Extended Chirp Scaling Algorithm for Air- and Spaceborne SAR Data Processing in Stripmap and ScanSAR Imaging Modes

Alberto Moreira, Member, IEEE, Josef Mittermayer, and Rolf Scheiber

Abstract—This paper presents a generalized formulation of the extended chirp scaling (ECS) approach for high precision processing of air- and spaceborne SAR data. Based on the original chirp scaling function, the ECS algorithm incorporates a new azimuth scaling function and a subaperture approach, which allow an effective phase-preserving processing of ScanSAR data without interpolation for azimuth geometric correction. The azimuth scaling can also be used for automatic azimuth coregistration of interferometric image pairs which are acquired with different sampling distances. Additionally, a novel range scaling formulation is proposed for automatic range coregistration of interferometric image pairs or for improved robustness for the processing of highly squinted data. Several simulation and processing results of air- and spaceborne SAR data are presented to demonstrate the validity of the proposed algorithms.

I. INTRODUCTION

SAR IMAGE FORMATION is based on a coherent processing approach to build a long azimuth synthetic aperture. This coherent processing can also be interpreted as the compression of a frequency modulated pulse, whereby the frequency modulation is caused by the natural movement of the sensor (Doppler effect). In addition, the transmitted pulses are also time dispersed and frequency modulated. This allows more energy to be transmitted (due to the time dispersion) and also a better range resolution to be achieved (due to the higher signal bandwidth). The range compressed pulse is obtained by means of a correlation of the received echo with the complex-conjugated time-inverted replica of the transmitted pulse.

Due to the curvature and the range variance of the azimuth modulation, SAR image formation is inherently a two-dimensional (2-D) process [7]. Commonly, the 2-D processing is split into two 1-D steps in order to simplify the image formation process. This requires however an interpolation to compensate the range migration before azimuth processing. Another effect that occurs for a great amount of range migration (e.g., for high squint angles and/or high range resolution or low frequency SAR systems) is the coupling of the range and azimuth signals, which is also range dependent. This coupling if not compensated leads to a defocusing of the range impulse response function (IRF). The distortion can be approximately compensated by means of a so called secondary range compression (SRC) which consists basically of slightly modifying the range modulation rate during range compression [14].

The first step in the case of the range-Doppler processing approach [1], [5], [14], [25] is the range compression in the frequency domain. The SRC applied is correct only for one reference range and one azimuth frequency value (normally the Doppler centroid). The interpolation of the data is carried out in the range-Doppler domain using a truncated interpolation kernel (e.g., sin(x)/x). After applying the azimuth compression phase in this domain, the final image is obtained by an inverse Fast Fourier Transform (IFFT). The main disadvantages of this algorithm are the limited SRC and the need of an interpolation.

The wavenumber algorithms [1], [3], [10], [11] can be interpreted as 2-D frequency correlations, whereby a 2-D FFT is used to transform the signal from the time domain into the wavenumber domain. In these algorithms, approximations and the need for the so called Stolt interpolation increase their implementation complexity and can degrade their phase preserving properties.

The chirp scaling (CS) algorithm allows the high precision SAR processing without using interpolation in the SAR processing chain [21], [22]. It consists basically of multiplying the SAR data in the range-Doppler domain with a quadratic phase function (chirp scaling) in order to equalize the range cell migration to a reference range, followed by a range compression and SRC in the wavenumber domain. Although the SRC is strictly correct only for one reference range, it is updated as a function of the azimuth frequency. The processing proceeds with phase multiplies and FFT operations, which make the algorithm extremely efficient. Reference [4] gives a detailed comparison of wavenumber domain and chirp scaling processors.

The extended chirp scaling (ECS) was developed originally for processing airborne data with strong motion errors (e.g., E-SAR system, [12]) and with variable Doppler centroid in range and/or azimuth [13], [17]. The ECS algorithm allows the following steps to be included in the processing:

- **Doppler centroid update with range** by means of an azimuth spectral length extension in the range-Doppler domain.
- **Doppler centroid update with azimuth** by means of azimuth subaperture processing.
- **Motion error correction for airborne processing** by means of an additional transformation into the signal domain.
Improved processing of highly squinted data by means of a subtraction of the offset value from the chirp scaling function.

This paper presents a generalized formulation of the ECS algorithm which is suitable for air- and spaceborne SAR and ScanSAR processing. The general lesson to be found in the original chirp scaling method is that a modified frequency modulation, exercised as a phase multiply in the appropriate domain, can lead to controlled and accurate image scaling. Our formulation includes a new range scaling function which allows the automatic range registration of interferometric image pairs. In addition, the formulation of the range scaling function can be used for improved performance when processing highly squinted data. Section II presents this formulation for stripmap SAR imaging. Section III introduces the azimuth subaperture approach into the chirp scaling algorithm for ScanSAR image processing. The azimuth compression is performed by means of the Spectral Analysis (SPECAN) approach [23]. In order to overcome the deficiencies and approximations of the SPECAN approach, a novel azimuth scaling function has been developed. This function removes the variation of the azimuth frequency modulation with range and induces a range invariant, purely linear frequency modulation. Thus, no interpolation is necessary for the azimuth geometric correction, which is required in the case of the normal SPECAN algorithm. A detailed analysis of the azimuth scaling is presented in Section IV. Results obtained for the processing of air- and spaceborne data are shown in Section V. Section VI concludes the paper and gives some suggestions for future work.

II. EXTENDED CHIRP SCALING ALGORITHM

The modeling of the ECS algorithm for air- and spaceborne SAR processing will be described in this section, detailing the formulation for simultaneous range scaling. Because this new task implies changes in all phase functions of the traditional chirp scaling algorithm [21], all functions are explicitly given and discussed in this section. It will be shown that in addition to the chirp scaling function for range cell migration (RCM) equalization, the new range scaling operation can be introduced without additional computation load. Practical benefits are discussed at the end of this section.

A. Theoretical Formulation

The basic block diagram of the ECS algorithm is shown in Fig. 1. In the following text, the basic operations (phase multiplications and signal transformations) will be formulated according to the signal flow in the processing chain.

