ScanSAR Focusing and Interferometry
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Abstract—We discuss an efficient phase preserving technique for ScanSAR focusing, used to obtain images suitable for ScanSAR interferometry. Given a complex focused ScanSAR image of the same area, an interferogram can be generated as for conventional repeat pass SAR interferometry. However, due to the nonstationary azimuth spectrum of ScanSAR images, the coherence of the interferometric pair and the interferogram resolution are affected, both by the possible scan misregistration between two passes and by the terrain slopes along the azimuth. The resulting decorrelation can be significantly reduced by means of an azimuth varying filter, provided that some conditions on the scan misregistration are met. Finally, the SAR-ScanSAR interferometry is proposed: here the decorrelation can always be removed with no resolution loss by means of the technique presented in the paper.

I. INTRODUCTION

ScanSAR IS A synthetic aperture radar (SAR) with a swath coverage, in slant range, which is wider than that of conventional SAR systems. This coverage is achieved by scanning different swaths, i.e., by switching on-the-fly, the antenna look angle into different positions [1]. The geometry of a two-beam and four-beam ScanSAR is shown in Fig. 1 and compared with a conventional SAR. The ScanSAR sensor gets data from each of the $N_{sw}$ subswaths, in a time interval $T_D$ ("dwell time"), that is approximately $1/N_{sw}$ times the time extent associated with the antenna beamwidth, $T_F$. The same subswath is cyclically imaged every $T_R/N_{sw}$ (in the case of a single look for each scan cycle, as assumed here), to get coverage of the entire scene. The dwell time is slightly lower than $T_F/N_{sw}$, due to the necessary antenna steering time [2]. ScanSAR raw data should be focused with a phase preserving processor to obtain complex images suitable for ScanSAR interferometry (first proposed in [3]).

The spectral properties of ScanSAR data, and an efficient ScanSAR phase preserving focusing algorithm, are presented in the following section [4], [5]. It will be shown that the ScanSAR complex focused images are characterized by a nonstationary spectrum, that cyclically spans the entire azimuth bandwidth, which is equal to the pulse repetition frequency PRF.

In the third section, the generation of interferograms, either from repeated ScanSAR passes or by combining SAR and ScanSAR passes, is considered. It will be shown that the coherence of the interferometric pair is affected by the possible scan misregistration between two passes, the variation of the Doppler centroids and terrain slopes along azimuth [3]–[5].

These effects are quantitatively evaluated, and a technique is proposed to cancel out most of the decorrelation. Experimental results are presented by simulating ScanSAR raw data obtained from ERS-1 SAR data.

II. SPECTRAL PROPERTIES OF SCAN SAR DATA

Two systems of coordinates will be used to get the expression of the ScanSAR pulse response: one for the "signal domain" (i.e., the domain of the signals collected by the sensor), and one for the "data domain" (i.e., the position of the targets on the ground). In this paper, we refer to the signal domain coordinates $(\tau, t)$ for range and azimuth times (also known as "fast time" and "slow time"), and to the data domain coordinates $(r_0, \xi)$. The couple $(r_0, \xi)$ defines the range and azimuth target location with respect to the sensor by identifying the closest approach distance, $r_0$, and the closest approach time, $\xi$ (i.e., the zero-Doppler time instant). An example of the geometries of the broadside SAR and ScanSAR systems is in Fig. 1.

The symbols used in the paper are summarized as follows:
1) $(\tau, t)$ and $(r_0, \xi)$ are the slant range and azimuth coordinates for signal and data domains;
2) $f$ and $f_z$ are the range and azimuth frequencies, conjugate to $(\tau, t)$;
3) $\omega$ is the angular range frequency; $\omega_0 = 2\pi f_0$ is the RF carrier, $\lambda = 1/f_0$ the carrier wavelength;
4) $R(t, r_0)$ is the satellite-target distance;
5) $v$ is the along-track satellite velocity.

A. Pulse Response of ScanSAR Systems

In the case of conventional SAR's, the pulse response of a target located in $(r_0, \xi)$ can be approximated as follows [6]:

$$h_{\text{SAR}}(\tau, t; r_0, \xi) = a_\beta \left(\frac{v(t - \xi)}{r_0}\right) \cdot \delta\left(\tau - \frac{2\Delta R((t - \xi); r_0)}{c}\right) \cdot \exp\left(-\frac{4\pi}{\lambda} \Delta R((t - \xi); r_0)\right).$$

The three terms on the right side of (1) have the following meaning.

