COMPARISON OF CHIRP SCALING AND WAVENUMBER DOMAIN ALGORITHMS FOR AIRBORNE LOW FREQUENCY SAR DATA PROCESSING

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ABSTRACT

In recent years a new class of Synthetic Aperture Radar (SAR) systems using low frequency have emerged. The combination of low frequency with high bandwidth allows a variety of new applications. Several new fields arise in forestry, biomass measuring and in archaeological and geological exploration. The P-band SAR technology benefits from technological advances in antenna design, low noise amplifiers, band pass filters, digital receiver technology as well as new processing algorithms [1], [2].

For all the new applications of an airborne P-band SAR system, the high-resolution imaging is an important parameter, but it cannot be easily achieved with conventional processing techniques. In this paper, the performance and limitations of the Extended Chirp Scaling (ECS) algorithm and wavenumber domain Omega-K processing algorithm are analysed and discussed. Additionally, modifications of both algorithms are proposed, which optimise the respective algorithm for processing low frequency, wide-beam and wide-band SAR data. The analysis is performed using simulated low frequency airborne SAR data.

1 INTRODUCTION

An increasing amount of interest has evolved in VHF/UHF SAR applications. For most of the new applications high quality SAR data focusing is necessary. Although wavenumber domain processors are commonly used to process low frequency wide-beam and wide-band SAR data [1], they show certain limitations in performing a high-precision motion compensation of airborne SAR data. On the other hand, the Extended Chirp Scaling (ECS) algorithm [2] is proven to be very powerful in processing airborne data, but has limitations concerning long aperture synthesis and heavily squinted geometries. The limits of the along-track resolution of an airborne wide-band and wide-beam P-band SAR system are investigated in this first part of the paper, through the comparison of the performance of the ECS and Omega-K processing algorithms using simulated data. An efficient and robust correction algorithm, which compensates the errors introduced to the data due to ECS approximations, is addressed as well. A detailed analysis of the motion compensation distortions related to the wide beam azimuth processing using both ECS and Omega-K algorithms is presented at the second part of this paper using mainly simulated data sets in different motion errors scenarios.

2 ECS AND OMEGA-K ALONG TRACK RESOLUTION LIMITATIONS

The range resolution of a SAR system is determined mainly by the transmitted pulse duration and it can be easily adjusted. On the other hand, high along-track resolution in high frequency (more than 1 GHz) narrow-beam SAR systems is related mainly with the used processing algorithm. For wideband and wide azimuth beam SAR systems the along-track resolution is stretched to its fundamental limits.

According to [3] in the ideal data collection scenario, where no motion errors are introduced to the data, the Omega-K algorithm provides the exact solution in the focusing procedure, resulting in images with maximum possible along track resolution and minimum residual phase errors.

On the other hand, at lower center frequencies, where longer synthetic apertures and large integration angle are necessary to achieve high along track resolution, the ECS processing algorithm, due to approximations made in chirp scaling processing, does not provide the exact solution in the focusing procedure. As a result of this, the introduced phase errors are limiting the maximum achievable along track resolution.

According to [2], there are two approximations in chirp scaling processing. First, there is the Taylor approximation in wavenumber domain, which leads to SAR signal formulation in range-Doppler domain. This approximation is the basis for the chirp scaling processes. The second approximation is related with the lack of update of the Secondary Range Compression (SRC) with range during signal processing.

The phase error, arising from the first approximation, is mainly cubic with range frequency and causes an asymmetric range impulse response function and, as a result of this, an increase of the sibelobe level. In any case, the residual phase error, introduced to the peak position, is small compared to the corresponding phase error introduced by the second approximation.

Several methods for phase error compensation, caused by the approximations in the chirp scaling processing, can be found in the literature [4]. For the needs of our analysis, we apply an efficient and robust correction algorithms as analytically described in [5].

2.1 SIMULATED DATA ANALYSIS

A P-band raw data simulation has been performed to compare the performance of ECS and Omega-K algorithms in processing low frequency, high along-track resolution, wide-band and wide-beam SAR data. The main simulation parameters for both processing algorithms are listed in Table 1. As mentioned above, no motion errors have been introduced during raw data simulation. The simulated raw data set consists of three point targets, placed in near, middle, and far range (point targets 1, 2 and 3 respectively) of the processed scene.

The phase response of the three simulated targets in frequency domain is shown in Figure 1. No weighting function has been applied to the data (alpha=1.0). From this figure it becomes clear, that in the case where no motion errors are introduced to the data, the Omega-K algorithms results to ideal point target response where almost no residual phase errors are present (solid line plots). Nevertheless, the standard ECS processing algorithm, due to the above-mentioned approximations, introduces phase errors. From Figure 1 it can be concluded, that for 100Hz processed Doppler bandwidth (which corresponds to 1.0m azimuth resolution or alternatively $\pm 10^0$ processed squint angle), the maximum residual phase error for far range point target is approximately 55^0 (doted line plots). The residual phase error is quadratic with range frequency, depends on the processed Doppler bandwidth and slant range.

