ScanSAR Processing Using Standard High Precision SAR Algorithms

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Abstract—Processing ScanSAR or burst-mode SAR data by standard high precision algorithms (e.g., range/Doppler, wavenumber domain, or chirp scaling) is shown to be an interesting alternative to the normally used SPECAN (or deramp) algorithm. Long burst trains with zeroes inserted into the interburst intervals can be processed coherently. This kind of processing preserves the phase information of the data—an important aspect for ScanSAR interferometry. Due to the interference of the burst images the impulse response shows a periodic modulation that can be eliminated by a subsequent low-pass filtering of the detected image. This strategy allows an easy and safe adaptation of existing SAR processors to ScanSAR data if throughput is not an issue. The images are automatically consistent with regular SAR mode images both with respect to geometry and radiometry. The amount and diversity of the software for a multimodule SAR processor are reduced.

The impulse response and transfer functions of a burst-mode end-to-end system are derived. Special attention is drawn to the achievable image quality, the radiometric accuracy, and the effective number of looks. The scalloping effect known from burst-mode systems can be controlled by the spectral weighting of the processor transfer function. It is shown that the fact that the burst cycle period is in general not an integer multiple of the sampling grid distance does not complicate the algorithm. An image example using X-SAR data for simulation of a burst system is presented.

I. INTRODUCTION

SCAN SAR is a method to image wide swaths by sweeping the antenna beam periodically from near range to far range in a stepwise manner [1], [2]. The typically 2–5 discrete beam positions define the subswaths; for each of them the radar works like a burst-mode synthetic aperture radar (SAR). The subswaths can be processed separately and later radiometrically corrected and assembled. In the following we restrict ourselves to a single sub swath; the results are as well applicable to other burst-mode SAR’s.

ScanSAR data is usually processed using the SPECAN (or azimuth deramp) algorithm [3]. Compared to other algorithms SPECAN is computationally efficient because it needs only one FFT for azimuth focusing and takes advantage of the sparseness of the data.

SAR systems like Radarsat and Envisat/ASAR [4] offer the ScanSAR option as one out of many modes, most of them being nonburst modes. Data from these will be processed by high precision algorithms like range/Doppler, wavenumber domain, or chirp scaling. For applications not requiring high throughput it may be tempting to use these standard processors also for ScanSAR data. Then the images from different modes will be mutually consistent, a fact that is especially convenient for validation, calibration, and experimental multipurpose processors. Some software development and maintenance effort could be saved in this case.

This paper describes how ScanSAR or burst-mode data can be processed employing standard high precision algorithms, no matter whether it is a carefully designed range/Doppler algorithm or a two-dimensional one. For the derivation of the algorithm the time-variant impulse response and transfer function of a burst-mode SAR system proves to be more adequate than the time frequency diagrams normally used.

II. GENERAL CONSIDERATIONS

Assume that the radar uses \( N_S \) beam positions (subswaths); the burst duration in the subswath under discussion be \( T_B \) and the burst cycle period \( T_P \). In general, the burst length is slightly different for different subswaths to keep the burst Doppler bandwidth constant; in the mean, however, the relationship \( T_P \approx T_B \cdot N_S \) holds. Let further \( T_A \) be the total synthetic aperture length used for processing. Then the number of bursts per subswath within the synthetic aperture is

\[
N_L = \frac{T_A}{T_B} \approx \frac{T_A}{T_B \cdot N_S}.
\]

\( N_L \) is also referred to as the number of looks (typical values: 2–8).

In order to pass burst data through one of the aforementioned high precision processors two approaches are possible.

1) Focus each burst separately and add the individually focused burst images (looks) incoherently. This requires that the azimuth processing blocks are of size \( T_B + T_A \), where during \( T_A \) the input data only consists of zeros. The processing blocks overlap and are placed \( T_P \) apart, i.e., they overlap \( N_L \)-fold. Hence, processing will be by a factor of \( N_L \) less efficient than regular SAR processing.

2) Focus arbitrarily long burst trains coherently and remove the resulting periodic modulation in the image point response by incoherent weighted pixel averaging (low pass filtering). This approach is as fast as regular SAR processing (although at least \( 2 \cdot T_P/T_B \approx 2 \cdot N_S \) times slower than SPECAN). It requires, however, that the burst cycle period \( T_P \) be an integer multiple of \( 1/PRF \) for every subswath in order to keep the sampling grid
between adjacent bursts coherent. This is not true in general, since each subswath needs its own PRF. Later we will see that this condition is not critical at all.

