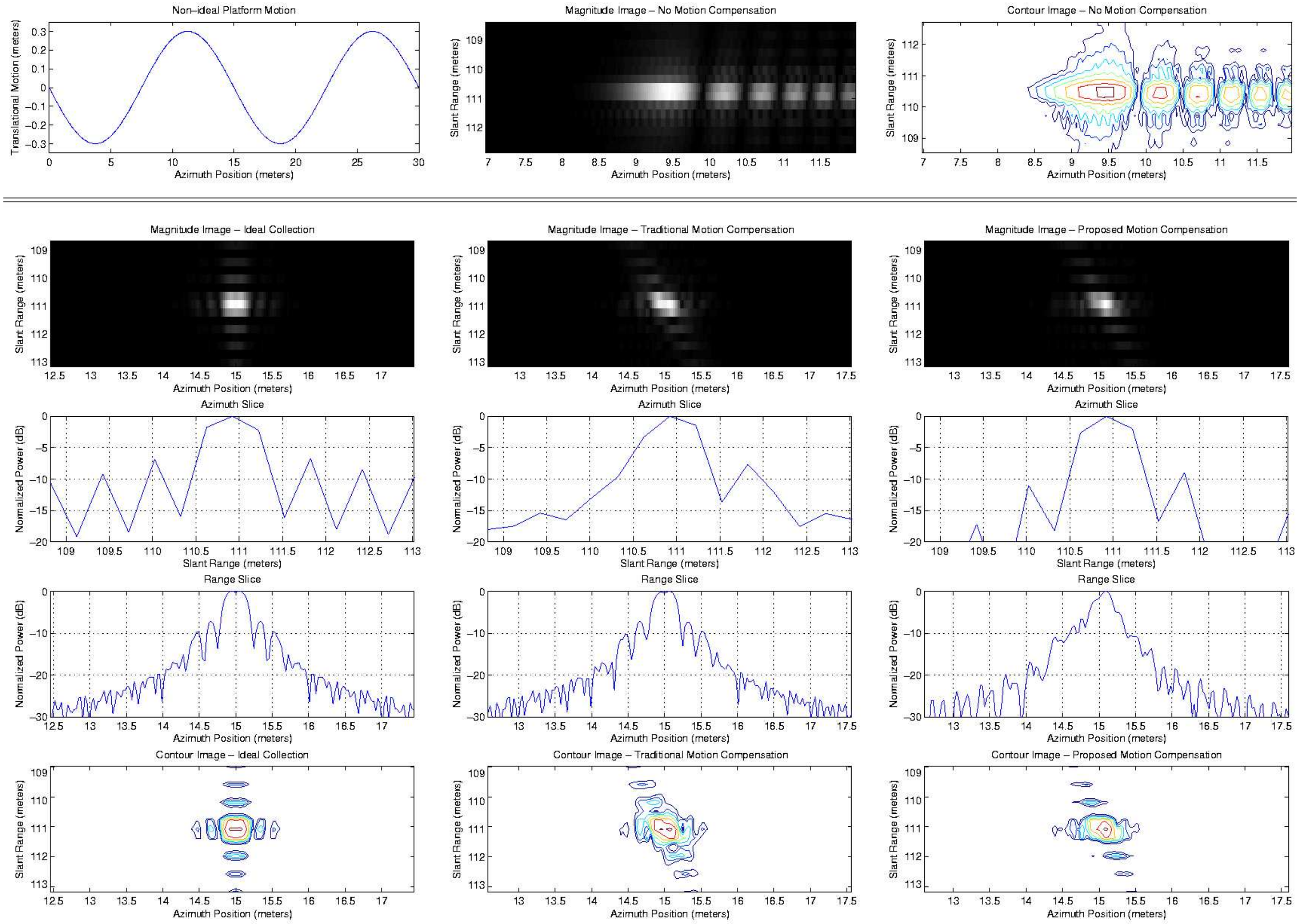

Figure 1: Simulated SAR data of a single point target imaged with sinusoidal translational motion. The first column shows an ideal collection without non-ideal motion, the top row shows the translational motion and the image without compensation, the middle column shows the results of traditional motion compensation, and the rightmost column shows the proposed motion compensation.

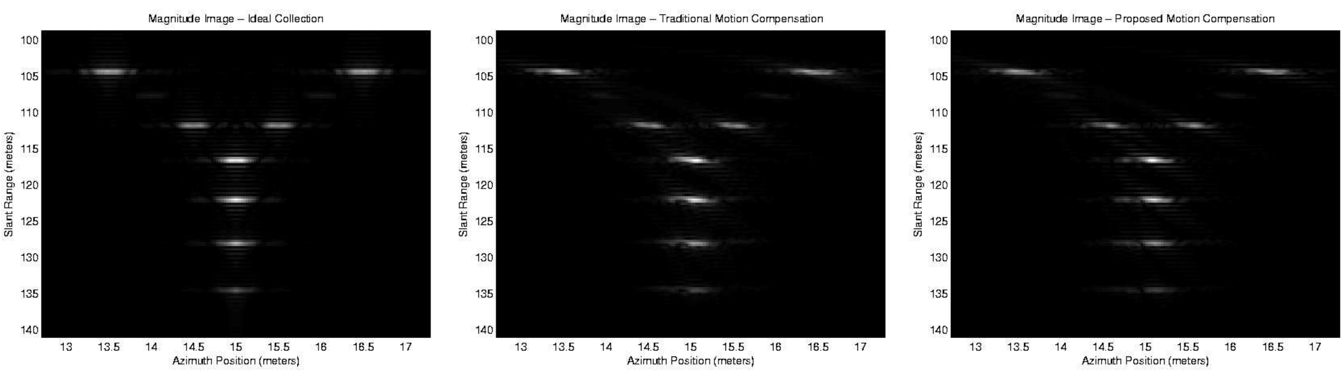

Figure 2: A simulation of an array of point targets showing the motion compensation algorithms working on an array of point targets. The left shows an ideal collection without translational motion, the center shows the traditional motion correction algorithm, and the right shows the proposed motion correction. The non-ideal motion in this example is the same as in **Figure 1**.

