Options for Airborne Interferometric SAR Motion Compensation

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***Abstract*—Airborne interferometric SAR (InSAR) has the potential to provide topographic data with a precision of the order of one meter. However, to generate data accurate to this level it is essential to measure and compensate for nonlinear motion of the two antennas which constitute the interferometric baseline. Conventional motion compensation techniques are extended to the two-channel imaging scenario of InSAR. Phase compensation of both channels to the same reference track and compensation to two separate tracks are considered and modeled using point target simulation, and real InSAR data. The single track approach allows track segmentation to follow aircraft drifts without causing discontinuities in the differential phase, but is sensitive to range cell migration effects. The dual track approach is not sensitive to these errors but suffers from discontinuous differential phase at segmentation boundaries, which complicates the phase unwrapping process. A new formulation for each approach is presented that compensates for unknown terrain coupled with low frequency aircraft motion. In addition, a new approach that uses the dual track approach initially and then converts to a single reference track after compression is proposed. This realizes the benefits of both approaches with only a small increase in computation.**

I. Introduction

In order for airborne Interferometric SAR (InSAR) to be capable of generating useful Digital Elevation Models (DEM's), accurate motion compensation must be performed on both simultaneously received channels. This paper addresses the issue of motion compensation for InSAR with the objective of improving the accuracy of the derived DEM. Motion compensation for InSAR differs from that appropriate to a conventional single channel SAR due to the fact that two antennas are involved and the differential phase between the two channels is critical to the correct derivation of elevation.

The use of motion compensation to achieve airborne SAR focusing has been studied for some time [1]–[3]. Ideal compensation requires precise knowledge of the relative geometry between the radar and each illuminated target for every transmitted pulse. The echo energy from each pulse for a given target is extracted by a resampling operation and phase corrected to simulate the transmission and reception from an antenna travelling in a straight line along a defined reference track [3]. For ideal compensation, the required phase correction for a given range cell of a given pulse is target dependent, therefore each output pixel requires unique processing of the aperture. Approximations to ideal compensation and processing are usually required to reduce computation. Furthermore, the off-nadir angle to the target is generally not known, requiring assumptions about the terrain during motion compensation.

Typically, motion compensation is applied assuming the terrain is flat at some reference level and only the zero Doppler pulse for a given target is properly corrected. For example, if the antenna trajectory is parallel but offset from the defined reference track used for motion compensation, then the phase correction is only range dependent. An important consequence of this case is that the FM rate of the compensated data has not changed. This implies that the azimuth matched filter should be chosen based on the actual antenna trajectory rather than the reference track position. The departure from the ideal case of motion compensation leads to defocusing, peak misplacement, and phase errors in the compressed image.

Two approaches to InSAR motion compensation have been used so far, but a detailed comparison has not been made. The first method involves defining two reference tracks, one for each antenna, and applying motion compensation for each channel separately [4]–[7]. When the reference tracks are segmented the displacements are small allowing various approximations to be made. When segmentation occurs the absolute phase of each segment can be determined using the split-frequency approach [6]. The interpretation of the resulting differential phase for terrain estimation is done with respect to the reference track positions and therefore assumes that ideal motion compensation has been performed.

The second method motion compensates both antennas to the same reference track [8]. This approach basically attempts to undo the relative phase mapping between the two images caused by the baseline or parallax. Any residual phase mapping is attributed to the unknown terrain, and can be used to solve for the terrain.

A number of assumptions will be made for the following analysis regarding the signal acquisition and subsequent processing:

1) Both antennas are yaw steered to nominal zero Doppler and azimuth processing is centered on zero Doppler for both channels.
2) The pitch of the aircraft is fixed.
3) The ground spacing between transmitted pulses is constant by adjusting the Pulse Repetition Frequency (PRF) to maintain a constant PRF/Velocity ratio.

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4) The receive-only channel is registered with the transmit/receive channel assuming flat terrain at some reference level.

These assumptions are reasonable for many strip-mapping systems such as the Canada Centre for Remote Sensing (CCRS) Convair 580 InSAR system [8].

In this paper, the requirements of motion compensation for InSAR will be addressed, followed by a new formulation of the single and dual reference track approaches which consider the biases resulting from unknown terrain. The main errors affecting InSAR when the compensation departs from the ideal case will then be discussed. It will be shown that by using the dual reference track approach in a segmented manner, followed by a new post-azimuth compression conversion to a single track, the main benefits of both approaches can be realized. An evaluation of the modeling will be made by using an InSAR processor with point target data, modeled and real Convair 580 motion data, and real InSAR data from the CCRS InSAR system.

II. Motion Compensation Requirements for InSAR

SAR Interferometry is concerned with extracting the phase difference between two processed images, pixel by pixel, in order to estimate the terrain elevation of the corresponding ground patch. InSAR accuracy is not affected by phase bias errors that exist in each channel provided they are common to both and thus cancel out in the differential phase of the interferogram (result of inter-channel complex conjugate multiply). As the two antennas are rigidly connected to the aircraft, much of the motion experienced by each channel will be common to both. What affects the height estimate is the variance and possible biases in the differential phase. In addition, geometric fidelity is important for map registration.

In order to relate motion compensation errors to elevation errors a model must be used to describe the differential phase mean and variance. In [9], a frequency domain analysis was conducted to evaluate the effect on the interferogram differential phase of differences in the transfer functions between channels. For distributed homogeneous targets the signals for the two channels can be characterized by circular Gaussian random variables. The expected differential phase bias was shown to be the phase of the inter-channel correlation coefficient (γ). The probability density function of the differential phase (Φ) can be shown to be a function of the magnitude of the inter-channel correlation coefficient [10, p. 46]:

$$p(\Phi) = \frac{1-\gamma^2}{4\pi^2}\,(1-\beta^2)^{3/2}\left(\beta\,\sin^{-1}\beta + \frac{\pi\beta}{2} + \sqrt{1-\beta^2}\right) \quad (1)$$

where

$$\beta = |\gamma|\,\cos(\Phi). \quad (2)$$

The corresponding variance has no closed form solution, but can be evaluated numerically:

$$\sigma_\Phi^2 = \int_{-\infty}^{\infty} \Phi^2 p(\Phi)\,d\Phi. \quad (3)$$

This formulation emphasizes the fact that differences in the transfer functions can lead to an increase in the differential phase variance and can produce biases. As an example of how this model can be used, it can be shown by simple integration that for rectangular transfer functions, or sinc-like point spread functions (PSF's), the inter-channel correlation coefficient factor due to inter-channel azimuth broadening of $\xi > 1$ is $\gamma \propto 1/\sqrt{\xi}$. Therefore, broadening that differs by about 10% between channels leads to a correlation factor of about 0.95. This will increase the differential phase variance but will not produce a phase bias.

