Trade-Off between Motion Measurement Accuracy and Autofocus Capabilities in Airborne SAR Motion Compensation

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Abstract: *When processing airborne SAR data, motion compensation is an unavoidable step. Accurate motion compensation requires the knowledge of the exact position of the platform at each pulse. This paper studies the trade-off between two approaches. The first approach is to get the most accurate position estimation as possible to be able to perform the motion compensation with correct input data. The second approach is to accept a less accurate position estimation and to analyze in which way an autofocus algorithm is able to compensate position measurement errors.*

1. Introduction

The position of the aircraft can be measured during flight typically by an inertial navigation system (INS) combined with a GPS receiver. In that case, the measured position will be characterized by a sawtooth pattern caused by the inherent drift of the INS which is corrected at regular intervals by the GPS. In this study, we use an actual measured flightpath. Figure 1 (a) and (b) show the cross-track errors of this flightpath compared to an ideal linear horizontal flightpath. Obviously, this cannot represent the exact aircraft position.

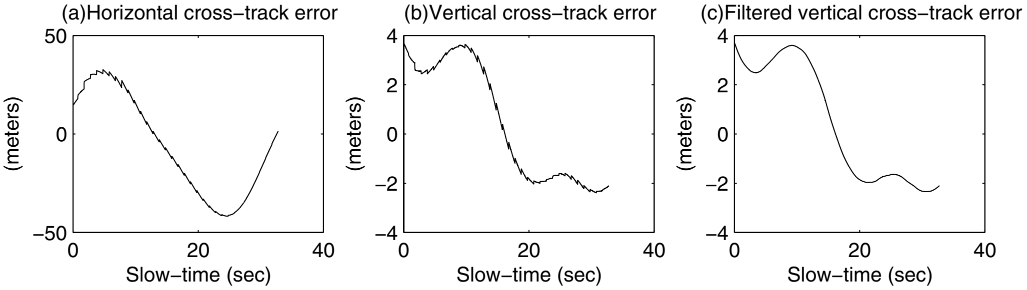


Figure 1: Measured Altitude Position

If motion compensation is applied with that kind of measured position data, the quality of the SAR image will be strongly degraded by the discontinuities.

A complete SAR processing algorithm is then composed of 3 steps. The first step is the filtering of the position data to eliminate the discontinuities and to extract the best estimate of the actual aircraft position. The second step consists of the SAR processing with motion compensation. The third step, which is not mandatory, is an autofocus step to compensate residual errors.

We compare two approaches. The first approach consists in trying to get the most accurate position estimation as possible to perform motion compensation to reduce the need for the autofocus step (figure 2 (a)). The second approach consists in simplifying the filtering step and trying to compensate the effects of the residual difference between real position and estimated position of the aircraft by means of the autofocus algorithm (figure 2 (b)).

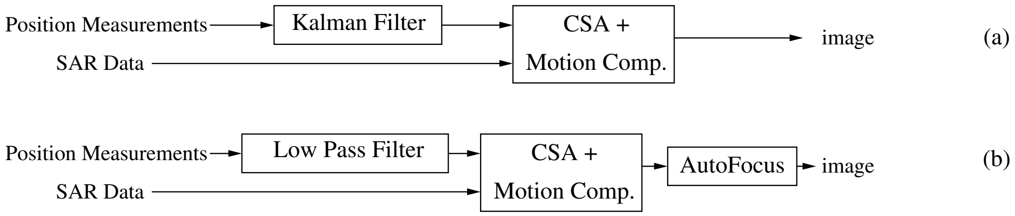


Figure 2: Motion Compensation approaches

In this study, we will only consider horizontal and vertical cross-track position errors.

2. Position Estimation

2.1. Kalman Filter

If we aim to perform accurate motion compensation, the filtering method may not be arbitrarily chosen and applied, as the output of the filter must be as close as possible to the real position of the aircraft. In [2], the best estimate is obtained through a Kalman Filter using a 17×1 system state vector and a 14×1 system noise vector and corresponding matrices. Several parameters are needed for the computation/estimation of those matrices. We also need the measurement of the state vector elements (position coordinates, velocity components, attitude angles, gyro drifts,...). All this information is not always available. Moreover, we cannot expect that the Kalman filter will deliver the exact position of the aircraft and so there will always be a residual error left.

2.2. Wavelet Shrinkage

If we rely on an autofocus algorithm to compensate the effects of measurement errors, the filtering method could be chosen and applied with less attention to the real motion equations of the aircraft. This simpler filter can, for instance, be a Gaussian filter or a filter based on wavelet shrinkage [1], as it is optimum for a wide class of signals. Let's assume an aircraft flying perfectly horizontal at a constant speed. If we consider a position measurement affected by INS drift and GPS corrections and not by other measurement errors, the result of wavelet shrinkage of the measured position will be a constant position error for each pulse, which will have no effect on position and quality of the SAR image.

Measured aircraft position errors are represented on figure 1 (a) and (b). A wavelet shrinkage filtering [1] has then been applied to the measured position data to remove all discontinuities. The result of the wavelet shrinkage of the altitude position error is depicted on figure 1 (c).

3. Motion Compensation

After the discontinuities of the position data have been filtered out, the filtered position data can be used for motion compensation.

