MOTION CORRECTION IN SYNTHETIC APERTURE RADAR USING SUBAPERTURE TECHNIQUES

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ABSTRACT

Motion correction is required in airborne synthetic aperture radar to generate high quality images. This paper proposes a new motion compensation method based on subaperture techniques which better approximates the space variant of compensation kernel. Motion errors are averaged and added to the system parameters. Only residue errors remain to be corrected. The subaperture images are compensated independently and added together coherently in the final step to generate a fine resolution image. Simulation results show that the new method outperforms the full aperture compensation methods, especially in the circumstances of large motion errors.

1. INTRODUCTION

Synthetic aperture radar is a fine resolution microwave imaging system mounted on aircraft or spacecraft. Range (cross track) resolution is obtained by emitting coded signals and matched filtering their echoes. Azimuth (along track) resolution is achieved by analyzing the phase history of received signals. To maintain an ideal flight trajectory is crucial to image quality as trajectory deviation, especially in the airborne systems, will severely destroy the phase history and produce blurred images [1]. It is reported [2] that flight path deviations of linear track can be several meters (Motion errors may be obtained by GPS or extracted directly from raw data [2]). Therefore, motion compensation is required to correct the actual trajectory to the nominal trajectory.

Several motion compensation techniques have been proposed to address this issue. In [3] and [4], a space invariant motion correction method is used. Fornaro [5] has proposed a more accurate space variant method, but is limited to a certain imaging algorithm. Besides this constraint, these methods all use linear approximation in the correction formula and fail to account for space variant in the azimuth direction. When motion errors exceed a certain level, the image quality is impaired (see simulation results).

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This paper presents a subaperture method that solves this problem to a certain extent. The main idea of this method is to divide the full aperture time to several (usually two to four) subapertures and compensate them separately. Within one subaperture, the motion errors can be averaged and added to system parameters. Only residue motion errors remain to be compensated using the space variant method. This ensures the accuracy of linear approximation and space variant in the azimuth direction. In a final step, these subaperture images are added coherently to produce fine resolution full aperture image.

Section 2 describes the geometry of airborne system and briefly reviews the full aperture motion compensation. Section 3 discusses the subaperture techniques and its implementation. Section 4 provides simulation results and computational requirements for the new method.

2. FULL APERTURE MOTION COMPENSATION

Consider the stripmap SAR geometry in figure 1, the aircraft takes a curved trajectory while the idea trajectory is a straight line. (Using a three dimensional coordinate is necessary for the airborne case, as the elevation angle is changing in the viewing area.) For the ideal track, the antenna is pointed to a reference point $[X_c, Y_c, Z_c]$ (relative position to the antenna). Motion error is a function of azimuth time *u*, and makes the reference point to $[X_c + x_e, Y_c + y_e, Z_c + z_e]$. For broadside SAR system, $Y_c = 0$ for the antenna is perpendicular to flight track. Motion error in the azimuth direction is usually caused by the change of aircraft velocity and is corrected by resampling the raw data [4], which is not discussed here. Thus we can assume the reference point to be $[X_c + x_e, 0, Z_c + z_e]$ and received echo can be formulated as

$$s(t,u) = p(t - 2R/c)$$
$$R = \sqrt{(X_c + x_e + x_n)^2 + (y_n + y_e - u)^2 + (Z_c + z_e)^2} \qquad (1)$$
$$R_0 = \sqrt{(X_c + x_n)^2 + (y_n - u)^2 + (Z_c)^2}$$

where t denotes fast time variable and u slow time respectively. R is the actual trajectory and R_0 the nominal one. x_n, y_n is the point position relative to the reference point. Fourier transform in fast time domain produces

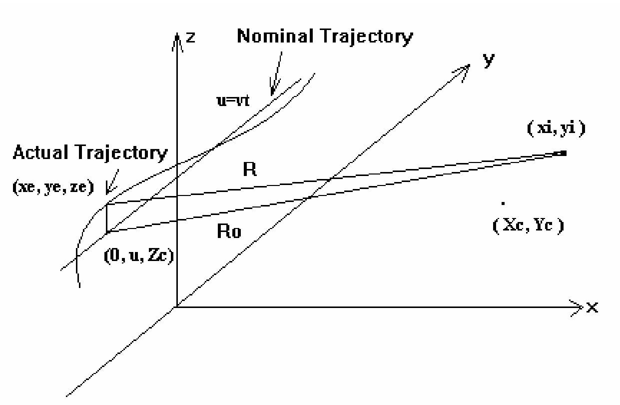

Figure 1. Geometry of airborne SAR

$$s(\omega,u) = P(\omega)\exp(-j2kR) \tag{2}$$

The phase needed to be compensated is

$$\exp[-j2k(R-R_0)] \tag{3}$$

which varies with range and azimuth and is unable to be compensated precisely because range related variables x, z are not available in this domain. To mitigate the problem, we notice that the radar bandwidth is much smaller compared with the carrier frequency. And approximates (3) as