Despite what the model might suggest, defocusing common to both channels has an effect on the InSAR system. The amount of phase noise from certain sources, such as baseline decorrelation [11], depends upon the transfer function in each channel. In addition, a more local estimate of the terrain elevation is achieved with a narrower point spread function (PSF). Given that errors in the height estimate are very sensitive to differential phase errors, significant spatial averaging is required in InSAR to smooth the phase and thereby facilitate phase unwrapping and reduce the height noise. Phase smoothing will reduce the variance of the phase noise provided all samples in the smoothing region have approximately the same true value (taking the sensitivity of the interferometer into account). If there are larger changes or discontinuities in the underlying phase, then phase smoothing may not facilitate phase unwrapping.

The need for phase smoothing relaxes the localization requirements because the averaging will typically take place over many resolution lengths. However, having a narrower PSF will make the samples more uncorrelated, and thus better phase smoothing will be accomplished. The amount of spatial averaging, and subsequent subsampling, may need to be reduced when the local elevation variation is large in order to avoid differential phase aliasing (inter-pixel differential phase changes greater than π). This will increase the sensitivity to focusing problems.

In addition, phase unwrapping for InSAR is a two-dimensional problem which requires continuity in the differential phase [12]. If the differential phase is discontinuous, as may be caused by reference track segmentation, the unwrapping process can become more complicated [6]. For example, pairs of residues that are bisected by the artificial segmentation discontinuity may not be handled correctly if the two segments are unwrapped independently. In addition, this discontinuity is undesirable for an operational system as it requires at least one control point per segment or some continuity processing. In contrast, terrain-induced discontinuities in differential phase are much more difficult to handle, and are independent of the motion compensation process.

In summary, identical, high resolution, geometrically correct, PSF's are desired for InSAR mapping. Thus while InSAR motion compensation has the conventional requirements of single channel SAR, such as resolution and sidelobe level control, the primary concern is to maintain the similarity in the transfer functions between the two channels. In this way, differential phase errors are minimized. In addition, the differential phase should be continuous for phase unwrapping. The ability to meet these requirements of motion compensation

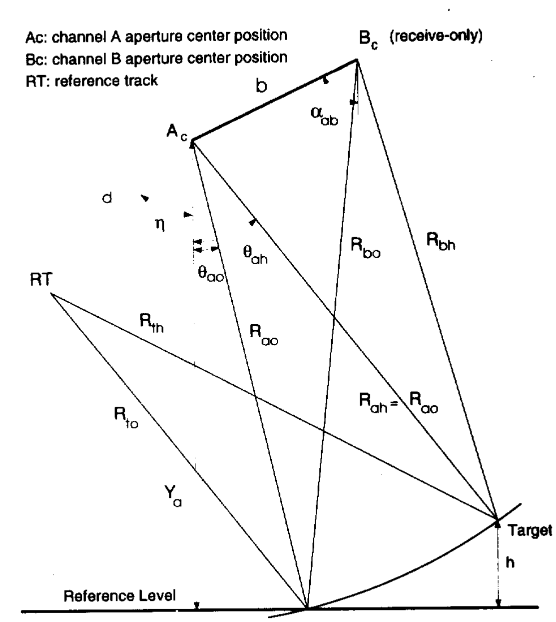

Fig. 1. Single reference track zero-Doppler geometry.

for InSAR will now be examined for the single and dual reference track approaches.

III. The Single Reference Track Approach

The single reference track approach to InSAR motion compensation was first proposed for InSAR by CCRS [8]. Both channels are phase compensated to the same reference track using the geometry of Fig. 1, assuming the terrain is flat at a selected reference level. For the following analysis, the arc on which the target lies is initially assumed to be centered at the transmit/receive antenna (channel A). An equivalent view centered on the receive-only antenna (channel B) could be used. An average of the two results leads to a more accurate estimate of the 3D terrain position.

If compensation had been applied knowing the terrain (the ideal case) then the differential phase would be zero everywhere because the relative phase mapping due to the parallax would have been removed. Due to the unknown terrain and computation limitations (nonideal compensation) it is usual to make a "center of aperture" assumption. The assumption is that the resulting differential phase of a compressed image sample of the interferogram is due to the relative geometry of the InSAR system, including the applied phase correction, at the zero Doppler pulse. This assumption is reasonable for low frequency aircraft motion. In addition, random phase errors cannot be considered in the phase to elevation equations, for example, due to thermal noise, misregistration, or baseline decorrelation, because they do not lead to bias errors [11].

By invoking the center of aperture assumption, the differential phase will be zero for scene patches that have the same elevation as the reference level and nonzero otherwise. The value of the residual phase is the difference in the errors of the phase correction applied between the two channels due to the flat earth assumption. These errors depend upon the imaging geometry and can be related explicitly to the elevation of the scene patch relative to the reference level.

The actual phase correction applied to the zero-Doppler pulse of each channel is obtained from the cross-track geometry of Fig. 1:

$$\phi_A(applied) = -\frac{2\pi}{\lambda}\left[2(R_{to} - R_{ao})\right]$$
$$\phi_B(applied) = -\frac{2\pi}{\lambda}\left[(R_{to} - R_{ao}) + (R_{to} - R_{bo})\right] \quad (4)$$

where λ is the carrier wavelength. Channel A has the two-way path length due to the transmit/receive antenna. Channel B has one path length from the transmit/receive antenna and one to the receive-only antenna. The ideal phase corrections are

$$\phi_A(ideal) = -\frac{2\pi}{\lambda}\left[2(R_{th} - R_{ao})\right]$$
$$\phi_B(ideal) = -\frac{2\pi}{\lambda}\left[(R_{th} - R_{ao}) + (R_{th} - R_{bh})\right]. \quad (5)$$

The resulting single track differential phase (Φ) can be shown to be

$$\Phi = \phi_A(applied) - \phi_A(ideal) - \phi_B(applied) + \phi_B(ideal)$$
$$= -\frac{2\pi}{\lambda}(R_{bo} - R_{bh}). \quad (6)$$

The off-nadir angle (θ_{ah}), measured from the instantaneous antenna position A_c, can be obtained in terms of known ($R_{ao}, R_{bo}, \alpha_{ab}$) and measured ($\Phi$) parameters from simple trigonometry, and simplified by a truncated binomial series in slant range

$$\theta_{ah} = \cos^{-1}\left[\frac{\left(\frac{\lambda}{2\pi}\Phi + R_{bo}\right)^2 - b^2 - R_{ao}^2}{2bR_{ao}}\right] - \alpha_{ab}$$
$$\approx \cos^{-1}\left[\frac{\lambda\Phi}{2\pi b} + \cos(\theta_{ao} + \alpha_{ab})\right] - \alpha_{ab}. \quad (7)$$