The first step in the ECS algorithm is the first order motion compensation (only for the airborne case) which is defined as being the phase error correction for a reference range, and it can be carried out directly with range uncompressed data (i.e., before the processing starts). By applying the first order motion compensation, the platform trajectory is corrected to a straight line only for the reference range. The update of the motion compensation phase function with range (second-order motion compensation) can only be performed after range compression [17].

$$S(\tau, f_a; r_0) = C \cdot w_0 \left( \tau - \frac{2 \cdot R(f_a; r_0)}{c} \right) \cdot \exp \left[ -j \cdot \frac{4 \cdot \pi}{\lambda} \cdot r_0 \cdot \beta(f_a) \right]$$

where $\tau$ is the range time (delay), $v$ is the relative velocity between the sensor and the target on ground, $r_0$ is the distance of closest approach, $\lambda$ is the radar wavelength, $c$ is the velocity of light, $C$ is a complex constant, $w_0$ is the two way antenna pattern, $r_0$ is the envelope of the transmitted range pulse and $f_a$ is the azimuth frequency, which varies within the following range

$$\frac{PRF}{2} + f_{dc} \leq f_a \leq f_{dc} + \frac{PRF}{2}$$
where $f_{dc}$ is the Doppler centroid and PRF is the pulse repetition frequency. The first phase function in (1) is the modulated range signal. The second phase function is the azimuth modulation in the frequency domain. The expressions for the range migration in the range-Doppler domain $R(f_a; r_0)$ and the modified modulation rate $k(f_a; r_0)$ of the chirp signal are expressed by [17], [21]

$$R(f_a; r_0) = \frac{r_0}{\beta(f_a)} = r_0 \cdot (1 + a(f_a)), \quad (3)$$

$$\frac{1}{k(f_a; r_0)} = \frac{1}{k_r} = \frac{1}{2} \cdot \frac{\lambda \cdot r_0}{c^2} \cdot (\beta^2(f_a) - 1) \quad (4)$$

where $k_r$ is the modulation rate of the transmitted chirps and

$$\beta(f_a) = \sqrt{1 - \left(\frac{f_a}{f_c} - \frac{1}{f_c}ight)^2}. \quad (5)$$

The inherent scaling of the range migration as a function of the azimuth frequency is shown in (3). The expression in the range-Doppler domain equals the natural range $r_0$, which corresponds to the distance of closest approach, only for $f_a = 0$. For all other frequencies, a linear scaling occurs. The purpose of chirp scaling is to equalize all the range migration trajectories to that of a reference range $r_{ref}$. The scaling shifts the phase centers of the range chirps to a new position, which is given by [see Fig. 2(a)]

$$\tau_{cs}(f_a) = \frac{2}{c} \cdot [R(f_a; r_{ref}) + r_0 - r_{ref}]. \quad (6)$$

Therefore the chirp scaling factor is calculated to be [17], [21]

$$a(f_a) = \frac{1}{\beta(f_a)} - 1. \quad (7)$$

Now, if we assume that we want to obtain an additional scaling of the image in the range direction by a factor of $\alpha$, the new locations of the phase centers of the chirps should be located at [see Fig. 2(b)]

$$\tau_{cs}(f_a) = \frac{2}{c} \cdot (R(f_a; r_{ref}) + \alpha \cdot (r_0 - r_{ref})). \quad (8)$$

Therefore a different scaling factor must be applied, which is the sum of the normal chirp scaling factor $a(f_a)$ and a range scaling factor $a_{rg}(f_a)$ (see derivations in the Appendix):

$$a_{cs}(f_a) = a(f_a) + a_{rg}(f_a) = \frac{1 + a(f_a)}{\alpha} - 1$$

$$= a(f_a) + (1 - \alpha) \cdot \frac{1 + a(f_a)}{\alpha}. \quad (9)$$

The new scaling $a_{cs}(f_a)$ leads to modifications for all phase functions of the extended chirp scaling algorithm.

The variations of the Doppler centroid as a function of range should also be considered to achieve accurate processing. In [17] a method was proposed for accommodating the Doppler centroid variations in a very accurate way. After transforming the SAR raw data into the range-Doppler domain, the azimuth frequency variation is artificially increased by means of an azimuth spectral length extension. The effect is, that all the phase functions ($H_1, H_2,$ and $H_3$) applied in the range-Doppler and in the wavenumber domain are unambiguous and the variations of the Doppler centroid with range can be accommodated correctly.

Considering the new scaling factor (chirp and range scaling) and the azimuth spectral length extension, the first phase function of the ECS becomes

$$H_1(f_a, \tau) = \exp \left[ -j \cdot \pi \cdot k(f_a; r_{ref}) \cdot a_{cs}(f_a) \right] \cdot \left( \tau - 2 \cdot \frac{R(f_a; r_{ref})}{c} \right)^2. \quad (10)$$

After the multiplication of the signal in the range-Doppler domain with the phase function $H_1$, the range migration trajectory of every point target will be equalized to that of the reference range. Furthermore, the range dimension of the signal will be scaled according to $\alpha$. This will become clear after performing range compression (RC) and bulk range cell migration correction (BRCMC) in the wavenumber domain. In this domain, a second phase function $H_2$, dependent on the new chirp scaling factor $a_{cs}(f_a)$ is applied to the signal

$$H_2(f_a, f_r) = \exp \left[ -j \cdot \pi \cdot \frac{1}{k(f_a; r_{ref}) \cdot (1 + a_{cs}(f_a))} \cdot f_r^2 \right] \cdot \exp \left[ j \cdot \frac{1}{c} \cdot \pi \cdot \frac{r_{ref}}{a(f_a)} \cdot a_{cs}(f_a) \cdot f_r \right]. \quad (11)$$

Fig. 2. Range cell migration trajectories in the range-Doppler domain for three point targets. The phase center positions before and after the chirp scaling operation are shown by the solid and dashed lines, respectively. (a) Standard chirp scaling. (b) Chirp scaling with additional range scaling.
The first term accounts for range compression with modified range modulation rate according to $a_{scl}(f_a)$, and the second term, which is identical to the normal chirp scaling case, performs bulk RCMC. In fact, the desired correction of range cell migration is the same in both cases of Fig. 2.