$$\begin{aligned} &\exp(-j2(k_0+k')(R_0-R)) \\ &\doteq \exp(-j2k_0(R_0-R))\cdot\exp(-j2k'(R_0-R)) \end{aligned} \tag{4}$$

The phase term containing varying k' is compensated in the wavenumber domain and the other term is corrected in time domain after range compression.

The limitation of this method, as stated above, is the lack of accuracy in the azimuth direction and linear approximation. Note that the first term of (4) can not vary with u as the track in azimuth typically lasts for hundreds to thousands azimuth lines. The second term can neither vary with range nor azimuth and is approximated linearly or using the reference point. As a result, only small motion errors can be precisely compensated.

3. SUBAPERTURE MOTION COMPENSATION

Aircraft system is subject to atmospheric turbulence and inability to maintain a straight line [5]. This motion error is a relatively small value in a short time but will accumulate along the duration of flight. Aperture time increases as the azimuth resolution increases and motion errors are no longer a small value within one aperture. (figure 2) For efficient processing, imaging algorithm typically requires two aperture lengths and makes the problem worse.

By the above assumption, we model the motion error as a stochastic process with time varying mean but relatively small variance in one subaperture. That is to divide u into several disjoint partitions.

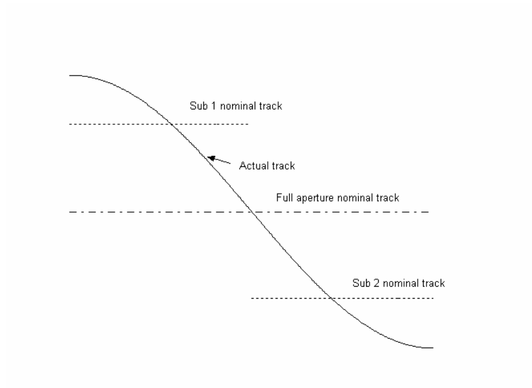

Figure 2. Motion Errors

$$u \in (U_1,U_2)\cup(U_2,U_3)\cup\ldots\cup(U_n,U_{n+1}) \tag{5}$$

For each subaperture, calculate the mean of motion error.

$$\begin{aligned} mex_i &= E[x_e(u)] \\ mez_i &= E[z_e(u)] \end{aligned} \qquad u \in (U_i,U_{i+1}) \tag{6}$$

We observe from (1) that the average error can be 'absorbed' into the system parameter and subtracted from motion errors. That is

$$\begin{aligned} X_{ci} &= X_c + mex_i \quad Y_{ci} = Y_c \quad Z_{ci} = Z_c + mez_i \\ x_{ei} &= x_e - mex_i \quad y_{ei} = 0 \quad z_{ei} = z_e - mez_i \end{aligned} \tag{7}$$

Each subaperture data is first compensated using the above full aperture correction method (only small residue errors x_{ei}, z_{ei} need to be corrected) and then focused using the processing algorithm of choice. Here, the wavenumber domain algorithm [6] is selected. Fourier transform in the azimuth direction is shown as

$$\begin{aligned} s_i(\omega,k_u) &= |P(\omega)|^2\exp(-j\sqrt{4k^2-k_u^2}\cdot r_i - jk_u y_n) \\ r_i &= \sqrt{(X_{ci}+x_n)^2+(Z_{ci}+z_n)^2} \end{aligned} \tag{8}$$

The azimuth wavenumber is denoted as k_u. After baseband conversion and Stolt interpolation [7], the processed signal in two dimensional frequency domain is

$$\begin{aligned} s_i(k_x,k_u) &= |P(\omega)|^2\exp(-jk_x(r_i-r_{0i})-jk_u y_n) \\ r_{0i} &= \sqrt{X_{ci}^2+Z_{ci}^2} \end{aligned} \tag{9}$$

Two dimensional inverse Fourier transform the data will produce image centered at r_{0i}.

