THEORY AND QUANTITATIVE COMPARISON OF DOPPLER CENTROID ESTIMATION METHODS

J. Siewerth

German Aerospace Research Establishment (DLR)

WT-DA/MV SAR

D-8031 Oberpfaffenhofen

West Germany

Abstract

The purpose of this paper is to describe the theory and implementation of three different Doppler centroid estimation methods and to present the first results of currently performed quantitative investigations.

The Doppler centroid shift caused by the relative velocity between the sensor platform and the targets is derived by analysing the received SAR data. In contrast to the conventionally used ΔF-method (also called 'energy balancing'), which is a frequency approach, the two other methods, the Correlation Doppler Estimator (CDE) and the Sign Doppler Estimator (SDE), are both performed in the time domain.

Keywords: Doppler centroid estimation, ERS-1, Intelligent SAR Processor

Introduction

The quality of a processed SAR image strongly depends on the accuracy of the estimation of the expected phase histories of the illuminated targets. Estimation errors lead to errors in the generation of the azimuth processing matched filter and thus to a degradation of image quality. More precisely, particularly a linear phase term estimation error (i.e., Doppler centroid error) leads to a significant degradation of the signal-to-noise ratio, the signal-to-azimuth ambiguity level and to an azimuth shift of the pixel location (Chang et al., 1985). In general, the Doppler centroid estimation must be accurate enough to meet specific SAR image quality requirements.

As the sensor ephemeris data and sensor attitude data are not sufficiently precise to provide accurate Doppler centroid estimation, the Doppler information has to be derived by analysing the coherent radar return.

Within the scope of the ERS-1 ground segment project, DLR (German Aerospace Research Establishment) is going to develop an Intelligent SAR (ISAR) processor. Specifically, in this German ISAR processor, as it is designed as an operational processor, an automatic method for estimating the Doppler centroid, using the radar echo return, must be employed. This automatic module also has to fit the three basic requirements of the overall ISAR processor system well, i.e., 'high quality', 'high throughput' and 'high flexibility'. These three 'major operational requirements' lead to some specific requirements due to the Doppler centroid estimation.

High quality images can only be achieved if the azimuth reference function is a precise matched filter of the radar echo return and the azimuth reference function is updated frequently enough, both in range and azimuth dimensions. In order to perform SAR processing within a minimum time span, the Doppler centroid estimation must also be performed within the shortest possible duration. Thirdly, the processing of radar echo data from various sensor types acquired over different terrain types must be possible.

In a first step toward the selection of an appropriate algorithm, three different Doppler centroid estimation methods have been implemented. The algorithms were taken from (Madsen, 1986) but have been adapted to the specific usage within the ISAR processor. In addition, these prototypes have been written using the programming language ADA, in order to obtain initial experience in the language in which the whole ISAR processor will be built up around.

At the moment, first investigations are being performed using only simulated ERS-1 point targets and some SEASAT scenes. The ISAR raw data simulator was used to generate ERS-1 sensor related raw data from single and multiple point targets. All simulations were based on the ERS-1 3 day reference orbit, assuming nominal operation (yaw-steering) mode. For a final assessment, the algorithms have still to be tested on a greater number of SEASAT scenes.

In the following, the implemented Doppler centroid estimation algorithm will be described and subsequent first results of the investigations will be presented.

The ΔF-Algorithm

The ΔF-algorithm is a well known frequency domain approach, which has already been described by (Curlander et al., 1982), by (Li et al., 1985) and by (Madsen, 1986).

The algorithm makes use of one of the basic SAR properties in azimuth dimension, that the frequency at beam centre, the Doppler centroid, corresponds to the maximum power of the antenna azimuth pattern in the frequency domain.

To detect this frequency which corresponds to the maximum power, the discrete azimuth signal \(a_n\), at a specific range \(r\), is transformed in the frequency domain via a Discrete Fourier Transformation:

\[
A_s\left(\frac{n}{N_s T}\right) = \sum_{k=0}^{N_s - 1} a(kT) \exp\left[-j \frac{2\pi n k}{N_s} \right] \quad n = 0, 1, ..., N_s - 1;
\]

\(N_s\) number of azimuth samples

\(T\) pulse repetition interval

and the periodogram \(P_s\) of the spectrum is calculated.

\[
P_s\left(\frac{n}{N_s T}\right) = \left| A_s\left(\frac{n}{N_s T}\right) \right|^2;
\]
Figure 1 shows the azimuth periodogram of 11 simulated point targets.

\[ P_n\left(\frac{n}{N_T}\right) = \frac{1}{N_l} \sum_{i=1}^{N_t} P_i\left(\frac{n}{N_T}\right) \]

Figure 1: Periodogram of 11 simulated point targets

For reducing the variance to mean square ratio of the periodogram, the accumulated periodogram is calculated (Figure 2).

\[ \begin{align*} N_o & \quad \text{number of accumulated azimuth periodograms} \\ n_l & \quad \text{lower range value boundary} \\ n_u & \quad \text{upper range value boundary} \end{align*} \]

Figure 2: Accumulated power spectrum of 11 simulated point targets \((N_t = 10)\)

This accumulated periodogram is now considered as a function, where the slowly varying antenna pattern function is multiplicatively superimposed by the amount of high frequency target backscatter information. Thus in addition to the Madsen approach, an appropriate low-pass filter is applied to the accumulated periodogram. The result of low-pass filtering is a modified azimuth periodogram, where the higher frequencies, corresponding to the target information, are discarded and almost only the slowly varying antenna pattern function remains (Figure 3).