Using the symmetrical view with the channel B antenna as the arc center yields:

$$\theta_{bh} \approx \cos^{-1}\left[\frac{\lambda\Phi}{2\pi b} + \cos(\theta_{bo} + \alpha_{ab})\right] - \alpha_{ab} \quad (8)$$

where θ_{bo} and θ_{bh} are the off-nadir angles measured from the channel B antenna to the reference level and target, respectively. A more accurate estimate of the terrain can be obtained by using the average slant range and off-nadir angle

$$R = \frac{R_{ao} + R_{bo}}{2}, \qquad \theta = \frac{\theta_{ah} + \theta_{bh}}{2} \quad (9)$$

both measured from the center of the antenna baseline. The scene patch elevation above the reference level is then found from (Fig. 1):

$$h = Y_a + \frac{b}{2}\cos\alpha_{ab} - R\cos\theta. \quad (10)$$

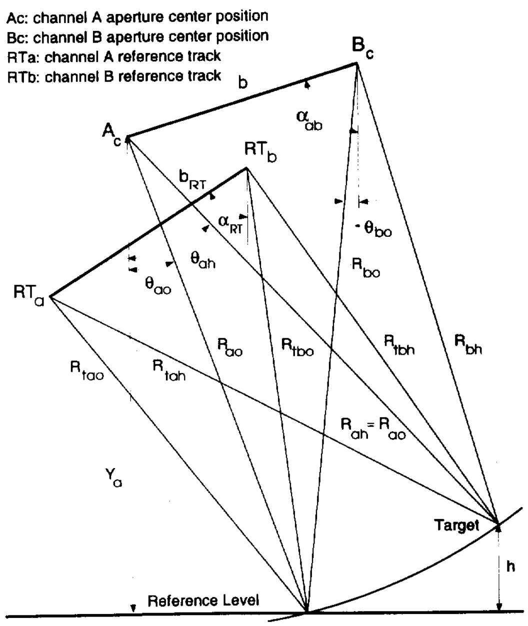

Fig. 2. Dual reference track zero-Doppler geometry.

The sensitivity of the height estimate to errors in the differential phase can be shown to be

$$\frac{\partial h}{\partial \Phi} \approx -\frac{\lambda R \sin\theta}{2\pi b \sin(\theta + \alpha_{ab})}. \tag{11}$$

The main benefit of the single reference track approach is that the resulting differential phase is continuous even if the reference track is segmented (provided the reference level is continuous). In addition, the flat earth fringes have been removed, as a result of undoing the relative phase mapping, which is a benefit for phase smoothing because the local fringe rate need not be considered when range filtering is performed [12].

IV. The Dual Reference Track Approach

In the dual reference track case each channel is motion compensated to its own reference track (RT_a and RT_b) assuming flat terrain at a defined reference level using the geometry of Fig. 2. Typically, the effects of motion compensation with unknown terrain are ignored and it is assumed that the data has been adequately corrected to the two reference tracks. The interpretation of the differential phase is therefore similar to the two-pass satellite case except for the one-way path difference, namely:

$$\Phi = -\frac{2\pi}{\lambda}(R_{tah} - R_{tbh}). \tag{12}$$

The off-nadir angle to the target (θ_b), measured from the channel B reference track (RT_b), can be obtained and converted into a height estimate [13].

Phase errors in each channel that result from motion compensation assuming flat terrain coupled with low frequency aircraft motion are not included in this interpretation. These errors can become significant for rugged terrain coupled with aircraft roll if reference track segmentation is not performed [14]. When these systematic terrain-induced phase errors are included, a new double reference track approach is obtained. The approach proceeds as in the single reference track case by considering the difference in the errors in the applied phase correction between channels plus the ideal component (12). The center of aperture assumption is used here in the same way as in the single track case, resulting in the following differential phase

$$\Phi = -\frac{2\pi}{\lambda}(R_{tao} - R_{tbo} + R_{bo} - R_{bh}). \tag{13}$$

The off-nadir angle to the target (θ_{ah}) can be related explicitly to the measured differential phase and other known parameters, and the expression can be simplified with a truncated binomial series in slant range

$$\begin{aligned}\theta_{ah} &= \cos^{-1}\\ &\quad\cdot\left[\frac{\left(\frac{\lambda}{2\pi}\Phi + R_{tao} - R_{tbo} + R_{bo}\right)^2 - b^2 - R_{ao}^2}{2bR_{ao}}\right]\\ &\quad - \alpha_{ab}\\ &\approx \cos^{-1}\left[\left(\frac{\lambda\Phi}{2\pi b} + \frac{R_{tao} - R_{tbo}}{b}\right)\right.\\ &\quad \left. + \cos(\theta + \alpha_{ab})\right] - \alpha_{ab}. \end{aligned} \tag{14}$$

Again, a symmetric result can be obtained using the channel B antenna as the arc center. Notice that the single reference track case is actually a special case of the dual track method with coincident tracks ($R_{tao} = R_{tbo}$).

The conventional dual track approach (12) measures the off-nadir angle from a reference track but the single and new double track approaches measure from the instantaneous antenna positions. The terrain elevation can be estimated by using (10) and the sensitivity of the height estimate to differential phase errors is identical to the single track case.

The differential phase depends upon the reference track position through R_{tao} and R_{tbo}. Therefore, reference track segmentation will result in discontinuous differential phase which will complicate the phase unwrapping process [6]. A comparison between the single and dual track approaches will be made based on the following motion compensation error analysis.

V. Motion Compensation Induced Errors

The primary errors resulting from nonideal motion compensation for InSAR will now be discussed. These include the effects of the range varying phase correction, unknown terrain, and inertial data errors. The dependence of these errors on the chosen reference track approach will be evaluated.

A. Range Varying Phase Correction

The applied phase correction for each channel, independent of the reference track approach used, is proportional to the displacement $d(t)$ from the reference track and varies across range (for example, Fig. 1)

$$\phi(t) = -\frac{4\pi}{\lambda}(R_{to} - R_{ao}) \approx \frac{4\pi}{\lambda} d(t) \cos[\eta(t) + \theta(t)]. \quad (15)$$

This correction is updated along azimuth as the displacement from the reference track changes. Since fast convolution using the Fast Fourier Transform (FFT) is used for azimuth compression, the phase correction cannot follow the range cell migration of the targets. The effect of this approximation will be investigated further in this section.

