Improved SAR Motion Compensation without Interpolation

Evan C. Zaugg and David G. Long - Brigham Young University - Microwave Earth Remote Sensing Lab
459 Clyde Building, Provo, UT 84602 - zaugg@mers.byu.edu
Michael L. Wilson - U.S. Naval Research Laboratory

1. Summary

Motion compensation for airborne synthetic aperture radar (SAR) has always been important for 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]. 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. 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 translational motion is greater than a range bin [6]. Interpolation is used to address this issue; however, it adds a computational burden. This is not acceptable for a real-time high resolution UAS SAR system. The new motion compensation method presented here uses chirp scaling principles to efficiently correct the range shift and phase variations caused by translational motion.

2. Translational Motion Errors

SAR processing assumes that the platform moves in a straight line, but this is not the case. Translational motion results in the target scene changing in range during data collection. This range shift 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 then range compressed, and a second, range-dependent, correction is applied, using differential corrections from the reference range. For each R, ΔR is calculated with the correction,

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

Now, the motion-induced range shift can be removed through a computationally taxing interpolation commonly used for range-Doppler (RDA) and chirp-scaling (CSA) processing.

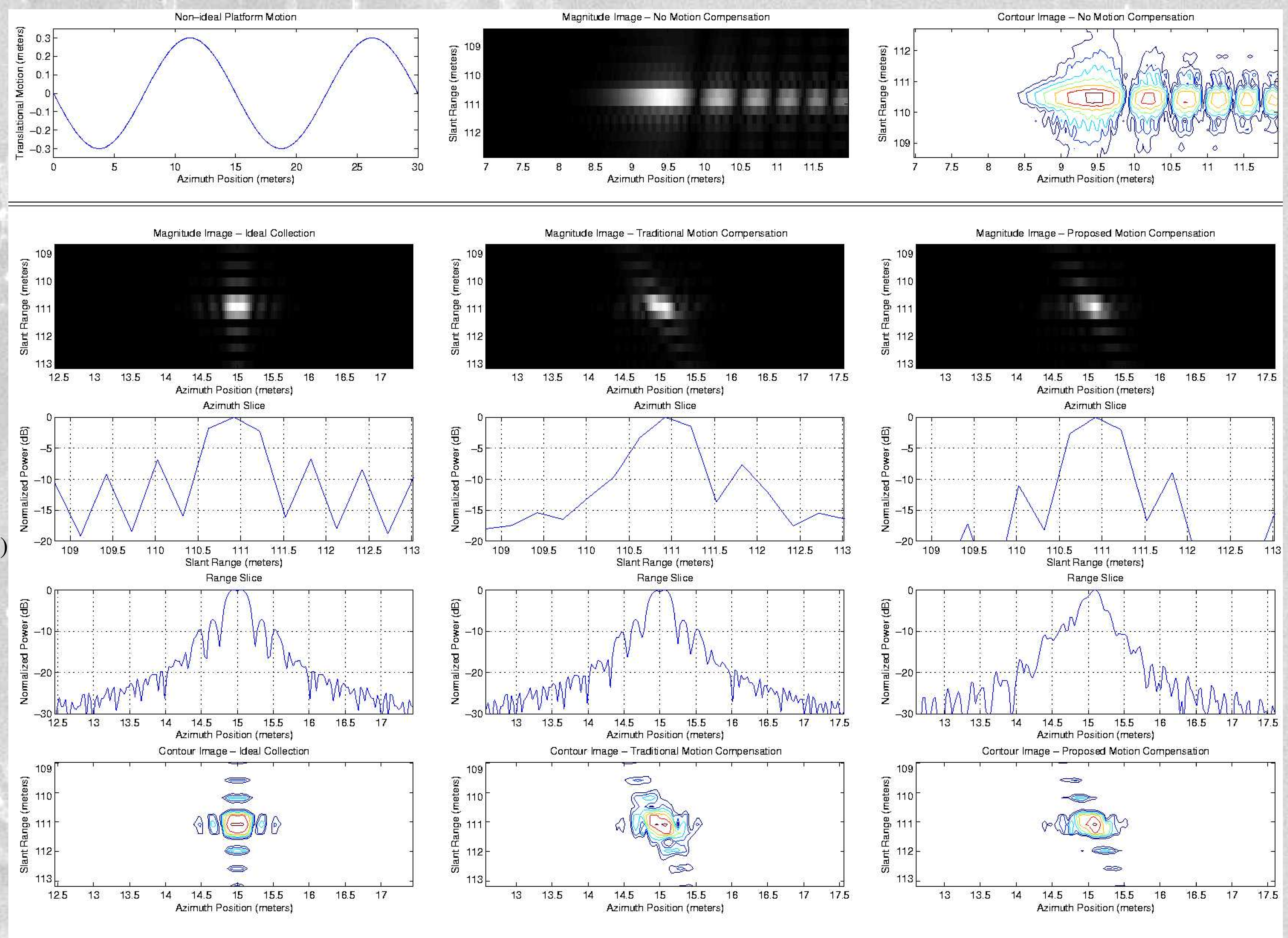

Figure 1: Simulated SAR data of a single point target with motion. The first column shows a collection without motion, the top row shows the motion and the image without compensation, the middle column shows the results of traditional motion compensation, and the rightmost column shows the proposed motion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