1) $a_\beta$ is the antenna gain pattern. It depends on the angle $\beta = v t / r_0$, shown in the geometry of Fig. 1.
2) $\delta(\tau)$ is the range compressed pulse. It is delayed by the antenna-target differential travel time. Here $\Delta R$ is defined as follows:

$$\Delta R(t - \xi; r_0) = R(t - \xi; r_0) - r_0 \simeq \frac{v^2}{2r_0} (t - \xi)^2.$$

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3) The complex exponential is the frequency dependent phase shift, proportional to the antenna-target travel time $\Delta R$.

Notice that the pulse response $h_{\text{SAR}}$ is stationary in azimuth, since it depends on the offset $t-\xi$ between the current satellite position $t$, and the closest approach time $\xi$.

The ScanSAR's pulse response, $h_{\text{SS}}$, is obtained by windowing the SAR pulse response $h_{\text{SAR}}$ with a square wave $w_{\text{inc}}(t)$ that takes into account the illumination pattern in a given subswath:

$$w_{\text{inc}}(t) = \sum_{k=-\infty}^{\infty} \text{rect}\left(\frac{t}{T_D} - kT_R\right).$$  (3)

A smooth transition between the raising and trailing edges of the square-wave must be assumed (the transition time being longer than the carrier period), to avoid the generation of spurious transient harmonics in the raw data spectrum.

If expressions (1) and (3) are combined, the following ScanSAR pulse response holds:

$$h_{\text{SS}}(\tau, t; \xi, r_0) = h_{\text{SAR}}(\tau, t; \xi, r_0) \cdot \sum_{k=-\infty}^{\infty} \text{rect}\left(\frac{t}{T_D} - kT_R\right).$$  (4)

Unlike the SAR case, the ScanSAR pulse response (4) is not stationary in azimuth, since it depends both on the satellite position $t$, and on the target's closest approach time $\xi$. Notice that the amplitude of the Doppler history of the scatterers within a footprint ($|\xi| \leq T_F/2$), is weighted by the window:

$$|h_{\text{SS}}(t, \xi)| = \left\{ \begin{array}{ll} a_\beta \left(\frac{(t-\xi)v}{r_0}\right) - \frac{T_D}{2} & \leq t \leq \frac{T_D}{2} \\ 0 & \text{elsewhere}. \end{array} \right.$$  (5)

For example, the pulse responses of three targets at different azimuth positions are shown in Fig. 2. Here the time origin of the scanning pattern has been chosen so that the target at $\xi = 0$ appears at the center of the antenna beamwidth when the ScanSAR acquisition is switched on (see Fig. 3). It can be noted that the Doppler history of each scatterer is observed in just one scanning cycle, except for the scatterers at the very edge of the antenna aperture, that are imaged twice in two subsequent scanning cycles.

The ScanSAR transfer function of a target located in $(r_0, \xi)$ can be derived by exploiting the SAR transfer function, i.e., the 2D Fourier transform of (1) (derived in reference [6], by assuming the stationary phase principle):

$$H_{\text{SAR}}(f_x; f; r_0) \approx A_1 \cdot a_\beta \left(\frac{\lambda}{2v}f_x\right) \cdot \exp\left(-j \frac{\pi}{f_R(1 + f/f_0)^2} f_x^2\right)$$  (6)

$$f_R = \frac{2v^2}{\lambda r_0}$$ being the Doppler Rate, and

$$f_x = \frac{1}{2\pi} \frac{d\phi}{dt} = f_R(t-\xi)$$  (7)

the instantaneous frequency. The ScanSAR transfer function is then obtained by (5)-(7):

$$H_{\text{SS}}(f_x; f; r_0, \xi) \equiv a_\beta \left(\frac{\lambda}{2v}f_x\right) \exp\left(-j \frac{\pi f_x^2}{f_R(1 + f/f_0)^2}\right)$$

$$f_R \left(\xi - \frac{T_D}{2}\right) \leq f_x \leq f_R \left(\xi + \frac{T_D}{2}\right)$$

elsewhere.

(8)
The ScanSAR azimuth spectrum is cyclostationary, since the Fourier transform of the pulse response spans the data spectrum with periodicity $\Delta f_z = f_R T_R$. The spectral shape depends on the target location in the acquisition time slot, as shown in Fig. 2(b).