Approach (1) is worth considering only if the number of looks is small ($N_L = 1, \cdots, 2$). Approach (2) is the more efficient method and will be discussed in the following. The case of integer sample burst cycle periods is assumed in Sections III–V, while the influence of noninteger sample burst cycle periods will be discussed in Section VI.

III. COHERENT PROCESSING OF SCAN SAR AND BURST-MODE DATA

Consider an arbitrarily long train of bursts input to a standard SAR processing algorithm. The interburst intervals are filled with lines containing zeroes. The processor performs range compression, range migration correction, and azimuth compression like on any regular SAR data. The only difference is that the input data has long "gaps" in azimuth. Therefore, it is sufficient to concentrate on azimuth focusing in the following. Of course, range compression is preferably performed before blowing up the data volume by inserting the zero-lines.

A. Transfer Function

The raw data azimuth response of a point scatterer at zero-Doppler position $t = t_0$ and beam center offset time $t = t_c$ is given by

$$h_{\text{raw}}(t; t_0) = A(FM(t - t_0 - t_c)) \sum_n \text{rect}\left(\frac{t - nT_b}{T_B}\right) \cdot \exp\left[j\pi FM(t - t_0)^2\right],$$

(2)

where $A(\cdot)$ is the azimuth antenna pattern expressed as a function of Doppler frequency and $FM$ is the Doppler rate of the azimuth chirp. For convenience the quadratic chirp approximation is adopted here, since we will be only interested in spectral envelopes. Of course, better approximations of the point scatterer phase may be used by the processor.

In (2) the bursted nature of the SAR signal is expressed by a sequence of rect-functions. Within the validity of the stationary phase principle the envelope $A(\cdot)$, scaled by the Doppler rate $FM$, is also found in the Fourier transform of

$$H_{\text{raw}}(f; t_0) = C A(f - f_{DC}) \sum_n \text{rect}\left(\frac{f - f_{DC}}{|FM| - nB_B}ight) \cdot \exp\left[-j\pi f^2 / FM + 2\pi t_0 f\right],$$

(3)

where $C$ is an inessential constant that will be omitted in the sequel, $f_{DC}$ is the Doppler centroid, and $B_B$ and $B_P$ are the burst bandwidth and the spectral burst cycle period, respectively:

$$B_B = |FM| \cdot T_B$$

and

$$B_P = |FM| \cdot T_P.$$  

(4)

Fig. 1. System transfer function $H_c(f; t_0)$ of a 4-lobe ScanSAR system (bold), envelope of raw data Doppler spectrum $A(f)$ (dashed), and weighting by processor $W(f)$ (thin). Simulation parameters: $PRF = 1300$ Hz, $PBW = 900$ Hz, $A(f) = \sin^2 (f/1000)$ Hz.

Of course, the rect-function in (3) is only an approximation for the envelope of a chirp spectrum; its real shape is not of interest here as long as its energy is sufficiently concentrated within $B_B$.

The processor focuses the data by eliminating the quadratic phase term in (3) and possibly applies an additional spectral weighting function $W(f)$ positioned at the estimated Doppler centroid $f_{DC}$. The final spectral envelope be denoted by $\hat{A}(f) = A(f - f_{DC})W(f - f_{DC})$. Then the coherent system transfer function is

$$H_c(f; t_0) = \hat{A}(f) \sum_n \text{rect}\left(\frac{f - f_{DC}}{|FM| - nB_P} \right) \cdot \hat{A}(f).$$

The appearance of $t_0$ in (5) shows that the transfer function depends on the azimuth position of the point scatterer relative to the burst train: it is periodically time-variant with a cycle period $T_P$.

Fig. 1 depicts the system transfer function in the case of the 4-beam Radarsat ScanSAR mode. A rectangular processor transfer function of bandwidth $PBW = |FM| \cdot T_A$ and $f_{DC} = f_{DC} = 0$ are assumed.

Within a sufficient approximation we may ignore the smooth modulation of the pass bands of $H_c(\cdot)$ and replace them by rect-functions:

$$H_c(f; t_0) \cong \sum_n \hat{A}(t_0) |FM| + nB_P) \cdot \text{rect}\left(\frac{f - f_{DC}}{|FM| - nB_P} \right)$$

$$= \hat{A}(f) \sum_n \delta(f - f_{DC}) \cdot \text{rect}\left(\frac{f - f_{DC}}{|FM| - nB_P} \right)$$

(6)

where "*" is the convolution operator.