After an inverse FFT in the range dimension, the range compressed SAR signal is expressed by

$$S(f_o, \tau) = C_1 \cdot u_o \cdot \left( -\frac{r_0 \cdot \lambda \cdot f_a}{2 \cdot \nu^2 \cdot \beta(f_a)} \right) \cdot \text{sinc}[\pi \cdot B_r \cdot (\tau - \tau_{scl}(0))] \cdot \exp \left[ -j \cdot \frac{4 \cdot \pi \cdot r_0}{\lambda} \cdot \beta(f_a) \right] \cdot \exp[-j \cdot \Delta \varphi],$$

(12)

where $C_1$ is a complex constant. The first phase function corresponds to the azimuth modulation and the impulse response function in range is given by the sinc-function assuming that the range envelope $u_r$ is constant and no weighting has been used during range compression. $B_r$ is the processed bandwidth in range. The last term in (12) is a residual phase term due to the chirp and range scaling operation

$$\Delta \varphi(f_a) = 4 \cdot \pi \cdot \frac{k(f_a; \nu_{ref}) \cdot a_{scl}(f_a) \cdot (1 + a(f_a))^2}{c^2 \cdot (1 + a_{scl}(f_a))} \cdot \left( \frac{r_0 - r_{ref}}{c} \right)^2.$$  

(13)

This phase term can be eliminated by multiplying the signal with

$$H_3 = \exp[j \cdot \Delta \varphi].$$

(14)

From (12) it becomes clear, that the range compressed point target is not located at $\tau = 2 \cdot r_0/c$. The new location using the scaling factor $\alpha$ is

$$\tau_{scl}(0) = \frac{2}{c} \cdot [r_{ref} + \alpha \cdot (r_0 - r_{ref})].$$

(15)

Image-points naturally located at $r_0$ will appear in the image as scaled by $\alpha$ with respect to the reference range $r_{ref}$. For $\alpha = 1$ no scaling will occur and all equations are reduced to the normal chirp scaling case. For $\alpha > 1$ the final image will be stretched in range dimension and for $\alpha < 1$ it will be compressed.

Considering the real case of an image, the variable $r_0$ is the location vector of the scatterers in the range dimension. By performing range scaling during processing, the relative range position of the scatterers within the image is changed. This means that the image and the location vector must be scaled in opposite directions in order to construct the correctly updated azimuth compression functions. The inversely scaled location vector $r_{o,scl}$ which must replace $r_o$ in the azimuth compression function, is expressed by

$$r_{o,scl} = r_{ref} + \frac{(r_0 - r_{ref})}{\alpha}. \tag{16}$$

Therefore the final phase multiply for the azimuth compression, which is performed in the range-Doppler domain, is given by the function

$$H_4(f_a) = \exp \left[ -j \cdot \frac{4 \cdot \pi \cdot r_{o,scl}}{\lambda} \cdot (\beta(f_a) - 1) \right]. \tag{17}$$

The result is a fully focused image which is scaled in the range dimension by $\alpha$.

B. Practical Benefits

One attractive application of the range scaling principle is the potential to coregister interferometric image pairs in the range dimension. For a wavenumber processor, a range scaling approach was already introduced in [9]. However, that approach requires additional range FFT's and IFFT's. For the case of the extended chirp scaling processor, we have shown that the images can be scaled during the processing without requiring additional computations. Also no interpolations are necessary for the coregistration in the range dimension of an interferometric image pair, assuming that the data were collected along parallel tracks and that the exact imaging geometry (baseline, flight altitude, etc.) is known. A similar scaling procedure has also been implemented in the azimuth direction for automatic azimuth coregistration of interferometric pairs, which were obtained in a multipass interferometry scheme with different PRF's and/or velocities [24].

Fig. 3 shows the result of processing 5 simulated point targets for different range scaling factors. The main simulation and processing parameters are given in Table I and they correspond to a typical case of the E-SAR system [12] in the high-resolution narrow swath imaging mode (C-band). In Fig. 3, the reference range was set to mid swath, so that its range position remains the same, independent of the range scaling. In the case of Fig. 3(a), the scaling factor of 0.9 was chosen, so that the image is compressed in the range dimension by 10%. In Fig. 3(c), a range scaling factor of 1.1 was selected. Table II summarizes the point target analysis for the cases without range scaling and with the two analyzed range scaling factors of 0.9 and 1.1. No deterioration could be found within the accuracy of the measurements. As far as the positioning accuracy is concerned, no errors could be found for a measurement accuracy of 1/32 of the range pixel spacing (1.5 m).

Table I: MAIN SYSTEM AND PROCESSING PARAMETERS FOR SIMULATION AND VERIFICATION OF THE RANGE SCALING FUNCTION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Sampling frequency</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Transmitted pulse duration</td>
<td>5 $\mu$s</td>
</tr>
<tr>
<td>Radar wavelength</td>
<td>0.0566 m</td>
</tr>
<tr>
<td>Aircraft velocity</td>
<td>70 m/s</td>
</tr>
<tr>
<td>PRF</td>
<td>1000 Hz</td>
</tr>
<tr>
<td>Flight altitude</td>
<td>2000 m</td>
</tr>
<tr>
<td>Near range</td>
<td>2964 m</td>
</tr>
<tr>
<td>Far range</td>
<td>6036 m</td>
</tr>
<tr>
<td>Reference range</td>
<td>4500 m</td>
</tr>
<tr>
<td>Processed range bandwidth</td>
<td>75 MHz</td>
</tr>
<tr>
<td>Processed azimuth bandwidth</td>
<td>100 Hz</td>
</tr>
</tbody>
</table>

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Another application of the range scaling function with range scaling is the processing of highly squinted SAR data. For high squint angles (>10°) and large swath width, the quadratic phase term of the chirp scaling function introduces a range dependent frequency shift in the range chirp signal, which can assume values as high as several MHz. If this frequency shift is high enough so that the signal bandwidth is aliased or
shifted outside the processed bandwidth, then the range IRF will deteriorate. In order to minimize this effect, the offset scaling factor due to the squint angle should be removed from the original chirp scaling factor \( a(f_a) \). In a first approximation, the offset value is given by the value of the scaling at the Doppler centroid frequency. Using (9), the exact scaling factor for the processing can be calculated as

\[
a_{\text{sel}}(f_a) = \frac{1 + a(f_a)}{1 + a(f_{dc})} - 1 = a(f_a) - a(f_{dc}) \cdot \frac{1 + a(f_a)}{1 + a(f_{dc})}
\]