### B. ScanSAR Data Simulation

Simulated ScanSAR data can be easily provided starting from either a raw or a range compressed SAR dataset, and by applying the time domain windowing in (3) (see [7]). A smooth cosinus transition, whose length is as short as a few pixel, can be used at the transition edges, since the time requested to steer the antenna in a different subswath is less than a sampling interval (if electric beam steering is assumed). For example, the data set used for the simulations have been generated by ERS-1 SAR raw data. The window $w_{sc}(t)$ was designed to give a return time $T_R \approx 0.6$ s ($\approx 85\%$ of the synthetic aperture $T_F$), and a dwell time $T_D \approx T_R/2 = 0.3$ s, to simulate a 2-beam-1-look ScanSAR, whereas $T_D \approx 0.15$ s was assumed for the 4-beam-1-look case. Results of processing these datasets are reported in the following.

### III. ScanSAR Focusing

Stripmap SAR focusing can be performed by filtering with the reference matched to (6):

$$H_r(f_x, f; r_0) = \exp \left( j \frac{\pi}{f_R (1 + f/f_0)} f_x^2 \right).$$

This processing can be easily extended to the ScanSAR case if computational efficiency is not crucial. First, the ScanSAR range compressed data should be zero-padded in azimuth to fill up the time intervals when the acquisition is switched off. Then the data can be focused in the same way as SAR data, e.g., by means of the matched phase reference (9).

The spectrum of a focused target located in $\xi$ can be computed by combining (8) and (9):

$$H_{SS}(f_x, f; r_0, \xi) H_r(f_x, f; r_0)$$

$$= \begin{cases} a_s \left( \frac{\lambda}{2v} f_x \right) & f_R \left( \xi - \frac{T_D}{2} \right) \leq f_x \\ 0 & f_x \leq f_R \left( \xi + \frac{T_D}{2} \right) \end{cases}$$

This spectrum is bandpass, and its center frequency, $f_R \xi$, varies with the target azimuth position $\xi$ (see Fig. 2(b)). The focused target’s bandwidth is $W = f_R T_D$, i.e., approximately $1/N_{sw}$ times the SAR bandwidth, PRF, which accounts for the reduced ScanSAR azimuth resolution. The focusing technique discussed here thus gets $N_{sw}$ times oversampled data.

The cyclostationary spectral properties of ScanSAR focused data are shown in Fig. 4. A 4-beam-1-look ScanSAR was simulated, as shown in Section II-B, and then focused with the technique presented here. Then short time periodograms were computed at different azimuth positions. The time extent of each periodogram was much lower than the synthetic aperture, $T_F$. The resulting azimuth varying power spectrum density is reported in Fig. 4(a). Notice the shift of the ScanSAR spectrum, due to the Doppler centroid $f_{dc} \approx -200$ Hz. The azimuth-varying power of the focused image, $a_s(\lambda f_x/(2v))^2$, that results from the interaction of the antenna pattern and the scan window, is shown in the Fig. 4(b). This could be compensated by a proper time domain equalization. In any case, an azimuth-varying SNR will occur.
A. Multiple-Look ScanSAR Focusing

The azimuth-varying SNR can be compensated by acquiring multiple looks, e.g., by imaging the same subswath more than once during a synthetic aperture $T_F$. If this is done, the return time $T_R$ should be reduced at least to a value $T_F/N_l$, where $N_l$ is the number of looks; at the same time the dwell time $T_D$ should be reduced by a factor $N_l$. Phase preserving focusing should then be performed on each look separately (e.g., by means of the above mentioned technique), obtaining $N_l$ complex images [8]. These images should be exploited to compute $N_l$ independent interferograms, which can then be coherently averaged to compensate for the azimuth varying SNR.

The pulse bandwidth of a $N_{sw}$-beams-$N_l$-looks ScanSAR is the full SAR bandwidth, scaled by the inverse of the beam-look product:

$$N_{isw} = N_l \cdot N_{sw},$$

and the ScanSAR resolution worsens by the same amount. As an example, the ASAR wide-swath mode assumes $N_l = 3$ looks and $N_{sw} = 5$ beams; in this case the look bandwidth is $W = 50$ Hz [9], which is less than 15 times the full SAR bandwidth.

B. Efficient ScanSAR Focusing Algorithms

The computational efficiency of the ScanSAR “standard focusing” previously discussed can be significantly improved if the amount of zero-padding is strongly reduced. Let us suppose we form an azimuth data strip of time duration $T_F$, which is slightly longer than $T_D$, i.e., by zero-padding the data collected during the scanning cycle (the role played by $T_P - T_D$, i.e., the amount of zeroes to be added, will be clarified below). This short azimuth strip can be focused by multiplying its Fourier transform by the matched SAR reference, $H_r$, in (9). One should be reminded, however, that even if the acquisition time $T_P$ is much smaller than $T_F$, the contributions of all the scatterers illuminated by the antenna are represented in the collected data (see Fig. 3). Thus, due to the low sampling rate in the frequency domain, the contributions of the $PRF \cdot T_D$ scatterers illuminated by the antenna are folded:

$$N_{rep} = \left\lfloor \frac{T_F + T_D}{T_P} \right\rfloor \approx N_{isw} + 1$$

times, as Fig. 5(a) shows the “rounding to largest integer” operator, $\left\lfloor \cdot \right\rfloor$, has been introduced in (12) to include the contribution of those targets whose echo is only partially contained in the strip of length $T_P$.