Parameter	Value
Wavelength	0.66601726 m
Range bandwidth	100 MHz
Chirp duration	5 μs
Sampling frequency	100 MHz
PRF	500 Hz
Velocity	93.0827 m/s
Azimuth resolution	1m
Hamming weighting	a=1.0
Motion Errors	Not simulated

Table 1. *Main parameters for P-band raw data simulator.*

According to [5], the error from the approximation $r_0 \approx r_{ref}$ (where r_{ref} is the chirp scaling reference range) after chirp scaling operation in wavenumber domain, can be expressed as:

$$E(f_a, f_r; r_0; r_{ref}) = \exp\left[j \frac{\pi \cdot f_r^2}{1 + a(f_a)} \cdot \frac{2 \cdot \lambda \cdot (\beta^2 - 1)}{c_0^2 \cdot \beta^3} \cdot (r_{ref} - r_0) \right] \quad (1)$$

Where $\beta(f_a) = \sqrt{1 - \left(\frac{f_a \lambda}{2v}\right)^2}$, $a(f_a) = \frac{1}{\beta(f_a)} - 1$, λ is the wavelength, f_a and f_r is the azimuth and range frequency, respectively, c_0 is the velocity of light, v is the mean velocity of the radar platform during data collection and r_0 is the distance to a point target at closest approach.

The error expressed by (1) can be corrected very efficiently by substituting the range frequency f_r by the maximum processed bandwidth MPB_r multiplied with a reduction factor F_r [5]. The reduction factor is dependent on the phase error at the end of the processed bandwidth and on the kind of weighting function [5]. The correction is only a function of azimuth frequency and slant range, and as a result of this it can be implemented in the azimuth compression stage of the chirp scaling processing without any additional computation effort. The correction can be expressed as [5]:

$$E_{corr}(f_a, r_0; r_{ref}; MPB_r) = \exp\left[j \frac{\pi \cdot MPB_r^2 \cdot F_r}{1 + a(f_a)} \cdot \frac{2 \cdot \lambda \cdot (\beta^2 - 1)}{c_0^2 \cdot \beta^3} \cdot (r_{ref} - r_0) \right] \quad (2)$$

The simulated raw data set has been processed using the modified version of the ECS processor. The results are shown in Figure 1 (dash-dotted line). From this figure becomes evident that the modified version of ECS, which takes into account the approximations made in the chirp scaling processing, reduces the maximum residual phase errors for all simulated point targets to less than 10^0. Figure 2 depict the simulation results of point target 3 located in far range of the processed scene. The improvement achieved by the modified version of ECS is evident.

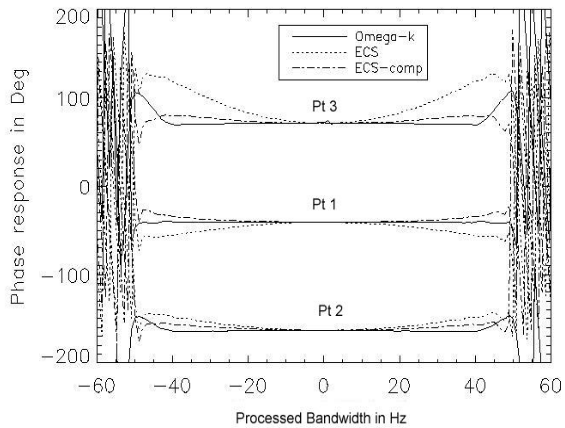

Figure 1: *Phase response in frequency domain of three simulated point targets located in near (Pt1), middle (Pt2) and far range (Pt3) of the processed scene. After the correction applied in the standard ECS processing algorithm, the residual phase error reduce the minimum.*

Recapitulating, when the standard ECS processor is used to process high-resolution low frequency SAR data, then the residual phase error, caused by approximations made in the chirp scaling processing, limits the maximum achievable along track resolution. In this case, a correction function, which compensates the error, is necessary. In the case where no motion errors are introduced to the data, the correction function reduces the phase error to the minimum resulting to accuracy, comparable with the ideal response of the Omega-K processing algorithm.

3 MOTION ERROR EFECTS IN ECS AND OMEGA-K PROCESSORS

A crucial problem in most airborne SAR sensors is the compensation of motion errors, induced by atmospheric turbulence (i.e. the compensation of changes of the platform forward velocity vector in orientation and/or in magnitude). Airborne sensors, in contrary to spaceborne sensors, always show deviations from the ideal flight track. SAR imaging from such unstable platforms requires an accurate measurement of the antenna position during the flight and a modified processing scheme, which takes into account the non-linear movement of the sensor [2].