The range dependence of the phase correction can be obtained by differentiating (15) with respect to slant range, yielding

$$\frac{\partial\phi(t)}{\partial R} \approx -\frac{4\pi\, d(t) \sin[\eta(t) + \theta(t)]}{\lambda R \tan\theta} \triangleq -\frac{4\pi d_{\perp los}(t)}{\lambda R \tan\theta} \quad (16)$$

where $d_{\perp los}$ is the component of the displacement perpendicular to the line-of-sight direction. This phase correction is locally linear in slant range and results in a range-dependent shift to the range spectrum given by

$$|f_o| = \frac{c|d_{\perp los}|}{\lambda R \tan\theta}\,\text{Hz} \quad (17)$$

where c is the speed of light. This shift has been recognized to potentially lead to problems, especially for systems with significant range migration [6].

If subsequent processing assumes baseband range data or the shift is different between channels then decorrelation and bias errors may result. For instance, the range varying phase correction (RVPC) causes a quadratic phase error along azimuth for a target when RCMC is performed. For the case of a parallel flight offset from the reference track the phase correction is constant along azimuth for a given range cell, but the phase error along the range migrating aperture is

$$\Delta\phi_{rcmc}(t) \approx \frac{\partial\Delta\phi(t)}{\partial R}\Delta R_{rcm}(t) \approx -\frac{2\pi d_{\perp los} v^2 t^2}{\lambda R^2 \tan\theta} \quad (18)$$

where $\Delta R_{rcm}(t)$ is the range migration and v is the along track velocity. In the interferometric case, the displacement to the track used to apply the phase correction can be different between channels leading to different quadratic phase errors. It can be shown that the angle of the inter-channel correlation coefficient (γ), which indicates the phase error at the compressed peak, is about 1/3 the quadratic phase error applied at the band edge. Using this result, an estimate of the differential phase error resulting from the difference in the displacements to the track(s) can be determined

$$\Delta\Phi_{bias} \approx \frac{1}{3}\frac{2\pi v^2 T^2}{4\lambda R^2 \tan\theta}\frac{\Delta d_{\perp los}}{2} \quad (19)$$

where T is the processed aperture time. The relative displacement $\Delta d_{\perp los}$ is divided by two because of the one-way path difference between the two channels. With processing to the 3 dB antenna beamwidth, the height estimate bias found from (11) is

$$\Delta h_{bias} = -\frac{\lambda^2 R \Delta d_{\perp los} \cos\theta}{24 b D^2 \sin(\theta + \alpha_{ab})} \quad (20)$$

where D is the antenna length.

When RCMC is not performed bias errors can still occur. This is a result of the coupling between the relative range varying phase correction and the uncompensated RCM. The difference in the phase correction between channels produces a range phase ramp across the interferogram PSF. The uncompensated RCM leads to a range shift of the PSF, but does not shift the phase ramp. The resulting phase bias at the peak, caused by this mis-match between the peak position and the zero-crossing of the phase ramp, can be minimized by maintaining a short processed bandwidth and minimizing the relative phase correction. Also, if motion compensation was performed uniquely over the aperture for each output pixel these range varying phase correction effects would be avoided. But this would greatly increase the computational load, because fast convolution could not be used.

For the single reference track case the relative displacement $\Delta d_{\perp los}$ is on the order of the baseline length, creating a significant relative phase correction. The relative phase correction can, in fact, be shown to produce an equal and opposite relative spectral shift to that caused by the parallax, as described in [15], for flat terrain at the reference level. Therefore, RCM-induced errors can be significant for the single reference track case.

If the dual reference track baseline length (b_{RT}) and angle (α_{RT}) is matched to the nominal antenna baseline (b, α_{ab}) for the dual reference track case, then the displacements from the reference tracks are very similar in the two channels. This greatly reduces the relative phase corrections, minimizing the sensitivity to RCM effects. For typical offsets from the reference track and roll of several degrees this effective difference in the displacement from the tracks is negligible. It is clear that if there is significant RCM in the processed data, the dual reference track approach should be used.

B. Unknown Terrain Elevation

Another source of error in InSAR motion compensation is due to the circular height estimation problem. The problem is that the terrain must be known in order to perform motion compensation properly, but, this is what InSAR processing is trying to estimate. The phase correction error due to unknown terrain that occurs along the aperture is the difference between the applied and ideal corrections ((4) minus (5)). For example, the error for channel A can be approximated by a truncated binomial series in slant range (Fig. 1)

$$\Delta\phi_{err} = -\frac{4\pi}{\lambda}(R_{to} - R_{th}) \approx \frac{4\pi h d_{\perp los}(t)}{\lambda R \sin\theta}. \quad (21)$$

When the displacement from the reference track, perpendicular to the line-of-sight direction ($d_{\perp los}$), varies linearly along azimuth (from cross-track velocity) the phase error will be linear, leading to a shift in the peak position after compression

$$\Delta P \approx -\frac{h}{v^2 \sin\theta}\frac{\partial d_{\perp los}}{\partial t}\,\text{s}. \quad (22)$$

When there is cross-track acceleration, the phase error will be quadratic, leading to defocusing and phase errors in the PSF. If an upper limit on the phase error of $\pi/2$ at the processed band edge is specified, the broadening will be less than about 5% and this limits the cross-track acceleration to

$$a_{\perp los} < \frac{\lambda R \sin\theta}{hT^2} \frac{\text{m}}{\text{s}^2}. \tag{23}$$

With processing to the 3 dB azimuth beamwidth, this yields

$$a_{\perp los} < \frac{D^2 v^2 \sin\theta}{h\lambda R} \frac{\text{m}}{\text{s}^2}. \tag{24}$$

If the relative motion is the same between the two channels then the shift and defocusing effects are essentially the same. This is true for purely translational motion along the aperture for both cases of single and dual reference track motion compensation. But, when aircraft roll is considered the relative motion is different between channels and differential phase biases can occur.

By evaluating the phase error due to unknown terrain for each channel, the difference between them is

$$\Delta\Phi(t) \approx \frac{2\pi h b_{\perp los}(t)}{\lambda R \sin\theta}. \tag{25}$$

where $b_{\perp los}$ is the component of the baseline perpendicular to the line-of-sight direction. Expanding this expression in a Taylor's series to consider aircraft roll yields

$$\Delta\Phi(t) \approx \frac{2\pi h b_{los} \Delta\alpha_{ab}(t)}{\lambda R \sin\theta} \tag{26}$$

where b_{los} is the line-of-sight baseline component and $\Delta\alpha_{ab}(t)$ is the roll angle variation. The resulting differential quadratic phase error, as in the preceding RVPC case, can be transformed into a differential phase bias error in the interferogram:

$$\Delta\Phi_{bias} \approx \frac{a_{roll} \pi b_{los} h T^2}{12\lambda R \sin\theta} \tag{27}$$

where

$$\Delta\alpha_{ab}(t) = \tfrac{1}{2} a_{roll} t^2 \tag{28}$$

and a_{roll} is the uniform roll acceleration. With processing to the 3 dB antenna beamwidth, the height estimate bias found from (11) is

$$\frac{\Delta h_{bias}}{h} \approx -\frac{\lambda^2 R^2 b_{los} a_{roll}}{24 b v^2 D^2 \sin(\theta + \alpha_{ab})}. \tag{29}$$

This error is independent of the reference track approach used.

