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SAR PROCESSING ALGORITHMS FOR ENVISAT ASAR IMAGE MODE AND ALTERNATING POLARIZATION MODE IN THE KSPT ENVISAT ASAR PROCESSOR

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ABSTRACT: This paper describes the Extended Exact Transfer Function (EETF) algorithm used in the Kongsberg Spacetec (KSPT) ENVISAT ASAR processor, in addition to RADARSAT and ERS SAR processors from KSPT. This processor is required to handle and process data from image mode (IM), alternating polarization (AP) mode and wide swath (WS) mode. IM and AP mode are both processed using the EETF algorithm. To process IM the KSPT ENVISAT ASAR processor uses the EETF as-is, and for AP mode it uses the burst-EETF algorithm for coherent processing of each polarization. This implies that both IM and AP mode products exploits high bandwidth and are phase preserving. The EETF algorithm is used because of its speed, ease of implementation and its ability to produce high quality, phase preserving imagery.

INTRODUCTION

This paper introduces the algorithms used in the Kongsberg Spacetec ENVISAT ASAR processor. In the first section the Exact Transfer Function (ETF) for a typical SAR system is devised, where the solution is the main part of a compression algorithm for SAR instruments used in the Kongsberg Spacetec ENVISAT ASAR, RADARSAT and ERS processors. The next section deals with the fact that the Doppler parameters are varying over time, and that the ETF needs a phase correction. This gives the Extended ETF (EETF) algorithm. The next section describes the needed factors and the technique used to coherently process ENVISAT ASAR Alternating Polarization mode products using the very same EETF with an extra filter added. This gives an algorithm which is named Burst EETF (B-EETF). A summary of the paper is given in the last section.

The reason to use the EETF algorithm for spaceborn SAR processing, is that the algorithm assumes from the very beginning a spaceborn geometry as indicated in figure 1. When assuming spaceborn geometry, we minimize the conventional errors introduced by assuming a straight line of flight as in SAR processing algorithms design for a airborne geometry. An airborne assumption for spaceborn geometry s only good for small azimuth beam angles. Airborne algorithms calculates a squint angle which is dependent on the Doppler centroid caused by earth rotation. The EETF has this built-in because it is developed from a general relative motion vector, $\mathbf{R}$, between a spaceborn SAR instrument and target on ground, including the earth's rotational vector $\boldsymbol{\omega}_{\text{earth}}$. This gives us an algorithm that can handle large squint angles. The relative movement vector is normally developed as a 3-dimensional second, third or fourth order vector. Todays generation of SAR satellites is very well handled on a second order basis, while [Eldhuset, 1998] reports that the fourth order version very well can handle future high resolution (< 1m) spaceborn SAR instruments.

In addition to geometrical advantages, the ETF uses a general transmitted waveform explicitly in the equations, as opposed to e.g. Chirp Scaling (SC) algorithm which assumes a linear FM chirp. The ETF would be exact (and sufficient) if the Doppler parameters were range invariant. This is not the case, and it is needed to develop a range-variant correction based on the deviations in Doppler parameters. This is called a phase correction, and leads to the name Extended ETF or EETF for short.