From the above derivation, each subaperture is focused separately and produces its own image. The last step is to sum these images coherently. From (9), the only difference of each subaperture lies in r_i and r_{0i}. These two variables contain the subaperture mean error and have different value for each aperture. If added directly, the resultant image will defocus in the azimuth direction and contain ghost points. (See figure 3)

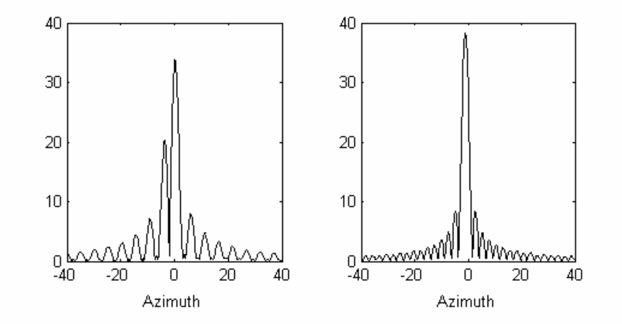

Figure 3. Direct add and Coherent Add

Left: Direct add Right: Coherent Add

The solution is to again exploit the bandpass property of SAR signal and compensate the phase difference in the final images. Starting from (9), we have

$$s_i(k_x, k_y) = |P(\omega)|^2 \exp(-jk_0(r_i - r_{0i})) \cdot \exp(-jk'(r_i - r_{0i}) - jk_u y_n) \quad (10)$$

Two dimensional IFFT renders image located at $r_i - r_{0i}$ and contains phase term

$$\exp(-jk_0(r_i - r_{0i})) \quad (11)$$

For typical airborne SAR parameters, the location difference $(r_i - r_{0i}) - (r_j - r_{0j})$ is the order of 0.05 cells and can be neglected. The phase difference of (11) has to be taken into consideration. For two subapertures, one image is multiplied by

$$\exp(-jk_0(r_i - r_{0i}) + jk_0(r_j - r_{0j})) \quad (12)$$

to make them equal. For several apertures, one aperture is selected as the reference one and the others corrected to it using (12). After phase adjustment, these apertures are added together, the full spectrum of signal is restored and full aperture resolution is achieved.

Figure 4 illustrated the procedure of this method.

Subaperture data is first padded with zeros to form a pseudo full aperture length. This is necessary because the frequency domain resolution should be maintained.

The choice of subaperture length is rather flexible. If one particular region contains large motion errors, this region can be separated and corrected independently. A choice can be made as where to separate the data into subapertures.

A point to note here is that the last phase correction step is somewhat similar to the SAR interferometry [2]. (Two separate antenna with different tracks) However, for InSAR, the phase difference is important information where height values can be obtained. In this case, the phase is detrimental for focusing and should be removed from the final image.

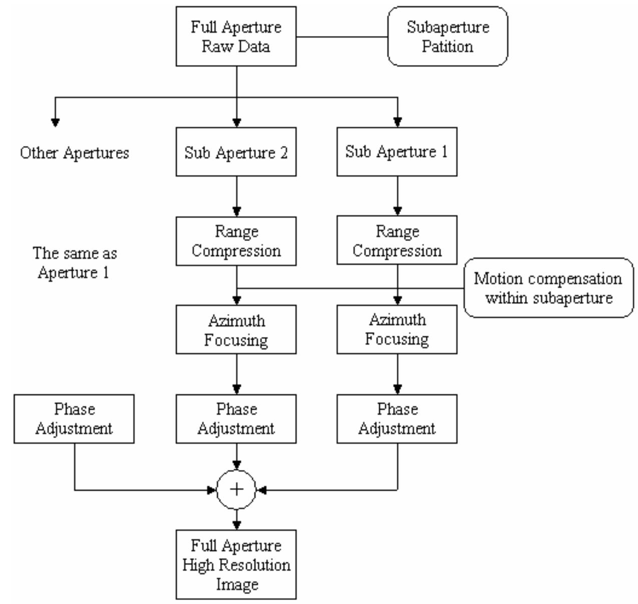

Figure 4. Flow Chart of Subaperture Algorithm

4. SIMULATION RESULTS

A typical airborne broadside SAR parameter is used to compare the proposed method with full aperture method. System parameters are listed in the following table. Motion error is modeled by sinusoidal displacement with a maximum value of 6 meters. For subaperture method, two subapertures are used in this test. No window is applied to range or azimuth direction.