C. Effects of Inertial Data Errors

Inertial Navigation System (INS) measurement errors can have a significant impact on the accuracy of InSAR. For the CCRS system, the phase centers of both antennas are modeled in the aircraft body coordinate system and accurate aircraft attitude data is required to transform the body coordinate vectors into the motion compensation reference frame. Errors in the assumed position of the phase centers of either antenna lead to motion compensation phase errors, but, more importantly, errors will also occur in the differential phase to elevation stage of the InSAR processing. Errors in aircraft roll are particularly important. Position and velocity errors in the INS system can be minimized by using differential GPS data. This is done post-flight in the CCRS system.

Effects of INS bias errors (long period compared to processed aperture) on the height estimate can be calculated by differential analysis of the interferogram phase to elevation equations. Results for the conventional dual track approach [13] and the single and new dual track method were the same. The height estimate sensitivity to errors in the antenna baseline length and angle are, respectively

$$\frac{\partial h}{\partial b} \approx \frac{R \sin\theta}{b \tan(\theta + \alpha_{ab})} \tag{30}$$

and

$$\frac{\partial h}{\partial \alpha_{ab}} \approx R \sin\theta. \tag{31}$$

The effect of INS bias errors on the height estimate due to motion compensation can be calculated by converting the position error into a differential phase error. Equation (11) can then be used to estimate the elevation error.

The effect of INS errors that vary over the aperture is more complicated. Quadratic or linear INS drifts will behave similarly to those analyzed for the case of unknown terrain coupled with quadratic or linear flight motion, respectively. Higher frequency errors can be treated as phase noise. Random phase noise in clutter data is not smoothed by compression but is simply re-arranged by the matched filter, resulting in differential phase noise. In addition, PRF/V errors (such as latency) and small pitch and yaw errors will produce defocusing or a reduction in the signal to noise ratio, but will be essentially identical in both channels.

All three methods, conventional double, new double, and single reference tracks, all have the same sensitivity to INS errors, so there is no preferred motion compensation approach to minimize these errors. In all three cases, differential phase smoothing will help reduce the effect of high frequency INS errors.

INS bias errors are much more difficult to deal with. By inserting realistic levels of bias into (30) and (31), one can see that bias errors can be appreciable. It has been found in practice that in many cases control points will be necessary in order to obtain height estimates on the order of one to two meters accuracy. In addition, simulation results presented in Section VII yield the same conclusion.

VI. Combination of Single and Dual Reference Tracks

A summary of similarities and differences between the single and new dual reference track approaches is shown in Table I. It is clear that performing dual reference track motion compensation is preferred due to the range varying phase correction (items 2 and 3), but it is desirable to have the single reference track differential phase for phase unwrapping and phase smoothing (items 1 and 5). One possible approach is to use dual tracks for the primary compensation then remove the originally applied phase correction to each channel after compression. The resulting differential phase is then interpreted with respect to the instantaneous antenna positions, removing the reference track dependence. But, this would require a phase correction to be applied to both compressed images. A simpler alternative will now be described.

TABLE I
COMPARISON OF SINGLE AND DUAL REFERENCE TRACK MOTION COMPENSATION PROPERTIES

	Properties	Single	Dual
1	Continuity of differential phase with segmented reference tracks	Yes	No
2	Equal range spectral shifts between channels due to RVPC	No	Yes
3	Insensitive to bias errors caused by RCM and RVPC	No	Yes
4	Compensation for unknown terrain coupled with low freq. motion	Yes	Yes
5	Automatic removal of flat earth fringes	Yes	No

The proposed approach is to convert back to the single reference track formulation after dual track motion compensation and azimuth compression have been performed. The differential phase error resulting from unknown terrain after dual track motion compensation and azimuth compression is

$$E(A) - E(B) = -\frac{2\pi}{\lambda}(R_{tao} - R_{tah} + R_{tbh} - R_{tbo} + R_{bo} - R_{bh}) \tag{32}$$

where $E(A)$ and $E(B)$ are the errors in each channel due to the unknown terrain. The next step is to apply a phase correction which makes the data at the channel B reference track appear as though it were at the channel A reference track, namely (Fig. 2)

$$\phi_B(applied) = -\frac{2\pi}{\lambda}(R_{tao} - R_{tbo}). \tag{33}$$

Notice that if motion compensation resampling is performed to maintain straight lines along track at the reference level then the correction is constant along the aperture. This allows the correction to be applied very efficiently as a range varying phase term for each azimuth matched filter. Otherwise, it must be applied, pixel by pixel, on the compressed channel B image or as a correction to the interferogram phase.

Considering the terrain, the phase correction would have been

$$\phi_B(ideal) = -\frac{2\pi}{\lambda}(R_{tah} - R_{tbh}). \tag{34}$$

Therefore, there is a differential phase error from this operation which is

$$E_s(B) = -\frac{2\pi}{\lambda}(R_{tao} - R_{tah} + R_{tbh} - R_{tbo}). \tag{35}$$

The resulting differential phase would be zero after the two operations if all corrections considered the terrain. Therefore, the differential phase is equal to the residual errors

$$\Phi = E(A) - E(B) - E_s(B) \tag{36}$$

which results in

$$\Phi = -\frac{2\pi}{\lambda}(R_{bo} - R_{bh}). \tag{37}$$

This is precisely the same result as if one step single track compensation had been applied (6), except that the range varying phase correction errors, specific to the single reference track approach (for example, (20)), will not be present. This approach realizes the benefits of both the single and dual reference track methods with a very small increase in computation if motion compensation resampling is performed.

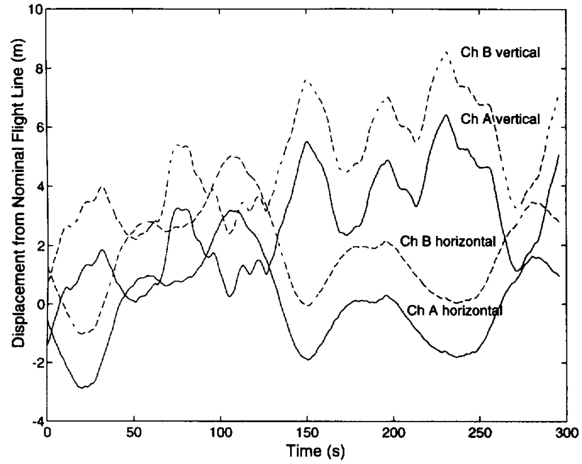

Fig. 3. Convair 580 two-channel antenna phase center horizontal and vertical displacement data.