The SAR processing of the data is performed with a Chirp Scaling Algorithm [5]. In [4], motion compensation is integrated in the chirp scaling algorithm and is performed in two steps. The position error induces a range-dependent phase error. A primary motion compensation corrects for the phase error corresponding to a reference range. A secondary motion compensation after range compression corrects for the residual range-dependent phase error.

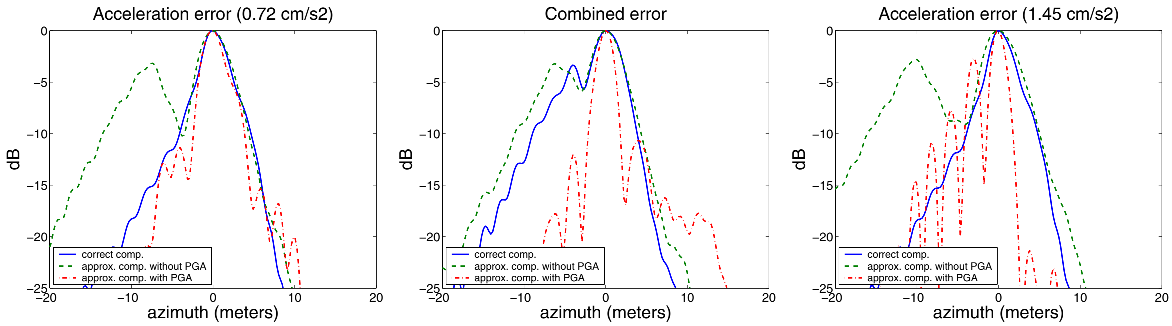
A phase gradient autofocus (PGA) [3] is then applied as a final step to compensate the effects of the remaining position estimation errors.

4. Simulation results

The data on figure 1 (c) and the filtered version of figure 1 (a) are the input data for the motion compensation. This data is different from the actual aircraft trajectory. We will assume that the error compared to the actual trajectory is a constant position, velocity or acceleration error in the cross-track direction. SAR data is then simulated with the assumed real trajectory data. A constant cross-track position error has no effect on the azimuthal Point Spread Function (PSF). A constant velocity error will induce a linear phase error which will displace the image in azimuth without alteration of the PSF. So we will consider acceleration errors or combinations of the 3 kinds of errors.

To quantify the size of the maximal error that the autofocus is able to compensate, we need a quality criterion. The chosen criterion requires that the first side-lobes of the final PSF be lower than those of the PSF obtained with exact motion compensation without autofocus. Exact motion compensation means that the motion compensation is performed with the same position data as the data used for raw SAR data simulation, and not that the SAR processing with motion compensation will give as result the ideal sinc-function for the PSF. This is represented on figure 5 where the degradation of the PSF obtained with exact motion compensation is shown in function of increasing deviations compared to the ideal flightpath (horizontal, linear, constant velocity).

Each graph of figure 3 shows the comparison of 3 azimuthal PSF. The first PSF is the one obtained by an exact motion compensation, in the sense that is described here above. This would correspond to the use of the ideal Kalman Filter on the position measurements. The ideal Kalman Filter is the filter that would give as result the exact position of the aircraft. The second PSF is obtained by motion compensation with different position data as the data used for simulation, without autofocus. The third PSF is the result of autofocus applied to the second PSF.



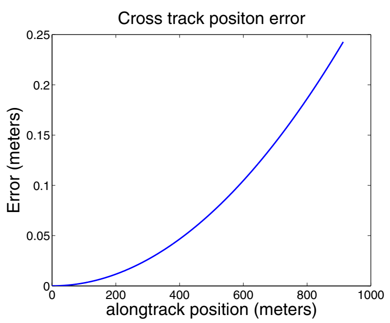
(a) (b) (c)

Figure 3: Autofocus effect on azimuth PSF

The graphs of figure 4 represent the difference in cross-track platform position between the position data used for the simulation of SAR data and the position data used for motion compensation.

Figure 3 (a) and 4 (a) represent a scenario with a constant acceleration error of 0.72 cm/s^2. This acceleration error is the maximal error that satisfies the chosen quality criterion.

Figure 3 (b) and 4 (b) represent a scenario with a combination of a constant position error of 0.9 m, a constant velocity error of 0.3 m/s and the same acceleration error as in (a). This combination of



(a) (b)

Figure 4: Platform position error

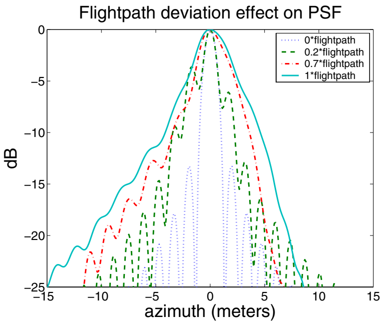


Figure 5: PSF degradation

errors is still sufficiently compensated to fit the quality criterion.

Figure 3 (c) represents a scenario with two times the same acceleration error as in (a). This does not fit the quality criterion any more.

5. Conclusions

In this paper, we have shown that an autofocus algorithm is able to compensate the effects of errors in the measured position data that is used as input for motion compensation.

This ability allows us to replace the design and implementation of a complex Kalman filter for retrieving the best estimate of the position data by a simple low-pass filter that is, in this case, based on wavelet shrinkage.

The size of the errors that can be compensated by the autofocus algorithm is limited by the desired image quality, which is dependent of the application we will use the image for. So the quantification of this error size is application-dependent.

Future work will test this strategy on real SAR data with corresponding position measurements.

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