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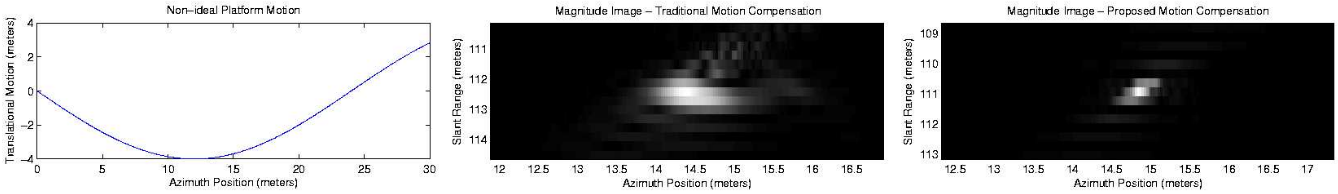

Figure 3: Non-ideal translational motion greater than a single range bin (shown on the left) clearly demonstrates the utility of the new motion compensation algorithm as seen in this image of a point target. The center image shows the result of applying tradition motion compensation while the right image shows the proposed method.

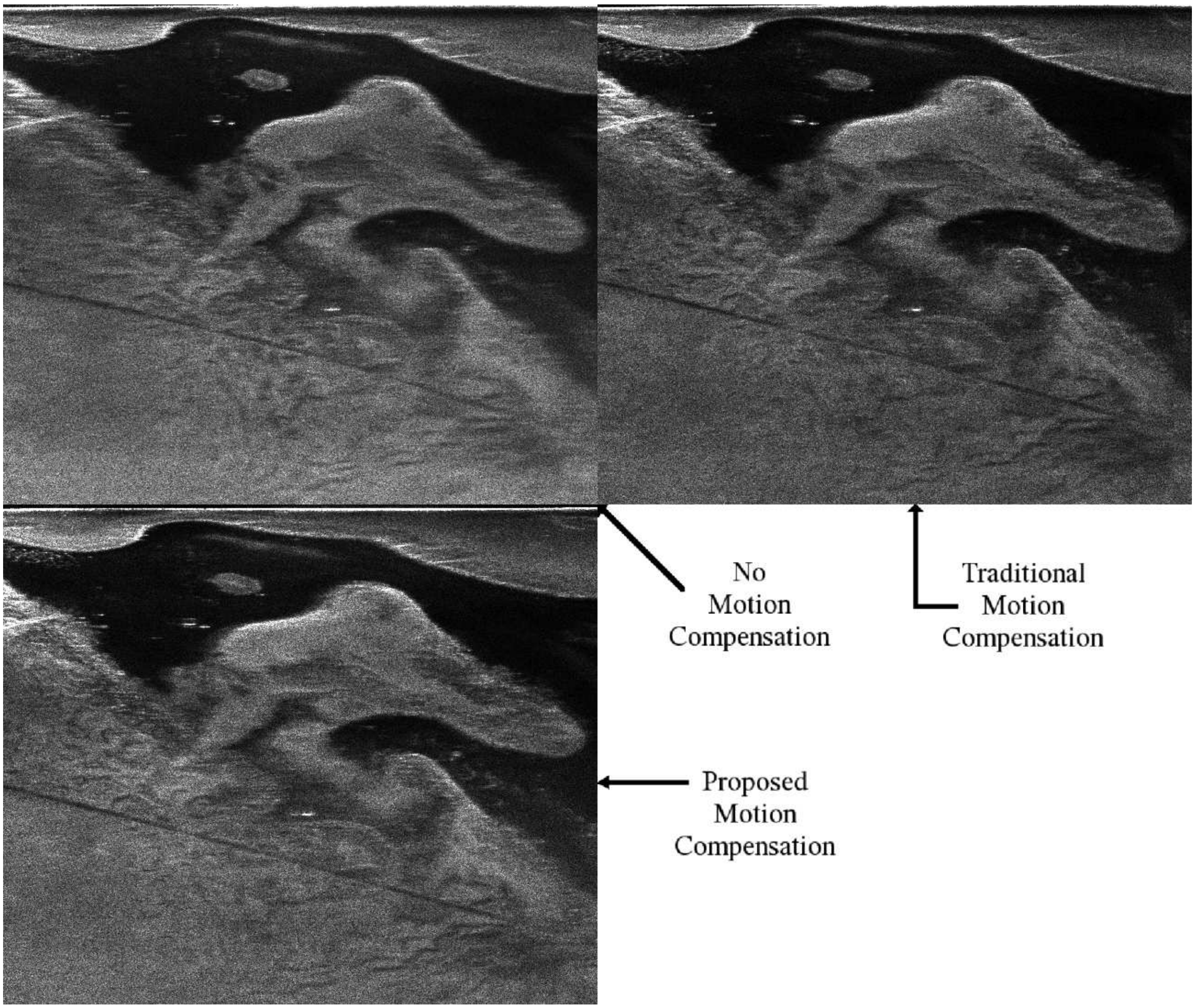

Figure 4: Images created from NuSAR data, spanning an area of 778x654 meters, are presented with the results of traditional and proposed motion compensation algorithms. Of note is that the road crossing the lower half of the image is properly straightened when using the proposed motion compensation method.

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