Fig. 4 illustrates the effect of the frequency shift introduced into the range signal by the standard chirp scaling function and by the modified version according to (18). The simulation parameters are the same of Table 1 and a squint angle of 30° has been assumed. From Fig. 4(a) it becomes clear, that for high squint data the normal chirp scaling operation not only causes aliasing but also induces a range dependent shift of the spectrum. The compensation of this effect would demand a range dependent spectral filtering. In Fig. 4(b) the scaling was performed according to (18). It can be observed that the effects are strongly reduced in this case, where the offset scaling factor is considered. In Fig. 5 the frequency shift is given as a function of the azimuth frequency since the chirp scaling function is applied in the range-Doppler domain [see (10)]. Actually, the spectra represented in Fig. 4(a) and (b) are plotted for an azimuth frequency \( f_a \) equal to the Doppler centroid \( f_{DC} \) (see Fig. 5 for \( f_a \) = 1230 Hz). It can be observed that for the near and far range chirps, a frequency shift of more than 40 MHz is introduced by the standard chirp scaling function. By removing the offset of the chirp scaling function according to (18), the maximum range frequency shift is reduced to ca. 10 MHz. It must be mentioned that as the squint angle gets larger, the frequency shift caused by the standard chirp scaling

<table>
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<th>Range</th>
<th>Geometric Resolution</th>
<th>PSLR</th>
<th>ISLR</th>
</tr>
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<tr>
<td>direction</td>
<td>0.905 m</td>
<td>-9.91 dB</td>
<td>-13.28 dB</td>
</tr>
<tr>
<td>azimuth</td>
<td>0.628 m</td>
<td>-9.32 dB</td>
<td>-13.26 dB</td>
</tr>
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</table>

| Table II: Image quality parameters of the impulse response function using the FCS algorithm with different range scaling factors. |

<table>
<thead>
<tr>
<th>Analysed</th>
<th>Measured</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>( \alpha = 0.9 )</td>
<td>( \alpha = 1.0 )</td>
</tr>
<tr>
<td>Range direction</td>
<td>Geometric Resolution</td>
<td>PSLR</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------</td>
<td>------</td>
</tr>
<tr>
<td>( \alpha = 0.9 )</td>
<td>1.805 m</td>
<td>-9.91 dB</td>
</tr>
</tbody>
</table>

Fig. 3. Simulated response of five point targets according to the system and processing parameters of Table I. Reference range is according to the target in middle swath. (a) Range scaling factor of 0.9. (b) Range scaling factor of 1.0. (c) Range scaling factor of 1.1.
near range spectrum

reference range spectrum

far range spectrum

(a)

(b)

Fig. 4 Shift and aliasing of range spectra caused by the chirp scaling operation in the range-Doppler domain for 30 degrees squint. (a) shows the case of standard chirp scaling for range chirps located in near, middle and far range, respectively. (b) illustrates the improvement caused by the new chirp scaling function with offset subtraction according to the Doppler centroid for range chirps located in near, middle and far range, respectively.

Fig. 5. Range frequency shift caused by the chirp scaling operation in the range-Doppler domain for 30° squint. (a), (b), and (c) correspond to the frequency shift caused by the standard chirp scaling function for range chirps located in near, middle and far range, respectively. (d) and (e) correspond to the frequency shift caused by the new chirp scaling function with offset subtraction for range chirps located in near and far range, respectively.

increases considerably while the frequency shift caused by the formulation according to (18) remains almost the same.

The scaling factor with the subtraction of the offset leads to an equalization of the range migration as in the case of the standard chirp scaling approach. However, the relative range positioning of the targets in the final image will be according to the slant range distances at the time $t_c$ (at the center of the azimuth illumination path). The range positioning can be changed to that of the broadside geometry (range distances according to closest approach) during the slant to ground range transformation.

III. PHASE PRESERVING SCAN SAR PROCESSING

In the conventional SAR operation mode, the swath width is limited by the constraint, that it is not possible to receive and transmit in the same time. For a PRF of 1500 Hz, a theoretical maximum swath width of about 100 km could be achieved. In practical cases, several other factors pose additional constraints (e.g. range and azimuth antenna diagrams, range pulse duration) so that practical values for the swath width are about 50 km (slant range). This constraint can be circumvented by using a scanning strategy of the antenna beam in elevation. With a phased array antenna, the antenna steering can be performed electronically.

The operation mode of a SAR system with this scanning strategy has been denoted as ScanSAR [2], [8], [15], [26]. The elevation pattern of the antenna is scanned between different look angles to obtain a wider swath composed of subswaths. The synthetic aperture is shared between the subapertures. The basic difference between ScanSAR and conventional stripmap mode SAR data is that each target is illuminated by different parts of the azimuth antenna for a shorter time, known as the burst duration. This means that each target has a different Doppler history depending on its azimuth position.

If the cycle interval of scanning (i.e., the summation of the time durations of the burst signal in each subswath) is less than the synthetic aperture, then azimuth multilooking can be performed. A multilook factor MLF can be defined as

$$MLF = \frac{\left( T_a - T_s \right)}{T_c}$$

where $T_a$ is the time interval corresponding to the full synthetic
aperture. \( T_b \) is the duration of one burst of the corresponding subswath and \( T_s \) is the cycle time of the scanning. Note that the multilook factor should be chosen as an integer number if the number of looks in the corresponding subswath should be kept constant. This is due to the fact that azimuth multilooking in ScanSAR is performed by incoherently adding the images obtained from adjacent bursts of the same subswath.

Based on the above considerations, the main differences of the ScanSAR to the stripmap SAR processing can be summarized as:

1. The azimuth signal consists of several bursts, each of them corresponding to a fraction of the full synthetic aperture.
2. The azimuth resolution is limited by the burst duration and is no longer determined by the synthetic aperture length.
3. The Doppler history of each target within a burst has a different frequency offset depending on its azimuth location.
4. The azimuth multilooking is constrained more by the scanning strategy rather than by the processing strategy.
5. The radiometric correction due to the azimuth antenna pattern is much more critical than in stripmap SAR since each target is illuminated by different parts of the azimuth antenna diagram.
6. An additional mosaic operation is required in azimuth and range directions to join the azimuth bursts and the range subswaths, respectively.