VII. EVALUATION OF INSAR MOTION COMPENSATION

The preceding analysis was verified by performing motion compensation experiments for typical C-band parameters. Initially, simulated point target data was processed and analyzed for modeled and real Convair 580 motion data. Following this, InSAR data from the CCRS InSAR system was processed using the various motion compensation approaches.

A. Point Target Simulation Results

The simulation experiments used the following processing steps:

1) Generate range compressed point target data for a particular type of aircraft motion, for a variety of target elevations, and for two channels where channel B is registered with channel A assuming flat terrain.
2) Apply phase correction to each channel assuming flat terrain and using either one or two reference tracks. No motion compensation resampling is performed.
3) Optionally, perform RCMC in the azimuth frequency domain by baseband interpolation for each channel (Range/Doppler processing).
4) Perform azimuth compression using a specific matched filter for each channel.
5) Analyze the compressed peak characteristics in each channel and in the generated interferogram.

The simulation and processing parameters used were taken from the CCRS InSAR system (Table II). The flight motion used in the simulation was taken from typical flight data for the CCRS Convair 580 aircraft (Figs. 3 and 4). Table III shows typical peak motions.

These peak flight motions were used, one at a time, in the simulator. The motions were divided into separate components in the line-of-sight direction and perpendicular to this allowing the theoretical error analysis to be evaluated more accurately. Both single and dual reference track motion compensation was performed. The results were essentially identical between the two approaches except for the differential phase errors. The

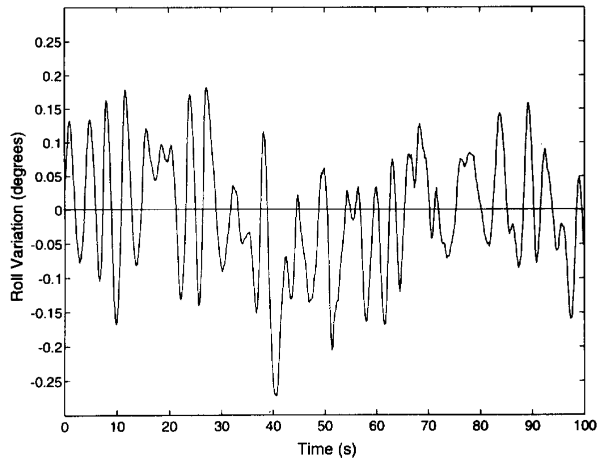

Fig. 4. Convair 580 antenna baseline roll variation about nominal angle.

TABLE II
TYPICAL CCRS C-B AND InSAR PARAMETERS

Parameter	Typical Value
Wavelength λ	$55.56\ mm$
Altitude H	$6\ km$
Baseline Length b	$2.8\ m$
Baseline Angle α_{ab}	40^o
Slant Range R_{ao}	$10\ km$
Pulse Repetition Frequency PRF	$337\ Hz$
Processed Aperture T	$2.25^o \sim 3\ s$
Azimuth Antenna Beamwidth	3.1^o
Range Bandwidth BW_r	$25\ MHz$
Range Sampling Rate F_r	$37.5\ MHz$
Along-track Velocity v	$131\ \frac{m}{s}$

TABLE III
TYPICAL PEAK FLIGHT MOTION FOR CCRS CONVAIR 580

Motion Type	Peak Flight Motion
Translational Velocity ($\frac{\partial d}{\partial t}$)	$0.5\ \frac{m}{s}$
Translational Acceleration ($\frac{\partial^2 d}{\partial t^2}$)	$0.01g$
Baseline Angular Velocity (roll) ($\frac{\partial \alpha}{\partial t}$)	$0.2\ \frac{deg}{s}$
Baseline Angular Acceleration (roll) ($\frac{\partial^2 \alpha}{\partial t^2}$)	$0.3\ \frac{deg}{s^2}$
Displacement Offset (d)	$10\ m$

extra phase bias measured in the single track case was in agreement with the predicted values using (20) for a range of processed apertures when RCMC was performed. For the nominal parameters the RCMC-induced bias error was about 0.4 m.

A number of motions yielded insignificant defocusing, mispositioning, phase errors, and differential effects. These motions include parallel offsets from the reference track of < 10 m, line-of-sight velocity or acceleration, and linear roll (or angular velocity). These results are in agreement with the analysis. In addition, there was negligible defocusing and elevation errors as a result of neglecting to resample in motion compensation.

TABLE IV
SIMULATED AND PREDICTED ERRORS DUE TO ANTENNA BASELINE ANGULAR ACCELERATION AND UNKNOWN TERRAIN (a_{roll} = 0.3 (deg/s^2), h = 1 km) ACROSS THE RANGE SWATCH

Slant Range (km)	Processed Aperture	$\Delta\Phi_{theory}$ ($mrad$)	$\Delta\Phi_{sim}$ ($mrad$)	Δh_{theory} (m)	Δh_{sim} (m)
10	2.2°	19	26	−0.5	−0.7
15	1.5°	14	15	−0.7	−0.7
15	2.2°	32	34	−1.6	−1.6
20	1.7°	30	31	−2.1	−2.1
20	2.2°	53	55	−3.8	−3.7

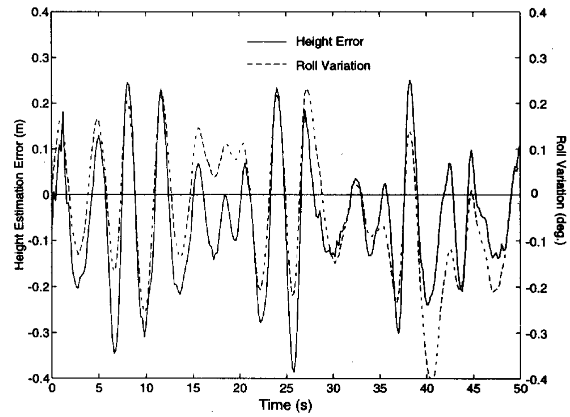

Fig. 5. Simulated height estimation errors from real Convair 580 flight motion with unknown terrain (R = 10 km, h = 1 km). The correlation between height errors and antenna baseline sinusoidal roll is clear.

However, the following motions did create significant errors. Azimuth defocusing occurred in both channels for $a_{\perp los}$ = 0.01 g, which was in agreement with the predicted broadening using (23). Table IV shows the results from a roll angular acceleration of 0.3 (deg/s^2) at several positions of the target across the range swath. Predicted differential phase errors using (27) and height estimate biases using (29) were compared with the simulation results (using no antenna beam pattern) with good agreement.