In other words, the focused pixel at a given azimuth is formed by the superposition of the echoes of the targets located at $\xi + NTP$ (for $N = 0 \cdots N_{rep} - 1$). Yet, these contributions are separated in the frequency domain by a gap:

$$\Delta f_g = |f_{c2} - f_{c1}| = f_R(T_P - T_D)$$

and $f_{c1} = f_r \xi$ and $f_{c2} = f_r(\xi - T_P)$ being the central frequencies of the two targets spectra, and $f_R$ their bandwidth [see Fig. 5(a)]. Thus, the resulting time domain aliasing can be removed by means of an azimuth varying filter\footnote{A technique that exploits the same azimuth-varying filter, but for a different purpose (e.g., focusing SAR data when the Doppler centroid varies linearly along azimuth) is presented in [10].} whose band is sketched in the Fig. 6(a). The filter should accommodate the Doppler rate variations with range. The filter selectivity can be reduced by increasing the frequency gap $\Delta f_g$ in (13), i.e., by increasing the amount of zero-padding $T_P - T_D$.

The ScanSAR focusing introduced here can be summarized by the following steps.

1) Padding the data strip acquired in a scan cycle with zero range lines up to a length $T_P \cdot PRF$ azimuth samples.

2) Focusing the resulting strip by means of a SAR processor.

3) Mosaicking $N_{rep}$ copies of the focused strip/filtering to remove the time-domain aliasing. At this step a strip of $N_{rep} \cdot T_P \cdot PRF$ azimuth samples is generated.
4) Selecting the correct data portion, e.g., the central \((T_R + T_P)\text{PRF}/N_{\text{lin}}\) range lines.

There are two efficient ways to implement step (3); by operating in the time domain or in the frequency domain. The \textit{time domain} approach, shown in the block diagram of Fig. 7, is accomplished by the following.

(3.1) Mosaicking \(N_{\text{rep}}\) replicas of the focused sequence (no computational cost).

(3.2) Filtering the resulting large image with the azimuth- varying filter (see Fig. 6(a)), to cancel the time-aliased contributions.

(3.3) Down-sampling the image, to get a pixel spacing close to the resolution, typically by a factor \(N_{\text{filt}}\).

Clearly, the last two steps should be done together to gain efficiency.

The \textit{frequency domain} implementation of the azimuth varying filter leads to the following steps.

(3.1) Deramping the short azimuth strip (time extent \(T_P\)).

This is done by multiplying the focused data by the linear frequency vs azimuth phase operator [11]:

\[
H_d(\xi) = \exp \left( -j2\pi \left( \frac{f_R}{2} \xi^2 - f_d \xi \right) \right), \quad \xi = -\frac{T_P}{2}, \ldots, \frac{T_P}{2}.
\]

As a result, the spectral contribution of all the scatterers in the strip are divided into \(N_{\text{rep}}\) blocks: one block is centered on the Doppler centroid \(f_d\), and the other blocks are frequency shifted by multiples of \(\Delta f_d = f_R T_P\) (see Fig. 5(b)). The gap between adjacent blocks is \(\Delta f_d\).

(3.2) Fourier transforming the deramped strip in the azimuth direction.

(3.3) Computing \(N_{\text{rep}}\) looks by windowing, and inverse Fourier transforming short sequences of extent \(\Delta f = f_R T_P\). The shapes of the spectral window (e.g., the filters’ masks) are represented in Fig. 5(c).

(3.4) Mosaicking the \(N_{\text{rep}}\) looks, in order to get the sub-sampled focused image.

It should be noted that since only one scanning interval is focused, the resolution changes for the scatterers at the edges of the antenna beam (e.g., referring to Fig. 5(a)), for \(\xi \leq \xi_m\) and \(\xi \geq \xi_M\). Thus, in order to get a stripmap ScanSAR image with constant azimuth resolution, subsequent focused scanning intervals should be combined by means of an “overlap-add” technique.