B. Impulse Response Function

Let us denote the coherent impulse response of a full bandwidth nonburst-mode system, i.e., the inverse Fourier
Fig. 2. Impulse response $h_c(\cdot) = |h_c(\cdot)|^2$ of the 4-look Scan SAR system of Fig. 1.

The transform of $\hat{A}(\cdot)$, by $h_c(\cdot)$, has a resolution of

$$\rho_{\text{full}} \approx \frac{1}{P \cdot BW} \approx \frac{1}{|FM| T_A}.$$  \hspace{1cm} (7)

Let further be $h_c(\cdot)$ the impulse response of a single burst which is the transform of $\text{rect}(\cdot)$: a sinc-function with resolution of

$$\rho_{\text{burst}} = \frac{1}{B_B} \approx \frac{1}{|FM| T_B} \approx N_L N_S \rho_{\text{full}}.$$  \hspace{1cm} (8)

Now the end-to-end coherent system impulse response is found from (6):

$$h_c(t; t_0) \approx h_c(\cdot) \times \frac{1}{B_P} \sum_n h_c(\cdot) \left( t - \frac{n}{B_P} \right) \exp \left( j 2 \pi \frac{t_0}{T_P} n \right).$$  \hspace{1cm} (9)

Obviously, $h_c(\cdot)$ contains the desired impulse response $h_c(\cdot)$ as its envelope but is modulated by a train of narrow pulses $h_c(\cdot)$. Fig. 2 shows the incoherent impulse response $h_c(\cdot) = |h_c(\cdot)|^2$ for the transfer function from Fig. 1.

IV. FILTERING OF THE DETECTED IMAGE

Now, is it possible to remove the undesirable periodic term in $h_c(\cdot)$ and maintain only the envelope $h_c(\cdot)$ by low-pass filtering the power detected image? The Fourier transform of $h_c(\cdot)$ which is the autocorrelation function (ACF) of $H_c(\cdot)$ reveals, that the periodic terms can be easily separated from the envelope as long as $B_P \geq 2 B_B$, i.e., $N_L N_S \geq 2$ which is true for any reasonable ScanSAR system:

$$H_c(f; t_0) = ACF h_c(\cdot) \approx B_P \sum_n \hat{A}(t_0 | FM | + n B_P) \hat{A}^*(t_0 | FM | + m B_P) \times \text{tri} \left( \frac{f - (n - m) B_P}{B_B} \right).$$  \hspace{1cm} (10)

Fig. 3 shows the incoherent transfer function $H_c(\cdot)$ from Fig. 1. The desired undisturbed part is the central triangular function; all other components cause the periodic modulation of the impulse response and will be suppressed by the incoherent low-pass filter operation.

If performed in the time domain this filter operation can be combined with the resampling to the final azimuth pixel spacing which has to be done anyway. There is some freedom in the design of the time domain filter (averaging) kernel; the only requirement is that its Fourier transform is sufficiently flat from $-B_R$ to $+B_R$ and that it suppresses well the undesired spectral terms. The higher the ratio $B_P/B_B \approx N_S$ the more the filter kernel may deviate from the sinc-shape.

Incoherent filtering can of course go further: the central triangular-shaped spectral band may even be additionally low-pass filtered in order to reduce resolution to a desired value and simultaneously suppress speckle. This is, for example, necessary for 1-look systems where usually multilooking would be done within each burst.

The filtered incoherent transfer function and the corresponding impulse response are finally

$$\overline{H}_c(f; t_0) \approx B_B \sum_n \left| \hat{A}(t_0 | FM | + n B_P) \right|^2 \times \text{tri} \left( \frac{f}{B_B} \right)$$  \hspace{1cm} (11)$$

and

$$\overline{h}_c(t; t_0) \approx \frac{1}{B_P} \sum_n \left| \hat{A}(t_0 | FM | + n B_P) \right|^2 \times h_c(\cdot).$$  \hspace{1cm} (12)

Fig. 4 shows the impulse response in a logarithmic scale before and after filtering.