Figure 3: Accumulated power spectrum of 11 simulated point targets after low-pass filtering

The frequency, corresponding to the maximum power of this modified azimuth periodogram, and therefore, the Doppler centroid frequency (modulo \(\pi\)), is related to the bin belonging to the curve maximum of Figure 3. The usual energy comparison (Madsen, 1986) is unnecessary if an appropriate low-pass filter is applied to smooth the periodogram.

The CDE-Algorithm

Although the CDE-algorithm takes place in the time domain of the azimuth signal, the approach is quite similar to the DFE-method. In contrast to the frequency domain algorithm, the respective processing steps are performed using the corresponding time domain equations.

The shift of the periodogram of the azimuth signal, due to the Doppler centroid, is hereby measured by calculating the phase shift of the corresponding time domain function.

First the autocorrelation function \(R_a\) of the discrete azimuth signal \(a\) at a specific range \(r\), is calculated

\[ R_a(kT) = \frac{N_s}{N_p} \sum_{n=0}^{N_s-1} a_n \left[(k + i)T\right] a_{(iT)} \]

\[ N_s \quad \text{number of azimuth samples} \]
\[ T \quad \text{pulse repetition interval} \]

It corresponds to the azimuth periodogram \(P_a\) via the Discrete Fourier Transformation.

\[ R_a(kT) \xrightarrow{\mathcal{F}} R_a\left(\frac{n}{N_T}\right) \]

Analogous to the DFE-Algorithm, several autocorrelation functions at range values \(n \leq r \leq n_u\) are summed.

\[ R_m(kT) = \frac{N_r}{N_p} \sum_{n=1}^{N_r} R_m(kT) \]

\[ N_r \quad \text{number of range values} \]
\[ r_l \quad \text{lower range value boundary} \]
\[ r_u \quad \text{upper range value boundary} \]

From the so called shifting property of the Fourier Transformation, it is known that the inverse Fourier Transformation of a shifted periodogram is simply the autocorrelation function of the unshifted function, multiplied by an exponential factor, having a linear phase (Gaskill, 1978).
Thus the phase difference between the autocorrelation function $R_R$ and the nominal (zero–Doppler) autocorrelation function $R_0$ is proportional to the Doppler shift.

As the SAR azimuth signal is sampled with a rate which is not much higher than the Nyquist rate, the phases of the respective autocorrelation functions are calculated at the correlation coefficient $j = 1$, to get a high unambiguous Doppler range (modulo PRI). After calculating the phase difference $\Delta \arg$, 

$$\Delta \arg = \arg \{R_R(T)\} - \arg \{R_0(T)\};$$

the Doppler Centroid estimation value is then given by

$$f_D = \frac{1}{2\pi T} \cdot \Delta \arg \pm n f_{PRI}, \quad n = 0, \pm 1, \pm 2, \ldots;$$

Note that the selection of the correlation coefficient $j = 1$ corresponds to the first harmonic of the azimuth periodogram. Thus, comparing the phases at $j = 1$ is analogous to the use of a very restrictive low-pass filter in the frequency domain approach. Figure 4 shows the first harmonic of Figure 3, which corresponds to the correlation coefficient of $R_R$ at $j = 1$.

![Figure 4: First harmonic of 11 simulated point targets](image)

The SDE–Algorithm

Just as the CDE–Algorithm, so the SDE–Algorithm also uses correlation coefficients to estimate the Doppler centroid.

The difference between both methods is only the way in which the autocorrelation function $R_R$ is calculated. While the CDE–algorithm uses the well-known standard equation for the calculation of the auto-correlation function of the azimuth signal, the basic idea of the SDE–Method is to use the so-called ‘Arcsine Law’ of Gaussian processes (Papoulis, 1965) to calculate the autocorrelation function.

The central statement of the Arcsine law is, that if the real part and the imaginary part of a complex digital signal are nearly Gaussian processes (which is fulfilled for SAR azimuth signals), the autocorrelation function can be calculated only by examining their signs.

Results

The first investigations of the Doppler centroid estimation algorithm were performed using only simulated ERS–1 point targets. As expected all three different methods yield the exact frequency, which has been computed by the ERS–1 simulator. The results varied only by 0.1Hz around the exact Doppler frequency. After these tests performed on idealised SAR data, the algorithms were applied to the well known SEASAT ‘Goldstone scene’. The results are shown in Figure 5. The solid curve represents the accumulated and low-pass filtered azimuth periodogram, calculated by the $\Delta \omega$–algorithm. The broken curve depicts the azimuth periodograms which corresponds, via the Fourier Transformation, to the correlation coefficient of the autocorrelation function, calculated by the CDE– and SDE–algorithms.

![Figure 5: Azimuth periodograms calculated from the Goldstone scene](image)

The difference between the frequency corresponding to the peak of the solid curve and the frequency corresponding to the peak of the broken curve is approximately 25 Hz. The comparison of the estimation results to the Doppler centroid frequency, which has been computed by the GSAR (Generalized Synthetic Aperture Radar Processor, developed by MacDonald Dettwiler and Associates Ltd), has shown that the frequency corresponding to the solid peak curve is in agreement with the frequency calculated by the GSAR. This leads to the preliminary result that the Doppler centroid frequency cannot be determined sufficiently precisely if only the first harmonic of the azimuth periodogram is examined.

Subject to further investigation, the Doppler centroid estimation method used for the German ISAR processor should be based on the $\Delta \omega$–algorithm, using an appropriate low-pass filter.

References