Due to the facts described in items 2 and 3 the Spectral Analysis (SPECAN) approach has been commonly used for the azimuth processing [8]. The SPECAN approach consists of first multiplying the range compressed signal in the time domain with a phase function having a positive Doppler rate. This operation is called deramping in the SAR literature [23]. After the deramping we obtain a signal which consists of a superposition of many signals with constant frequencies. By means of an azimuth FFT, a frequency analysis is carried out so that each target is located according to its central frequency position.

The main disadvantages of the SPECAN algorithm are:

- no accurate correction of range cell migration. Normally only the linear part of the RCM is corrected during the range compression in the frequency domain;
- limited accuracy of the deramping operation. Since the deramping function consists of a linear frequency modulation, the higher order terms are not considered in the processing. In addition, due to the different Doppler history of each target, even an accurate deramping function (including the higher order terms) can be matched only to one target history;
- need of additional resampling for azimuth geometric correction. Due to the use of the SPECAN processing, the azimuth image scaling is changed from the time domain to the frequency domain scaling \( (\approx f/\kappa_a(r_0)) \), where \( \kappa_a(r_0) \) is the azimuth modulation rate. This means that for each range position, the image data must be resampled according to a different scaling factor to compensate for the azimuth scaling variation.

Due to the above reasons, the SPECAN algorithm cannot be used as a phase-preserving algorithm. However, the SPECAN algorithm is appealing because it is efficient. Only one FFT is required for azimuth compression.

Based on the above considerations, we have introduced a subaperture processing in the first part of the extended chirp scaling and combined it with the SPECAN algorithm for efficient ScanSAR processing. The subaperture processing means that the long FFT's in the azimuth direction are substituted by short azimuth FFT's having the size corresponding to the next power of two size which is greater than the number of pulses included in the burst. For example, if the burst has 43 valid pulses, an azimuth FFT size of 64 points is used. The missing points are filled with zeroes.

The combination provides also an accurate correction of the RCM. However, the deficiencies of the deramping operation remain and also the need of the azimuth interpolation. In order to eliminate the disadvantages of the deramping operation, a novel azimuth scaling function is proposed which has the following impact on the processing:

- Elimination of the hyperbolic azimuth phase history in the range-Doppler domain.
- Introduction of a purely quadratic azimuth phase history in the range-Doppler domain.
- No interpolation is required for azimuth geometric correction. This is possible by introducing a quadratic phase function for the whole subswath which has a phase history corresponding to that of a selected range distance (i.e., scaling range).

Fig. 6 shows the block diagram of the proposed algorithm including all necessary phase multiplications. In the following text, the processing steps will be described according to the signal flow in Fig. 6.

A. Azimuth Weighting for Sidelobe Suppression

The first step in the processing is the weighting of the burst signal in the azimuth direction for sidelobe suppression. At the same time, the size of the burst signal is extended to the next power of two value.

B. Azimuth FFT, Spectral Length Extension, and Chirp Scaling

The burst signal is transformed to the range-Doppler domain by means of an azimuth FFT. The azimuth spectral length extension accommodates the variation of the Doppler centroid with range. Multiplication with the phase function \( H_1 \) performs the chirp scaling for a reference range. The additional range scaling function can be introduced at this step if necessary. The formulation of the chirp scaling function is the same as in (10), but includes an azimuth frequency vector \( f_a \) with many fewer points (corresponding to the size of the azimuth FFT).

The new azimuth frequency vector is also used for the phase functions \( H_2 \) and \( H_3 \).

C. Range FFT, Compression, and IFFT

Range FFT’s are carried out to map the burst data from the range-Doppler domain into the 2-D frequency domain.
Fig. 6. Block diagram of the extended chirp scaling (ECS) algorithm for phase-preserving ScanSAR processing with variable Doppler centroid with range. The signal representation of the SAR data for three point targets (A, B and C) at the scaling range in the different domains of the processing is shown on the left side, where \( f_a \) and \( f_r \) are the azimuth and range frequencies and \( t \) and \( \tau \) are the azimuth time and the range delay, respectively.

The multiplication with the phase function \( H_2 \) [see (11)] carries out an accurate range compression with azimuth frequency update of the SRC. Additionally, this function includes a linear phase term in range, which removes all the bulk range cell migration. No azimuth compression is performed in the wavenumber domain. Range IFFT’s are performed to transform the data back into the range-Doppler domain. The multiplication with the function \( H_5 \) compensates...
the slowly varying azimuth phase which was introduced by
the chirp scaling operation [see (14)].

D. Antenna Pattern Correction

As discussed before, the 2-D antenna pattern must be known
accurately for precise radiometric correction of ScanSAR data.
The 2-D pattern can be theoretically calculated for each
imaging geometry or measured by means of calibration ex-
periments. After this correction, all target amplitude histories
will be independent of the antenna diagram (see point target
representation in Fig. 6).

E. Azimuth Scaling

The azimuth scaling phase function \( H_5 \) removes the hyper-
bolic azimuth phase history for all targets and introduces a
constant linear frequency modulation for the whole subswath.
From (17) the new azimuth scaling function can be calculated
as

\[
H_5(f_a; r_o) = \exp \left[ \frac{j \cdot \pi \cdot 4 \cdot r_o \cdot (\beta(f_a) - 1)}{\lambda} \cdot \exp \left[ j \cdot \pi \cdot \frac{f_a^2}{k_{a,scal}} \right] \cdot \exp \left[ j \cdot 2 \cdot \pi \cdot (t_c(r_{scal}) - t_c(r_o)) \cdot f_a \right] \right]
\]

where \( k_{a,scal} \) is the linear Doppler rate at a selected scaling
reference range, \( t_c \) is the azimuth time at the center of the
illumination period (i.e., at Doppler centroid) and \( r_{scal} \)
is the selected range for the azimuth scaling. The first exponential
term in (20) removes the hyperbolic phase history while
the second term introduces the linear frequency modulation
with the Doppler rate \( k_{a,scal} \). The last exponential term is
essential for avoiding a time shift of the azimuth bursts before
the deramping operation. Actually, the first exponential term
would lead to a shift proportional to \( t_c(r_o) \) and the second
term to a shift proportional to \( -t_c(r_{scal}) \). This time shift is
compensated by the third exponential term in (20) which
avoids a wrap around effect during the deramping operation.