The approximation introduced in (6) that has been used so far is not applicable, if the processing filter $W(\cdot)$ contains discontinuities and $t_0$ takes a value so that one or two looks fall onto the processing band boundaries and get cut off. In this case these looks contribute to the final impulse response with a lower resolution. For the parameters chosen in Fig. 1 the azimuth position $t_0 = 0$ would cause such a situation. Fig. 5 shows the impulse response for $t_0 = 0$ in comparison with the
corrections in azimuth (see Section V) it is recommended to vary also the processing bandwidth \( PBW \) accordingly, i.e., to keep the reference function length in time always an integer multiple of the burst cycle period.

So far we have assumed that each burst has a rectangular envelope leading to the \( \mu \)-shape of the final impulse response \( \tilde{h}_t(\cdot) \). Of course, it is possible to apply a time domain azimuth weighting to each burst before processing to control the sidelobe behavior of the impulse response. In this case the rect-functions in the equations presented here have to be replaced by the corresponding weighting functions. Note that \( W(f) \) does not influence the shape of \( \tilde{h}_t(\cdot) \), it rather determines how the different burst images (looks) are weighted before being coherently summed. Therefore, \( W(f) \) is used to control the clutter-to-noise ratio, the effective number of looks (see below), and the azimuth signal-to-ambiguity ratio.

V. RADIOMETRY

A. Azimuth Scalloping

Due to the bursted nature of ScanSAR signals the end-to-end system transfer function is time-variant. We have seen that the shape of the filtered impulse is almost independent of \( t_0 \). The total gain, however, may vary periodically over azimuth, an effect often referred to as scalloping. When processing burst trains using long azimuth block sizes the single burst images are no longer accessible, they are summed up already in the processor. Hence, the scalloping effect tends to be smoothed out.

Let us define the processing gain relative to the power of a single burst image with its spectrum located at the maximum of the transfer function:

\[
G(t_0) = \frac{\int |H_s(f; t_0)|^2 df}{B_P |\hat{A}(0)|}.
\] (13)

Fig. 6 shows the gain as a function of azimuth for different Doppler centroid estimation errors adopting the simulation parameters from Fig. 1. The gain function for \( \hat{f}_{DC} - \hat{f}_{DC} = 0 \) Hz may be used to radiometrically correct the image. If this is done, a radiometric error still remains in the presence of
a wrong Doppler centroid estimate. Fig. 7 shows the uncompensated gain error in this case.

The gain variations shown in Figs. 6 and 7 have been calculated assuming a rect-shaped processor transfer function containing strong discontinuities at the bandwidth boundaries. A more appropriate choice for \( W(f) \) both with respect to signal-to-clutter ratio and to azimuth scalloping are functions that decrease more smoothly toward their boundaries. As an example a \( \text{sinc}^2 \)-weighting (the same as the Doppler spectrum \( A(f) \)) has been applied for the plots of Figs. 8 and 9. With this design there is no need to correct for azimuth scalloping, if the Doppler centroid error is in the order of 50 Hz (error less than 0.04 dB). For higher errors correction may be required but the residual radiometric variation is negligible (\( \leq 0.06 \) dB for 100 Hz). The design of \( W(f) \) is an area for optimization.

### B. Equivalent Number of Looks

The equivalent number of looks (ENL) is always less than the number of bursts \( N_b \), within a synthetic aperture because of the weighting by \( A(.) \) and \( W(.) \). Using the same reasoning as for regular SAR processing with image domain filtering it can be easily shown that the ENL is identical to the normalized gain \( G \) from (13) [5], [6]. For the examples of Figs. 6 and 8 we find an equivalent number of looks of 2.7 and 2.1, respectively.

![Burst-mode image (part) before incoherent filtering. Note the periodic modulation of the corner reflector’s response. Raw data has been simulated from X-SAR data. Burst duration is 13 lines, burst cycle period 39 lines.](image)

**VI. INFLUENCE OF NONREGULAR AZIMUTH SAMPLING GRID**

So far we have assumed that the burst train can be represented in a regular sampling grid, i.e., that the burst cycle period is an integer multiple of \( 1/\text{PRF} \); this is not true in general. In order to avoid a time consuming interpolation of the raw data, each burst in (2) may be shifted by an amount \(-1/(2\text{PRF}) < \epsilon_n \leq 1/(2\text{PRF})\) to make it fit into the sampling raster. This subpixel shift introduces a linear phase \( \exp(-j2\pi\epsilon_n f) \) for every burst spectrum. The gross phase contribution comes from the Doppler centroid frequency offset...
and can be easily corrected for in the raw data by multiplying each burst with a complex constant. Then the coherent transfer function from (5) becomes

$$H_c(f; t_0) = \hat{A}(f) \sum_n \text{rect} \left( \frac{f - t_0 \tau M}{B_B} - \frac{n B_P}{B_B} \right) \exp \left(-j2\pi\epsilon_n(f - \hat{f}_{DC})\right).$$ (14)