Actual motion data (Figs. 3 and 4) were also used in the simulator combined with relief to 1 km from the reference level. A strip of point targets was simulated along azimuth separated by about 25 m (or 0.2 s). Results in Figs. 5–8 indicate the size of errors that would result from this typical Convair 580 flight motion coupled with unknown terrain (up to 1 km) but precise inertial data measurements.

Examining the first part of the run in detail, Fig. 5 shows how the resulting height estimation errors generally follow the roll motion of the aircraft. Given the sinusoidal nature of the roll motion (and thus sinusoidal instantaneous acceleration) this is consistent with the prediction that differential phase errors will be proportional to angular acceleration (27).

Figs. 6 and 7 compare the height estimation errors for the conventional (12) and new dual reference track approaches for two different slant range values (R = 10 & 15 km). The reference tracks were chosen to minimize the possible biases

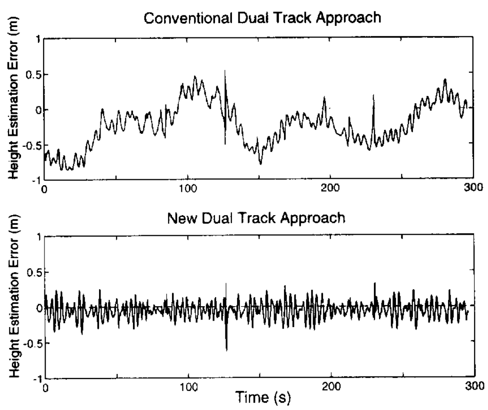

Fig. 6. A comparison of simulated height estimation errors from real Convair 580 flight motion with unknown terrain (R = 10 km, h = 1 km) between the conventional and new dual reference track approaches.

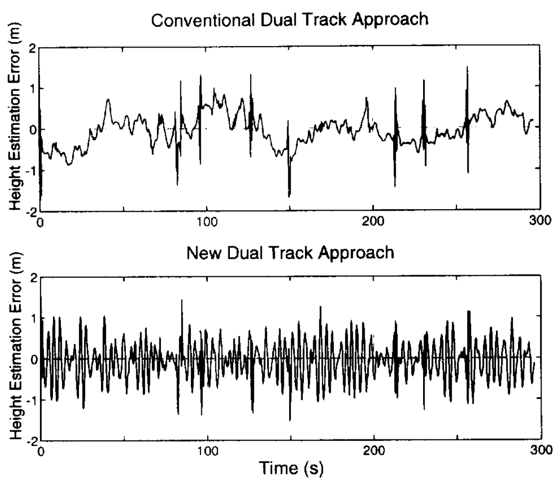

Fig. 7. A comparison of simulated height estimation errors from real Convair 580 flight motion with unknown terrain (R = 15 km, h = 1 km) between the conventional and new dual reference track approaches.

that can occur in the conventional approach [14] by using the mean antenna positions. At near range the errors resulting from the aircraft roll are small in the new approach compared to the residual biases of the conventional approach. At larger ranges the errors are about the same size but the new approach has larger higher frequency errors due to the roll. The conventional dual track approach is less sensitive to aircraft roll because the measured differential phase only partially follows the instantaneous antenna baseline roll. This happens because the angular acceleration-induced differential phase errors are of opposite sign to the change in the expected differential phase of the sinusoidal roll. In addition, the finite aperture extent effectively smooths out the roll. Both approaches yield negligible errors for targets at the reference level despite the aircraft motion. It should be noted that this experimental case is a worst case example for the new approach and a best case for the conventional approach because the aircraft motion had very small low frequency roll drifts yet high frequency oscillatory roll.

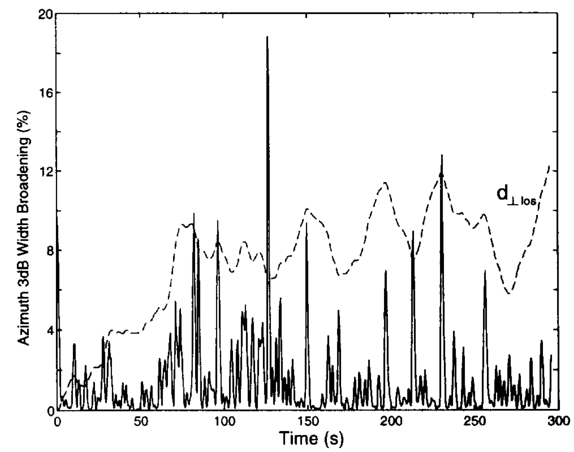

Fig. 8. Simulated azimuth broadening from real Convair 580 flight motion with unknown terrain (R = 10 km, h = 500 m).

Note that spike errors in estimated height occur in both approaches in Figs. 6 and 7. These are caused by large accelerations perpendicular to the radar line-of-sight, coupled with unknown terrain. The accelerations can be noted from the displacement curve in Fig. 8, and the effect of the accelerations is azimuth defocusing (see Fig. 8) and differential phase errors. The differential phase errors lead directly to the observed height estimation errors.

Fig. 8 shows the resulting azimuth broadening 3 dB width for a target elevation of h = 500 m above the reference track. Also plotted is the variation of the displacement from the reference tracks perpendicular to the line-of-sight direction (6 m displacement corresponds to about 12% on the vertical axis). As noted above, moderate defocusing occurred at a few positions along the flight line, coinciding with the peaks of translational acceleration. When the target elevation was increased to 1 km, extreme defocusing (>100% occurred at the same isolated positions along the flight line. At these positions some small differential defocusing was observed < 10%). The measured defocusing is consistent with the theory.

The resulting mis-positioning of the peak in azimuth for targets with $h = 1$ km was also observed. The results were the same across the range swath with an average of 1 m rms. Using (22), and by filtering the motion data with a one second long rectangular filter to estimate the velocity, the predicted shift was calculated. The predicted and measured results agreed to within a 0.1 m rms error. The differential shift was negligible.

Although the simulations were only performed at C-band, the modeling can be used to extend the results to other bands. For instance, the range varying range spectral shift (17) will be smaller at L-band and larger at X-band. But, the height estimate biases due to RCM effects (20) and unknown terrain (29), and defocusing due to unknown terrain (24), will be larger at L-band and smaller at X-band.

B. Processing CCRS InSAR Data

Processing with CCRS C-band InSAR data was carried out to illustrate the differences in the various motion compen-

Fig. 9. Slant range SAR image of Three Hills, Alberta. Image extent: 4 km in azimuth (vertical) by 8 km in slant range (horizontal) (1024 × 2048 samples). Gray level mapping shown at left.