For calculating the value of \( t_c(r_o) \) in (20), the exact relation
between azimuth time and frequency is used

\[
t_c(r_o) = -\frac{\lambda \cdot r_o \cdot f_{dc}}{2 \cdot v^2 \cdot \beta(f_{dc})}.
\]

The value \( t_c(r_{scal}) \) in (20) is calculated considering the linear
frequency modulation:

\[
t_c(r_{scal}) = \frac{\lambda \cdot r_{scal} \cdot f_{dc}}{2 \cdot v^2}.
\]

The effects of the azimuth scaling and the right choice of
the scaling range \( r_{scal} \) will be analyzed in the next section.

F. Azimuth IFFT and Deramping

By means of short azimuth IFFT’s, the data is transformed
from the range-Doppler domain into the range and azimuth
time-domain (signal domain). At this step, all targets are range
compressed and have straight azimuth trajectories (without any
range migration).

The deramping function compensates the linear frequency
variation and is given by:

\[
H_6(t; r_o) = \exp[j \cdot \pi \cdot k_{a,scal} \cdot t^2] \cdot \exp[j \cdot 2 \cdot \pi \cdot k_{a,scal} \cdot (t_c(r_{scal}) - t_c(r_o)) \cdot f_a].
\]

The first term in (23) corresponds to the deramping op-
eration which is independent of the range distance since all
azimuth chirps have been scaled to the Doppler rate of the
scaling range \( r_{scal} \). The second term introduces an azimuth
time shift in order to locate the targets according to their
Doppler zero position. Actually, this term leads to a shift which
is exactly opposite to the shift introduced by the third
term in (20). The wrap around effects due to this shift, which
can arise for high Doppler centroid values, can easily be
accommodated during the azimuth mosaic. These additional
shifts are necessary only for ScanSAR processing in order to
consider the limited azimuth extension of the signals due to
the burst operation mode.

After the final azimuth FFT’s are performed, the azimuth
signal will be compressed at the zero Doppler geometry which
is advantageous for most SAR image products. If phase-

preserving image products are desired, no detection operation
should be made at this stage. Additionally, a quadratic phase
error caused by the SPECAN approach.

G. Multilooking, Azimuth, and Range Mosaic

If the multilook factor is greater than one, the images
of adjacent bursts can be incoherently added in order to
reduce the speckle noise and also to improve the radiometric
calibration. Since the bursts of one subswath are separated
by a distance, which is used for the illumination of other
subswaths, a time shift operation is required to overlap the
bursts accurately. This time shift will have an integer part
(which is removed by a simple array shift) and also a fractional
part which can be compensated by introducing an additional
frequency offset in the deramping operation.

The azimuth mosaic consists of the azimuth image forma-

tion process and is performed at the same time, in which each
burst has been processed. The processing of each subswath is
performed separately and the range mosaic is carried out after
the processing of all subswaths is finished.

H. Simulation Results

ScanSAR data has been simulated and processed using the
proposed algorithm. The system and processing parameters
were selected for the processing of SIR-C data in L-band (VV
polarization) corresponding to the data take DT 82.1 of the
second mission in October 1994 (see table III). Basically,
the ScanSAR imaging mode for this data take includes the
scanning of 4 subswaths, whereby a multilook factor of at
least 4 is provided for the near range subswath. The number
of pulses per burst and the selection of the PRF in each
subswath leads to a Doppler bandwidth which varies from
approximately 36 to 41 Hz within the full range swath.
Accordingly, the resulting azimuth resolution varies from ca. 175 to 220 m.

Fig. 7 shows a contour plot of the impulse response function for a simulated point target located in the first subswath. Due to the burst operation mode, the time-bandwidth product TBP in azimuth direction is less than 1. Extensive simulation has been performed with several point targets in all subswaths in order to verify whether the principle of stationary phase can still be applied. The main results of this simulation work were:

- Deviation of the measured range and azimuth resolution from the theoretical value is less than 1.5 and 4%, respectively.
- Sidelobe suppression is better than $-13.18$ dB (no weighting).
- Integrated sidelobe ratio is better than $-9.74$ dB (no weighting).
- Range and azimuth registration of point targets located in different subswaths is better than 1/20 of the image pixel spacing (the azimuth scaling was selected to provide a 100 m azimuth pixel spacing).

After analyzing the signal flow of several point targets in the different steps of the processing, we have found that the deviations of the measured azimuth resolution (4%) are due to the low TBP. In the azimuth frequency domain, the energy shape of a point target is similar to a $\sin(x)/x$-function, so that most of the signal energy is concentrated in the main lobe, but the sidelobes are spread over the spectrum. As far as the main lobe is concerned, all correction of the ECS algorithm will be carried out accurately. For the sidelobes, there will be an incorrect range cell migration correction since they are not located at the correct spectral position (which should be the same of the mainlobe position).

This effect also explains the fact that the azimuth sidelobes of the IRF in Fig. 7 are not parallel to the azimuth direction. Normally, in processing with the chirp scaling algorithm the azimuth sidelobes are parallel to the azimuth direction since all the RCM is corrected before azimuth compression. In the case of a low TBP, the RCM correction of the energy of the sidelobes in the azimuth frequency domain is wrong and they will not be positioned in the same range bin position as the mainlobe. Our simulation has verified that the energy of the sidelobes in the frequency domain contributes to the azimuth sidelobes of the IRF in the time domain. This means that the sidelobes of the IRF are positioned according to the RCM correction in the azimuth frequency domain. For a high value of the Doppler centroid ($-1941$ Hz), the RCM correction is mainly linear, as it can be observed in Fig. 7.