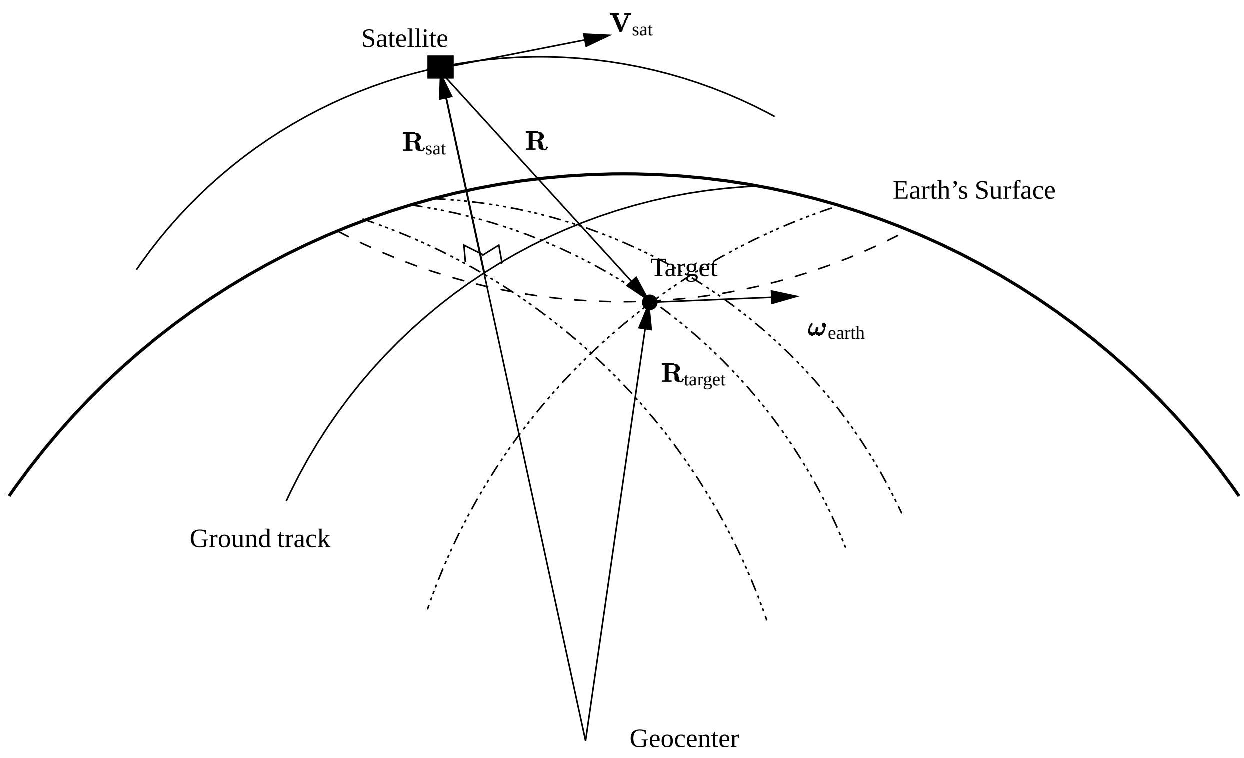

Figure 1: Illustration of the satellite-target geometry.

EXACT TRANSFER FUNCTION (ETF)

The core processing part of the Kongsberg Spacetec (KSPT) ENVISAT ASAR IM and AP mode processor is the EETF algorithm. For Wide Swath mode the KSPT ENVISAT ASAR processor uses SPECAN2. EETF is short for Extended ETF, where the ETF is a transfer function devised from the system impulse response. The general form of this impulse response (point target response) can be written as

$$h(t_r, t_a) = \exp\left[j\left(\Phi_a(t_a) + \Phi_r\left(t_r - \frac{2R(t_a)}{c}\right)\right)\right] \tag{1}$$

This equation consists of the phase history of the propagated signal in azimuth and range; Φ_a and Φ_r respectively. The propagated distance of the SAR pulses in the pointing direction is ct_r. $R(t_a)$ is the length of the relative motion vector between the satellite and the target on ground. $\Phi_a(t_a)$ is the azimuth phase function given in terms of the Doppler parameters. A Fourier transform of equation (1) gives the exact system transfer function, and is used (complex conjugated) as the core processing part of all KSPT SAR processing software for ENVISAT ASAR, RADARSAT and ERS (except for Wide Swath modes).

The ETF is given as the Fourier transform of equation (1)

$$H(\omega_r, \omega_a) = \mathcal{F}_r\left\{\exp\left[\Phi_r(t_r)\right]\right\} \cdot \int \exp\left[j\phi(t_a)\right] dt_a, \tag{2}$$

where the azimuth time phase function integrand is

$$\phi(t_a) = 2R(t_a)\left(\frac{2\pi}{\lambda} - \frac{\omega_r}{c}\right) - \omega_a t_a \tag{3}$$

An integration with the integrand from equation (3) can be solved by the principle of stationary phase [Franceschetti and Lanari, 1999], with a stationary point t_a^* given as

$$\phi'(t_a^*) = 2R'(t_a^*)\left(\frac{2\pi}{\lambda} - \frac{\omega_r}{c}\right) - \omega_a = 0 \tag{4}$$

With the solution of stationary point t_a^* from (4) the ETF can be written as

$$H_{\text{ETF}}(\omega_r, \omega_a; R) = \sqrt{\frac{2\pi}{|\phi''(t_a^*)|}} \exp\left[j\frac{\pi}{4}\text{sgn}[\phi''(t_a^*)]\right] \mathcal{F}_r\{\exp[j\Phi_r(t_r)]\} \exp[j(\Phi_a(t_a^*)] \tag{5}$$