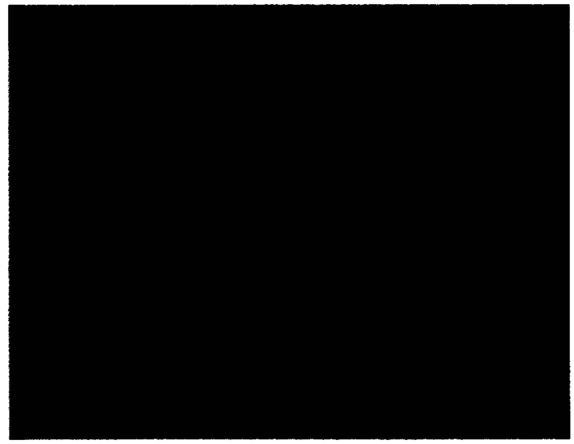

Fig. 10. Differential phase of interferogram generated using dual reference track motion compensation for Three Hills scene. One cycle of color wheel (at left) corresponds to 2π radians. There is a discontinuity in the reference tracks at the center of the azimuth extent.

sation approaches. The InSAR processor will be described first, followed by a description and display of the resulting interferograms. Some additional experiments with inertial data errors will also be described.

A basic InSAR processor was implemented to process the range compressed data obtained by the CCRS InSAR system. The main processing steps included:

1) Resample channel B to register with channel A at the reference level.
2) Perform motion compensation phase correction to each channel using single or dual segmented reference tracks. No motion compensation resampling was performed.
3) Perform azimuth compression using fast convolution without RCMC.
4) Form the interferogram and perform azimuth phase smoothing.
5) Optionally, apply extra phase correction if dual tracks used.

The data set processed was of the Three Hills area in Alberta, Canada. The data was acquired by the CCRS InSAR system in Feb. 1992. The scene is of farm land with rolling hills (Fig. 9). The processing parameters used were those of Table II. The raw data processed was 12 000 range lines with a swath width of 2048 samples. The interferograms were phase smoothed by sample averaging of 10 samples in azimuth and down sampled by 10 producing a final image 2048 samples in range by 1024 in azimuth. This yielded about equal sampling intervals of 4 m in each direction.

Fig. 10 shows the resulting interferogram differential phase for the dual reference track case. One cycle of the color wheel corresponds to a change of 2π rad. The dominant variation is due to the flat earth fringes which depend upon the reference track positions. The discontinuity in the reference tracks at azimuth sample 512 will clearly pose unwanted constraints on phase unwrapping. The flat earth fringes have to be removed before the variation due to topography will be visible in the interferogram. This is what the proposed extra phase correction accomplishes.

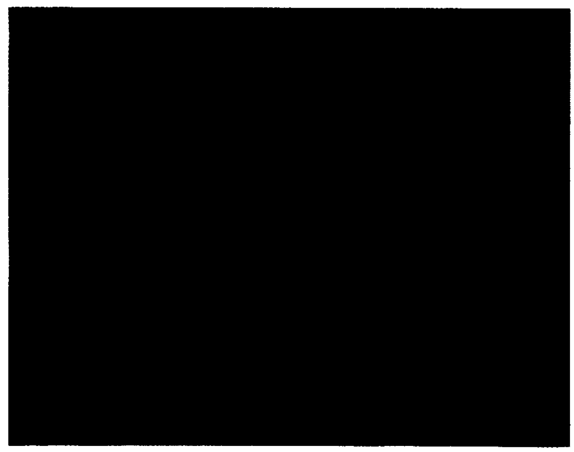

Fig. 11. Differential phase of interferogram generated using new dual/single reference track motion compensation for Three Hills scene. One cycle of color wheel corresponds to π radians. There is a discontinuity in the reference tracks at the center of the azimuth extent.

Fig. 11 shows the resulting interferogram differential phase for the new dual/single track case. One cycle of the color wheel corresponds to a change of π rad. The extra phase correction was applied to the phase smoothed and down sampled interferogram to reduce computation given that motion compensation resampling was not performed. The new dual/single approach has the expected continuous differential phase across the segmentation boundary. This result was compared to the interferogram generated using the single reference track approach yielding a mean difference of 6 cm in elevation and an rms difference of 3 cm. It is clear that for the CCRS case the single reference track approach without RCMC is adequate if the processed RCM is small ($<\frac{1}{3}$ of a resolution cell).

To check the equivalence of all approaches with regard to inertial data errors, real data experiments were carried out. A clutter data set was selected from the Three Hills data and processed using the "correct" INS data supplied by CCRS for motion compensation and elevation estimation. Following this benchmark run, the same raw data was processed but with bias errors or zero mean, independent from pulse to pulse, Gaussian errors added to the INS data. The single and both dual track motion compensation approaches were used. The height estimates were compared to the height estimates from the baseline run and the errors computed. All methods produced the same variance of height errors. As an example of the results for the CCRS processing parameters, a 1 mm rms error in the position of the receive-only antenna produced about a 0.4 m rms height estimation error at near range ($R = 10$ km). For the bias case, a 1 mm bias error in the horizontal and vertical position of the receive-only antenna position led to a height estimation bias of about 0.5 m at near range. Clearly, very accurate antenna position information is needed in order to meet the accuracy goal of one meter, likely requiring a combination of the Global Positioning System (GPS) for long term stability and INS systems for the high frequency response.

VIII. Conclusions

In this paper, the main accuracy issues involved in motion compensation for airborne interferometric SAR have been discussed and evaluated using point target simulation and by processing CCRS C-band InSAR and inertial data. In general, if the two antennas are rigidly connected then many of the phase errors due to nonideal motion compensation are common to both channels and cancel out in the interferogram. Exceptions to this can occur when the range varying phase correction (RVPC) is different between channels, when the antennas drift away from the reference track(s) leading to large range spectral shifts, when there is unknown terrain coupled with aircraft roll, and from inertial data errors. Errors common to both channels are defocusing and azimuth shifts due to unknown terrain coupled with cross-track motion perpendicular to the line-of-sight direction. The azimuth shifts are correctable as a post-InSAR processing step, but defocusing correction would require an autofocus scheme or an iterative processing approach using some initial estimate of the terrain elevation. The range varying range spectral shift will be larger for shorter wavelengths, but the height bias errors due to RCM effects and unknown terrain, and defocusing due to unknown terrain, will be smaller.

The single and dual reference track approaches each have their own advantages. A new approach has been proposed which combines the benefits of both. The method uses the original approach of dual reference tracks that are segmented to remain near the antenna positions, but this is followed by a new post-compression phase correction to simulate a single segmented reference track. This approach produces accurate differential phase that is continuous across the segmentation boundaries and compensates for bias errors caused by unknown terrain coupled with low frequency aircraft motion. One consequence of using the instantaneous antenna positions for the phase to elevation conversion is that there can be an increased sensitivity to errors from oscillatory roll coupled with large deviations from the reference track.

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