In spite of this effect, the characteristics of the IRF in all subswaths as well as the registration accuracy are excellent. However, if the TBP is much lower than one (not common for practical cases), the azimuth compression and the RCM correction should be performed in the time domain.

### IV. AZIMUTH SCALING

The azimuth scaling function described by (20) can be interpreted as a correlation of the SAR azimuth signal with
phase term of the azimuth phase history. For far range, the Doppler frequency offset, correspondingly different frequency of the scaling function and has a rapidly varying frequency far range as well as the targets in the frequency domain. The azimuth scaling function

![Fig. 8](image-url)\(\text{a) and (c) Amplitude history of the azimuth scaling function for reference and far range, respectively. These plots correspond to the real part of the scaling function in range-Doppler domain. (b) Contour plot of 6 point targets in the range-Doppler domain. The scaling function of Fig. 8(a) is applied to the 3 targets in scaling range, while the scaling function of Fig. 8(c) is applied to the 3 targets in far range.}\)

another low rate chirp function. Fig. 8 shows the amplitude history of the scaling function for the scaling range and for far range as well as the SAR signal representation of 6 point targets in the frequency domain. The azimuth scaling function at the scaling range (set at the position of the three point targets in near range—see Fig. 8b) consists basically of a slowly varying function (see Fig. 8c), which removes the hyperbolic phase term of the azimuth phase history. For far range, the azimuth scaling function changes the Doppler rate to that of the scaling function and has a rapidly varying frequency modulation [Fig. 8(a)]. This azimuth scaling function was calculated for the three point targets in far range of Fig. 8(b). The scaling function removes the hyperbolic phase term and changes also the Doppler rate of these targets to that of the scaling range. Since each target within a burst has a different Doppler frequency offset, correspondingly different frequency components of the scaling function are applied to the azimuth signal.

These different frequency components lead to different locations in the final image. Fig. 9 explains this effect in a representative way for three point targets having different frequency offsets. After the azimuth scaling, all the targets will have the Doppler rate \(k_{\theta \text{,scl}}\). The central time position of a target is not changed for the Doppler zero location (see target B and B' in Fig. 9). For targets A and C, there will be a time shift. The additional azimuth time extension \(T_1\) required to avoid wrap around effects in the burst signal after deramping can be derived from Fig. 9 and is expressed by

\[
T_1 = T_0 \cdot \left( 1 - \frac{r_{\text{scl}}}{r_0} \right) - T_s \cdot \left( 1 - \frac{r_{\text{scl}}}{r_0} \right). \tag{24}
\]

In addition to the effect explained in Fig. 9, (24) includes also the required time extension due to the wrap around effect arising from the correlation of the burst signal with the azimuth scaling function.

![Fig. 9](image-url)\(\text{Doppler history of 3 points targets before (A, B and C) and after azimuth scaling (A', B' and C'). An additional azimuth time extension } T_1 \text{ is required by the azimuth scaling to avoid wrap around effects in the time domain.}\)

For \(r_o = r_{\text{scl}}\), no azimuth time extension would be required. However, the block processing of each burst does not allow a different azimuth time extension to be applied for each range position. Thus, the maximum value of \(T_1\) for each subswath must be selected and the time extension must be carried out before the first azimuth FFT in the processing is performed. In most cases, the time extension, which is required to obtain an array size of a power of two value for the FFT operation suffices. If not, the azimuth array size must be extended to the next power of two value.

In order to obtain the desired azimuth sampling space (pixel separation) \(\Delta x\) in the final image, the scaling range \(r_{\text{scl}}\) is selected according to

\[
r_{\text{scl}} = \frac{2 \cdot r^2 \cdot \Delta x \cdot N_{\text{FFT}}}{\text{PRF} \cdot \nu_0 \cdot \lambda} \tag{25}
\]

where \(\nu_0\) is the ground velocity and \(N_{\text{FFT}}\) is the number of points used for the azimuth FFT after the time extension. The smallest azimuth time extension is obtained when the difference between the scaling range \(r_{\text{scl}}\) and the actual range values \(r_o\) for each subswath is minimized. This can be done if the scaling range is selected to provide a sampling space, which is an integer submultiple of the desired final azimuth sampling space. For the SIR-C case, a final sampling space of 100 m is desired and the following values are obtained.

- \(\Delta x = 25\, \text{m for subswath 1 (near range)}\)
- \(\Delta x = 25\, \text{m for subswath 2}\)
- \(\Delta x = 33.3\, \text{m for subswath 3}\)
- \(\Delta x = 33.3\, \text{m for subswath 4 (far range)}\).

The above sampling space optimizes the selection of \(r_{\text{scl}}\) by means of minimizing the required azimuth time extension. Even for the SIR-C case, where the total range variation from near to far range is more than 68%, the required size for the azimuth FFT's is kept under 128 points. By means of an azimuth resampling by 4 and 3, respectively, the final sampling space of 100 m is obtained for all subswaths without interpolation.
V. IMAGE PROCESSING

Two raw data sets were selected for verification of the processing algorithms. The first one is from the E-SAR system according to the parameters given in Table I and Fig. 10. In addition to the standard processing, the following motion error corrections are included: first and second order motion compensation (i.e., line of sight phase correction), azimuth resampling to correct the forward velocity variations and range delay adjustment to compensate for the line of sight displacements.

In Fig. 10, five corner reflectors are located beside the runway. The image quality analysis of these point target responses is summarized in the following:

- Measured range and azimuth resolution: 2.5 x 4.4 m (theoretical values: 2.4 x 3.8 m).
- Peak sidelobe ratio: < -29 dB
- Integrated sidelobe ratio: < -20 dB.

All the above values are better or equal to the results obtained by the image processing with the range-Doppler algorithm. The greatest difference was found in the range resolution which is ca. 20% better for the ECS algorithm. This is due to the more accurate SRC, which is carried out by this algorithm. The deviation of the azimuth resolution from the theoretical value are due to the non ideal motion compensation.

The second raw data set selected for the processing was the data take DT 82.1 (SIR-C ScanSAR data). The sensor and processing parameters are summarized in Table III (see also simulation results in the previous section) while Fig. 11 shows the processed ScanSAR image. Although no calibration or corner reflector analysis was performed for this image, a visual analysis of a high quality print out does not show any scalloping or modulation effects due to processing errors or inaccurate mosaic.