The first two parts (on ϕ'') are does not vary significantly over the variables of interest and are defined as a constant $\mathcal{C}_a$[Eldhuset, 1998]. This constant may be omitted. Equation (5) then takes the from

$$H_{\text{ETF}}(\omega_r, \omega_a; R) = \mathcal{C}_a \cdot \mathcal{F}_r\{\exp[j\Phi_r(t_r)]\} \cdot \exp[j(\Phi_a(t_a^*)] \tag{6}$$

The Φ_r part of equation (6) is the Fourier transform of an arbitrary transmitted range signal. Hence the algorithm can use any given chirp replica. Test done with ERS data shows that the use of downlink replica instead of a linear FM chirp gives a better range resolution. This part thus performs the range compression.

Equation (6) is now a two part function describing the spaceborn SAR exact transfer function. The first part (on t_r) is the Fourier transform of a given chirp replica or linear FM chirp. The second part (on t_a^*) is further developed, and is dependent on a sufficient approximation of the relative radar motion vector. For the KSPT ENVISAT SAR processing facility a second order approximation is sufficient. For future high resolution SAR missions a fourth order approximation is sufficient.

To develop an azimuth phase history $\Phi_a(t_a)$, the relation to the relative radar motion vector is given as

$$\Phi_a(t_a) = \frac{2\pi}{\lambda} R_r(t_a) \tag{7}$$

Assuming a second order approximation, implemented and sufficient for the ENVISAT, RADARSAT and ERS1/2 SAR instruments, the range function is the length of a vector given as

$$\mathbf{R}(t_a) = \mathbf{R} + \mathbf{V}t_a + \mathbf{A}t_a^2 \tag{8}$$

where $\mathbf{R}$ is the relative distance between the satellite and the target, $\mathbf{V}$ is the relative velocity (including earth rotation) and $\mathbf{A}$ is the acceleration. Equation (8) is a 3-dimensional vector. Time $t_a = 0$ is defined as the time where the target is in the middle of the azimuth beam pattern.

The generic procedure for developing a ETF transfer function can be done as:

- Given an integrand from equation (2) and (3), independent on the assumed order of the range vector estimate.
- By use of the principle of stationary phase the integral may be solved. This is done by finding the stationary point of equation (3), using equation (4).
- An estimate of the range vector $\mathbf{R}(t_a)$ (relative motion between a target on ground and the satellite) is needed. The relevant measure is the length of this vector $R(t_a)$. In addition an estimate of $dR(t_a)/dt_a = R'(t_a)$ is needed. On a general Nth order polynomial form these estimates can be written as

$$\begin{aligned} R(t_a) &= \sum_{i=1}^{N} c_i t_a^i \\ R'(t_a) &= \frac{d}{dt_a}\left[\sum_{i=1}^{N} c_i t_a^i\right] \\ &= \sum_{i=1}^{N} i c_i t_a^{i-1} \end{aligned} \tag{9}$$

  This implies that equation (4) can be written as

$$\phi'(t_a) = 2\left(\frac{2\pi}{\lambda} - \frac{\omega_r}{c}\right) \sum_{i=1}^{N} i c_i t_a^{i-1} - \omega_a \tag{10}$$

- Find the stationary point t_a^* of equation (10)

$$\phi'(t_a^*) = 0 \tag{11}$$

  By using equation (9), equation (11) this has an analytical solution for a second order EETF, and two analytical solutions for a third order which implies a discussion of physically adequate solution. It is also possible to bring up analytical solutions for a fourth order approximation, but some of them are complex.

- After substitution with

$$c_i = \frac{-\lambda}{2i} a_i \tag{12}$$

in the solution on t_a^* of equation (11) the final Exact Transfer Function is given as

$$H_{\text{ETF}}(\omega_r, \omega_a) = \mathcal{F}_r\{\exp[j\Phi_r(t_r)]\} \exp[j(\Phi_a(t_a^*)] \tag{13}$$

which is equation (6) without the constant.

EXTENDED ETF (EETF)

With spatially independent Doppler parameters for a full SAR dataset, the same ETF could be used for a full processing. Real life SAR measurements does not possess this property, which implies that the Doppler parameters will need to be updated during the processing.