Table 1 Simulation Parameters

Center Range	10000m
Height	6000m
Velocity	50m/s
Sample Rate	200MHz
Range Bandwidth	90M
Pulse Repetition Rate	500Hz
Wavelength	0.02m
Aperture Time	2.2s

Simulation results are presented here.

Table 2 Simulation Results

	Resolution m		PSLR dB		ISLR dB	
	Ran	Azi	Ran	Azi	Ran	Azi
Full	2.26	0.90	-13.1	-11.2	-10.2	-8.4
Sub	2.21	0.88	-13.5	-13.2	-11.0	-10.0

Simulation results listed in Table 2 and Figure 5 show that the subaperture method produces images better than that of full aperture method. The mainlobe is narrower and sidelobes are lower.

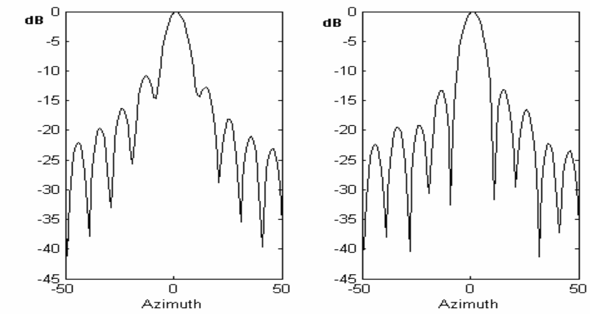

Figure 5 Point Spread Function

Left: Full Aperture Right: Subaperture

Peak sidelobe rate (PSLR) is about 1-2dB lower and integral sidelobe ratio (ISLR) also improves about 1dB. The above figure shows the point spread function of two algorithms in azimuth direction. The subaperture algorithm generates better results (no window is applied). The improvements are attributed to the small motion errors within one subaperture. For points apart from reference range and azimuth, the motion errors are compensated more precisely.

The following simulation compares the two algorithms in the circumstances of large motion errors (up to 15 meters). In this case, full aperture method fails to produce acceptable images in the azimuth direction. The points are blurred and resolution is two to three times of the theoretical values. Subaperture method maintains the resolution in range and azimuth direction and the points are not blurred. The results compare favorably for the subaperture method. (see figure 6)

Computational requirements increase as the number of aperture increases. However, for two subapertures, no more computation time is required. The focused subaperture image can be stored temporarily and used for next processing. For full aperture imaging, usually two aperture time is processed at one time and two successive processing require the raw data to overlap. Using two subapertures avoids this problem.

CONCLUSION

This paper presents the subaperture motion compensation techniques. By partitioning the raw data into several subapertures, range and azimuth variant motion errors are compensated more accurately. Simulation results show that the image quality is better than that obtained using full aperture compensation methods.

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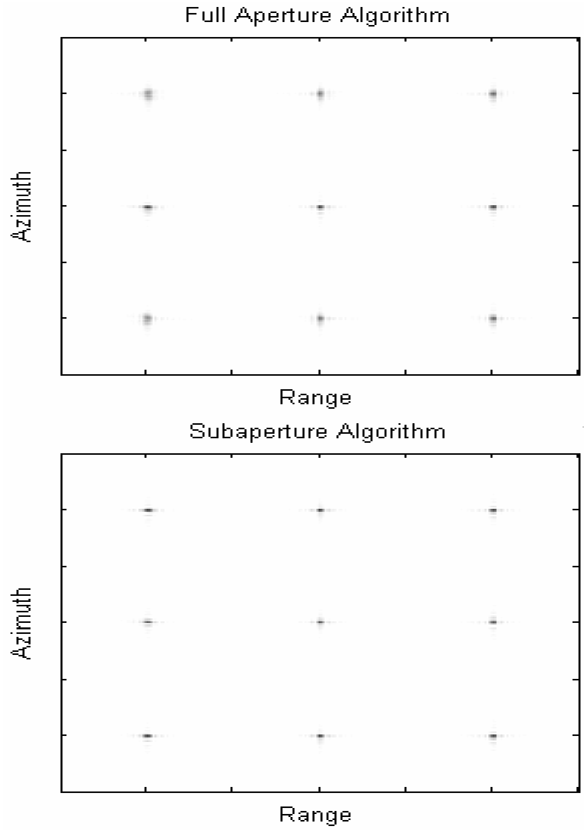

Figure 6 Comparison under large motion errors

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