Future work includes the calibration of this image using another data take of the same area recorded in the stripmap imaging mode.

VI. DISCUSSION

This paper proposes and describes the following approaches for SAR processing:

- Extended chirp scaling for processing of air- and spaceborne SAR processing in stripmap and ScanSAR imaging modes.
- Range scaling for automatic coregistration of interferometric image pairs or for improved robustness in the case of high squint data processing.
- Azimuth scaling for ScanSAR processing without azimuth interpolation using the SPECAN approach or for automatic azimuth coregistration of interferometric image pairs.

In addition, the azimuth subaperture processing proposed for ScanSAR processing can also be used in stripmap SAR, whereby the SPECAN approach is substituted by a modified approach to achieve high resolution images [16], [18]. This approach allows the variations of the Doppler centroid in azimuth to be updated within a processing block and the memory requirements in the first part of the chirp scaling approach to be reduced. The subaperture processing can also be used for the update of the range scaling function for the case that the interferometric image pair (multipass) was acquired in a non parallel flight geometry.

Future work includes the specification and concept of a real-time processor for air- and spaceborne SAR processing. The processing of spotlight SAR data [4] using the azimuth scaling in connection with the SPECAN and extended chirp scaling algorithm is under investigation. This approach will allow the
Fig. 11. Processed SIR-C ScanSAR image using the ECS algorithm with azimuth scaling. This image shows the region of Chickasha, Oklahoma, USA acquired during the second SIR-C flight (data take DT 82.1). Image dimensions are 236 x 252 km in ground range and azimuth, respectively. The extension of each subswath (SS1 to SS4) are shown on the right-hand side of this image.

accurate processing of spotlight data without any interpolation for the conversion of the data from polar to cartesian format.

APPENDIX

The scaling factor \( a_{sccl}(f_a) \) for simultaneous chirp and range scaling is derived in the following text. The scaling principle is used which applies to large time-bandwidth linearly frequency modulated signals [19]. The multiplication of a chirp signal with another linearly frequency modulated signal having a much smaller FM-rate will change the modulation rate of the initial signal and its phase center. The location of the phase center is defined to be the zero position of the phase derivative.

Considering only the range modulation of the signal in the range-Doppler domain without any weighting, (1) is simplified to

\[
S(f_a, \tau) = \exp \left[ -j \cdot \pi \cdot k(f_a; r_{ref}) \cdot \left( \tau - \frac{2 \cdot R(f_a; r_{ref})}{c} \right)^2 \right]. \tag{A1}
\]

The usual approximation of \( k(f_a; r) \approx k(f_a; r_{ref}) \) was assumed as well. According to the scaling principle the scaling function can be formulated as

\[
H_{sccl}(f_a, \tau) = \exp \left[ -j \cdot \pi \cdot k(f_a; r_{ref}) \cdot a_{sccl}(f_a) \cdot \left( \tau - \frac{2 \cdot R(f_a; r_{ref})}{c} \right)^2 \right]. \tag{A2}
\]

where \( a_{sccl}(f_a) \) is to be evaluated. By multiplying (A1) and (A2), the phase of the range signal is expressed as

\[
\varphi_1 = -\pi \cdot k(f_a; r_{ref}) \cdot \left[ \left( 1 + a_{sccl}(f_a) \right) \cdot \frac{\tau^2}{c} - \frac{4}{c^2} \right] \cdot a_{sccl}(f_a) \cdot R(f_a; r_{ref}) + R(f_a; r) \cdot \tau + \frac{4}{c^2} \cdot R^2(f_a; r_{ref}) + R^2(f_a; r). \tag{A3}
\]

By applying the first derivative, the phase center of (A3) is calculated as

\[
\tau_{sccl} = \frac{2 \cdot a_{sccl}(f_a) \cdot R(f_a; r_{ref}) + R(f_a; r)}{c \cdot (1 + a_{sccl}(f_a))}. \tag{A4}
\]

Comparing the phase center of (A4) with the desired position given in (8), the new chirp scaling factor for simultaneous chirp and range scaling is calculated to be

\[
a_{sccl}(f_a) = \frac{1 + a(f_a)}{a} - 1. \tag{A5}
\]

A similar calculation has been performed in the azimuth direction to obtain the desired scaling factor for the azimuth coregistration of interferometric image pairs which were acquired with different PRF's and/or velocities [24].
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Alberto Moreira (M’92) was born in Sao Jose Campos, Brazil, in 1962. He received the B.S.E.E. and the M.S.E.E. degrees, in 1984 and 1986, respectively, from the Aeronautical Technological Institute (ITA), Brazil and the Eng. Dr. degree from the Technical University of Munich, Germany, in 1993.

From 1985 to 1986, he was with ITA as a research assistant and consultant. In 1986 he joined the German Aerospace Research Establishment (DLR) where he is currently head of the SAR Technology Department. In 1995 he participated in the SIR-C/X-SAR Mission Operations Team at JSC, Houston, TX, as a X-SAR realtime processing engineer. His main areas of interest include digital signal processing algorithms, data compression, interferometry and advanced SAR concepts.

In 1995, Dr. Moreira received the DLR Science Award for his contributions to the development of algorithms for SAR image quality improvement.

Josef Mittermayer was born in Erding, Germany, in 1967. He received the Diploma degree in electrical engineering in 1995 from the Technical University of Munich, Germany, with a thesis on Scan SAR processing.

Since 1994, he has been with the Signal Processing Group of the Institute of Radio Frequency Technology, German Aerospace Research Establishment (DLR), Oberpfaffenhofen, Germany. His current activities are the development of processing algorithms for SAR and Scan SAR processing.

Rolf Scheiber was born in Sibiu, Romania, in 1967. He received the Diploma degree in electrical engineering from the Technical University of Munchen, Germany, in 1994 with a thesis on the estimation of the Doppler parameters for the 2-D SAR processing.

In 1994, he worked with the Telecommunications Institute of DLR on channel measurements for mobile satellite communications. Since 1995, he has been with the Signal Processing Group of the Institute of Radio Frequency Technology, DLR, as a research scientist working in the field of SAR processing and interferometry.