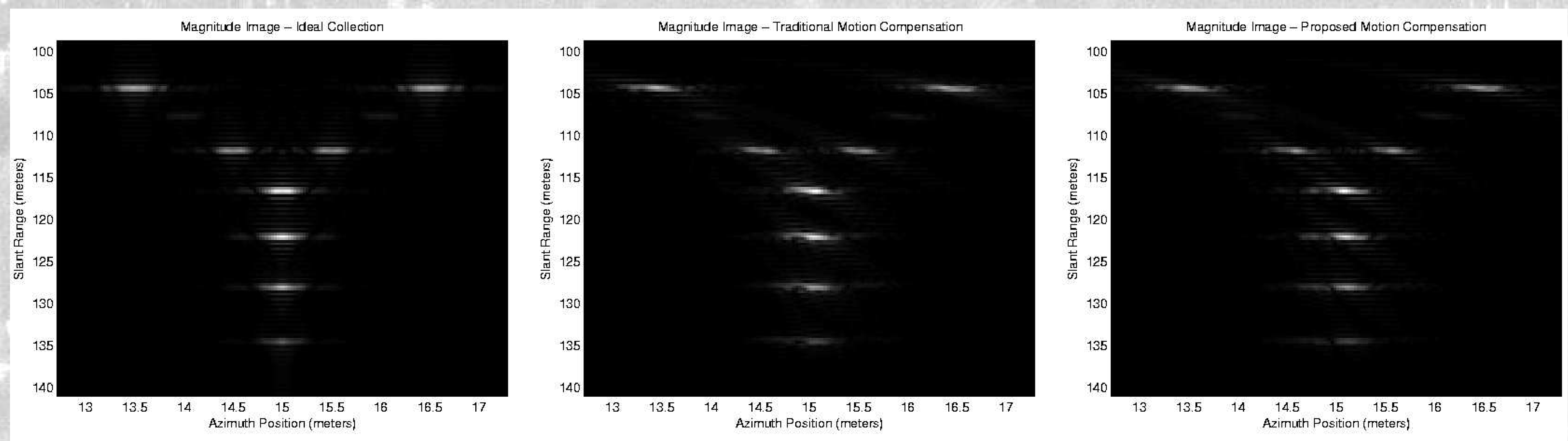

Figure 2: An array of point targets imaged with the same motion as in Figure 1.

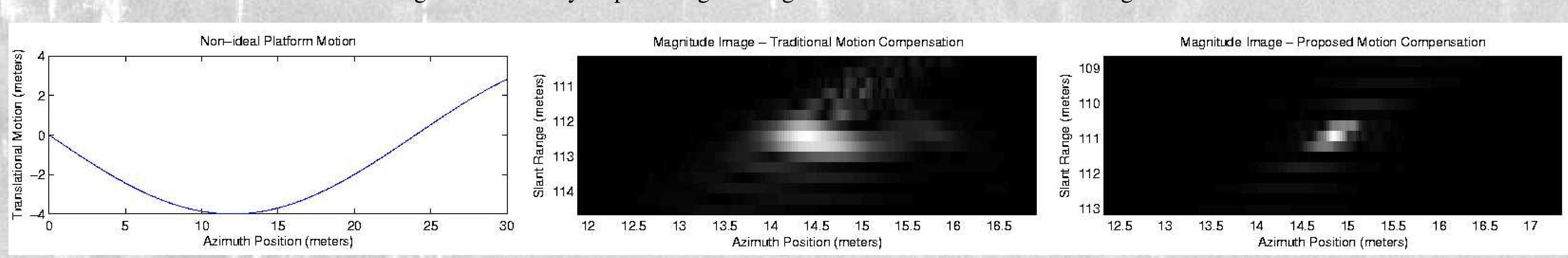

Figure 3: Non-ideal translational motion greater than a single range bin clearly demonstrates the utility of the new motion compensation algorithm.

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],

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

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, $\Delta R_{\mathrm{diff}}(\eta)$, and range-independent, $\Delta R_{\mathrm{ref}}(\eta)$, terms,

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

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

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

which expands into

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

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.

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

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,

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

where $\tau = 2R/c$.

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Figure 4: A 778x654 meter area imaged by the NuSAR and processed with the CSA. Note the road crossing the image is properly straightened when using the proposed motion compensation while the processing time is virtually identical. The U.S. Naval Research Laboratory (NRL) UAS SAR (NuSAR) is designed for UAS flight operating at L-Band or X-Band with a 500 MHz bandwidth and real-time processing. It was developed as part of the 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.