To implement the *extended* ETF, a phase correction is derived from a matched filtering of the ETF transfer function with itself.

$$U(t_r, \omega_a) = \mathcal{F}_r^{-1}\left\{ H_{\text{ETF}}(\omega_r, \omega_a)\big|_{a_i} \cdot H_{\text{ETF}}^*(\omega_r, \omega_a)\big|_{\hat{a}_i} \right\} \tag{14}$$

which includes the complex conjugate, H_{ETF}^*, with a set of reference Doppler parameters $\hat{a}_i$. The result is called $\Delta\Phi(\omega_a)$.

The figure below shows the data flow in the EETF algorithm, including where the discussed filters are applied. The extra $D(\omega)$ filter is discussed in the next section.

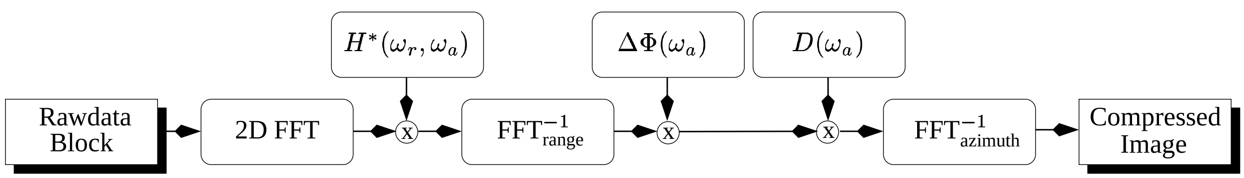

Figure 2: The EETF compression algorithm (here without detection/multilooking), including the burst filter needed for AP mode processing.

BURST EETF (B-EETF)

The Alternating Polarization Mode of the ENVISAT ASAR instrument delivers two polarizations in the same data stream. Each polarization is called a burst. The duration of one of these bursts is called T_B, and the burst period is called T_P. The burst period for ASAR AP mode is

$$T_P = 2T_B \tag{15}$$

The strategy for processing of ASAR AP mode in the KSPT processor is based on coherent focusing of arbitrarily long burst trains, and afterwards removing the resulting periodic modulation in the image point response by incoherent weighted pixel averaging (low pass filtering with $D(\omega)$, as illustrated in figure 2) [Bamler and Eineder, 1996]. This approach is just as fast as regular SAR processing, but slower than SPECAN processing. The reason for using the "slower" coherent processing, is that the EETF is highly phase preserving. Phase preservation is one of the key goals for all Kongsberg Spacetec SAR processors.

The uncompressed AP mode SAR data is going trough 3 steps:

1. Coherent compression/focusing with the EETF algorithm.
2. Low-pass filtering of the detected data, with low-pass bandwidth given by the burst bandwidth B_B.
3. If applicable: Multi-looking/detection of the resulting low-passed signal.

Item 1 in the list above is already discussed. Item 2 implies the selection of a filter shape and the low-pass bandwidth B_B. Filter selection is loosely governed by the ratio

$$\frac{B_P}{B_B} = \frac{|\text{fdr}|T_P}{|\text{fdr}|T_B} = \frac{2T_B}{T_B} = 2 \tag{16}$$

where fdr is the Doppler rate. Higher value of the equation (16) implies that the time domain filter shape can deviate more from a sinc-shape (or a ideal box shaped filter in frequency domain). In the case of the ASAR Wide Swath mode, there is an option of using up to six beam positions. This means that equation (16) is three times higher for Wide Swath than for Alternating Polarization. [Bamler and Eineder, 1996] mainly discusses wide swath SAR modes, which implies that the choice of low-pass filter is narrowed down to a shape that is in the form of a box or very close to a box. According to [Bamler and Eineder, 1996] the only requirement for this incoherent low pass filtering, is that the filter is sufficiently flat over the frequency area $f \in [-B_B, B_B]$, and that it suppresses well all other unwanted spectral terms.

SUMMARY

The EETF algorithm in figure 2 is a 2D coupled algorithm, which implies that range and azimuth directions are not decoupled. The algorithm contains of two filters which implies a very practical implementation of the compression. In these two filters ($H^*(\omega_r, \omega_a)$ and $\Delta\Phi(\omega_a)$ in figure 2) the EETF contains:

- Azimuth compression
- Azimuth localization
- Range migration correction
- Range compression
- Secondary range compression
- Optionally: Skew handling implemented in the ETF filter

With the addition of an extra low pass filter $D(\omega_a)$ as illustrated in figure 2, the same EETF my be used for AP mode processing.

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