In principle, these phase terms tend to deteriorate the quality of the final impulse response function. Note however, that the introduced delays are small compared to the system resolution $\rho_{burst} \approx 1/B_B \approx 1/(N_L N_S P_B W)$. The number of bursts $N_L N_S$ per period is typically in the order of 16 and $P_B W$ is considerably smaller than $PRF$, i.e., $|\epsilon_n|_{\text{max}} \approx \rho_{burst}/50$. From that we expect the effect of forcing the bursts into a coherent sampling grid to be negligible. Simulations with several different sets of $\epsilon_n$‘s confirm this intuitive expectation: in all cases the impulse response functions (after incoherent filtering) were indistinguishable from the one of Fig. 4.

VII. COMPLEX SCAN SAR DATA FOR INTERFEROLOGY

The algorithm described so far assumes that the pictorial information in the Scan SAR images is used for radiometric interpretation; then the modulation in the impulse response from Fig. 2 was disturbing and had to be filtered off. Scan SAR interferometry, on the other hand, is an interesting possibility for very wide swath topography reconstruction [7] and is currently under discussion for the third Space Radar Lab (SIRC) mission. The focused data before detection [i.e., in the stage described by (9)] contains all the phase information required. In other words, the proposed algorithm is automatically as phase preserving as the underlying standard SAR processor.

Of course, Scan SAR repeat-pass interferometry requires exact synchronization of the burst sequences in the two surveys; otherwise the same area on the ground is imaged under different azimuth angles and coherence is lost. In the case of only partial synchronization azimuth coherence can be improved in the following way: First a part of the interferometric pair is processed and the relative azimuth offset of the two images is determined. This offset is used to co-register the two raw data sets in azimuth. Then only the common portions of the bursts are used for final processing, all other range lines are set to zero. This procedure is the azimuth pendent to the spectral shift filtering necessary to remove baseline decorrelation [8]. It cannot be blamed to reduce resolution; it rather restricts the burst spectra to the common bands that carry useful interferometric information.

VIII. EXAMPLE

The proposed algorithm has been implemented using DLR’s X-SAR processor without any algorithmic modifications. This processor produces full resolution single-look images and uses subsequent incoherent weighted pixel averaging (image domain filtering [5], [6]) in range and azimuth for flexible “look” processing to accommodate different imaging geometries. Ground projection is included in the range migration correction. The incoherent filter kernel has not been modified in its shape, although it is only suboptimal for our purposes.

A 4-look 3-swath system has been simulated from X-SAR data by choosing a burst duration of only 13 (!) lines followed by 26 lines of zeroes. The $PRF$ was 1395 Hz and the mean Doppler rate $-10016 Hz/s$. Fig. 10 shows a part of the image after coherent focusing but before incoherent filtering. The response of a corner reflector is visible. It exhibits the periodic modulation expected from Fig. 2. The final image (24 km x 14 km) after weighted pixel averaging is shown in Fig. 11. The pixel spacing is 35 m in both azimuth and ground range. The theoretical azimuth resolution is 78 m, the measured one 82 m. Note, however, the extremely small time-bandwidth-product of the simulated X-SAR bursts and the use of an unmodified processor.

IX. CONCLUSION

We have shown how Scan SAR and burst-mode SAR data can be processed employing standard high precision SAR
algorithms. Although the computational effort is higher than with the SPECAN algorithm, it is still comparable to regular SAR processing. The proposed approach is phase preserving and the images are consistent with standard mode images with respect to both geometry and radiometry. Cross-calibration of the standard and ScanSAR processing modes is straightforward.

Due to the fact that the proposed algorithm processes whole burst trains coherently, the individual burst images are no longer accessible. Hence, the energy ratios in the burst image overlap regions cannot be used for Doppler centroid estimation [9] as with SPECAN. For the sensors under discussion (Radarsat, ASAR) the attitude drift in azimuth is however, so small, that estimating the Doppler centroid as usual from large blocks of unfocused raw data is fully sufficient. In order to eliminate the influence of image content on the Doppler estimate the azimuth extent of the estimation windows should be at least 2–3 times the synthetic aperture length.

REFERENCES


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