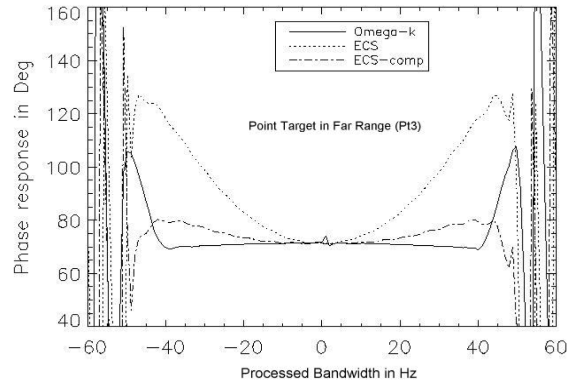

Figure 2: *Phase response of simulated far range point target in frequency domain. The residual phase error reduces from 55^0 to less than 10^0 after the correction implemented at the standard ECS processing algorithm.*

The Chirp Scaling (CS) algorithm [6] was developed mainly to avoid interpolations, which were necessary when we had to deal with strong range-cell migration data (i.e. when wide azimuth beam data have to be processed). A improved version of the CS was the ECS algorithm, which was developed originally for processing airborne data with strong motion errors (like the E-SAR Do-228 platform [7]) and variable Doppler centroid in range or/and in azimuth direction. According to [2], the ECS processing algorithm performs motion compensation in two steps. The first order motion compensation is defined as being the phase error correction for a reference range, and it is carried out directly with uncompressed raw data. After the range compression of the data has been performed, the motion compensation phase function is updated with range. This called second order motion compensation and it is performed right before the azimuth compression.

It has been demonstrated that motion errors up to some tens of meters can be compensated in the case of the E-SAR system using the ECS processor. Additionally, the implementation of a of a sub-aperture algorithm in the ECS algorithm, when it is used to process low frequency wide beamwidth SAR data, as described in [8], suppresses the residual motion compensation error to minimum possible extend. The combination of the ECS correction function, as described in the first part of this paper, with the sub-aperture correction, results to maximum possible along track resolution with a residual phase error comparable to the error illustrated in the ideal processing case of Fig. 1 and 2. In most of the operational examples, the remaining errors are strongly related with the accuracy of the position-measuring units (INS/IMU) and not with the improved ECS motion compensation correction algorithm itself.

On the other hand, due to processing architecture of the Omega-K algorithm, a high precision motion correction cannot be applied in it. Compared with the ECS two-step motion compensation, in Omega-K only the first order motion error correction can be applied [3]. The first-order MoCo is the range-independent part of the real MoCo, and is applied directly after range compression. The range-dependent part can only be applied after correction of the RCM, which is not possible in Omega-K.

The P-band raw data simulator has been used to compare the performance of ECS and Omega-K algorithms in processing low frequency, high along-track resolution and airborne SAR data with motion errors. The same simulation parameters of Table 1 have been used again, now adding one quarter of typical motion errors occurring in case of the E-SAR. The phase response of one simulated point target in frequency domain located in the center of the processed scene is shown in Figure 3. From this figure becomes clear that even in the case of small motion errors the Omega-K algorithm fail to remove completely the introduced phase errors. The residual phase error is in the order of 45^0. On the other hand the modified ECS processor compensates most of the motion errors resulting to maximum possible along track resolution. It has to be noted that the first order MoCo correction of Omega-K has been optimized for the range distance of the target; usually even worse results can be expected.

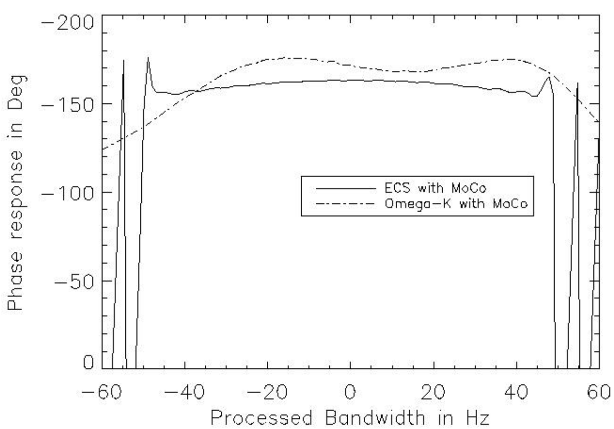

Figure 3: *Phase response of one simulated point target with motion errors in frequency domain located in the center of the processed scene using both algorithms. The Omega-K algorithm fails to completely compensate even small motion errors resulting to a maximum residual phase error of 45^0.*

4 CONCLUSIONS AND FUTURE WORK

The limits of the along track resolution of an airborne wide-band and wide-beam P-band SAR system have been analyzed in this paper through the comparison of the performance of the ECS and Omega-K processing algorithms. Simulated data analysis proves that a correction function can be introduced to the ECS, which results in a focusing accuracy comparable with the ideal response of the Omega-K processing algorithm.

In the case, where strong motion errors are introduced to the data, the modified ECS processor compensates successfully most of the errors, even in the case of low frequency wide-band and -beam SAR data processing, resulting to maximum possible along-track resolution with minimum residual phase error. On the other hand the Omega-K processor fails to compensate even small phase errors introduced by motion of the radar platform during data acquisition.

A modified version of the Omega-K processor, which combines its ideal point target response accuracy with the ECS motion compensation correction performance, is under development with quite promising results.

5 REFERENCES

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