C. Stripmap ScanSAR Focusing

The stripmap implementation of the ScanSAR focusing is achieved by focusing the data acquired in each scan cycle as shown in the previous subsection, and applying the “overlap-add” technique to the corresponding output blocks. This technique is illustrated in Fig. 6(b). The resulting processor can be efficiently implemented on a common workstation, because of the short azimuth kernel that fits in the core memory. One advantage of this technique is that it exploits a conventional SAR processor, simply by adding a simple postprocessing step to get the ScanSAR focused image.

The efficiency of the focusing technique just proposed can be compared with the “standard ScanSAR” focusing, which is performed on the zero-padded dataset of \(N_{\text{az}} \approx \text{PRF} \cdot T_R\) azimuth samples (here assumed to be range-compressed). If we implement a wave-number domain algorithm, like the one in [12], two 2D FFT and 2 complex multiplications for each sample (1 for filtering + 1 for Stolt interpolation) are required for focusing. The computational cost, in terms of complex multiplications, is

\[
N \approx \frac{\text{PRF} \cdot T_R (2 + \log_2(\text{PRF} \cdot T_E))}{N_{\text{az}}} \\
\approx 2 + \log_2(\text{PRF} \cdot T_D N_{\text{filt}}) \tag{14}
\]

for each input data sample (1-look). Note that the output image comes at the SAR sampling rate, therefore is \(\approx N_{\text{filt}}\) times oversampled. On the other hand, the computational cost of the implementation proposed here is the sum of the cost for processing a strip of \(N_{\text{az}}^I = \text{PRF} \cdot T_P\) azimuth samples, + the postprocessing, that requires one complex multiplication for each input sample (for deramping), and
forward + inverse FFT. If we assume \( T_F = k T_D (k \geq 1) \), the total number of complex multiplications per sample is (15), shown at the bottom of the page. The focused image comes sampled close to the Shannon limit. The gain in computational complexity grows with the factor \( N_{lw} \) as can be seen by comparing (14) and (15). As an example for a 4-beam-1-look ScanSAR, and assuming \( T_F = \frac{3}{2} T_D \), the computational complexity is approximately half the cost of the standard SAR mode focusing, whereas for the ASAR Wide-Swath Mode \( (N_{lw} = 15) \) the cost is approximately 9 times less.

IV. ScanSAR INTERFEROMETRY

ScanSAR images from repeated satellite passes can be exploited for generating interferograms by means of the usual conjugate cross-multiplication of the images [3]-[5]. The main difference of ScanSAR interferometry with respect to the usual SAR interferometry is the possible scan misregistration between two passes. In this section the following points will be shown.

1) A ScanSAR interferogram can be generated whenever the scan misregistration time \( \Delta T_D \) is smaller than the dwell time \( T_D \). The larger the \( \Delta T_D \) the higher the phase noise (the resolution in azimuth is not affected).

2) The difference between the Doppler centroid of the two takes and the terrain azimuth slopes causes a relative shift of the corresponding azimuth spectra. This shift can be consistent when compared to the effective bandwidth: \( W = \text{PRF} / N_{lw} \text{x beams} \), particularly when the number \( N_{lw} \) of looks \times beams is large.

3) The ScanSAR interferogram quality (signal to noise ratio) can be greatly improved by means of an azimuth varying filtering of the images before their cross-multiplication.

For the sake of simplicity, we will discuss the principle of ScanSAR interferometry, assuming that the images are not subsampled in azimuth (as shown in the previous section to get an efficient focusing). The extension to the subsampled images, is trivial.

A. Asynchronous Scanning Decorrelation (ASD)

The azimuth spectral support of one subswath is sketched in Fig. 8. An ideal rectangular antenna pattern has been considered for simplicity. As already shown in Section III, the recovered azimuth bandwidth, whose central frequency linearly changes along the azimuth direction (\( \xi \)), has the following expression:

\[
W = f_R T_D = \frac{T_D}{T_F} \text{PRF.} \tag{16}
\]

Let us now suppose we have a second image of the same subswath with the same dwell time \( T_D \) and a scan misregistration \( \Delta T_D \). The azimuth spectral supports of the two ScanSAR images are shown in Fig. 9. From this figure it can be noted that the two supports partially overlap. The overlapped azimuth bandwidth \( W_i \) is proportional to \( \Delta T_D \) (for \( \Delta T_D \leq T_D \)) as

\[
W_i = \frac{T_D - \Delta T_D}{T_F} \text{PRF} = (T_D - \Delta T_D) f_R. \tag{17}
\]

The uncorrelated parts of the azimuth spectra reduce the interferometric pair coherence \( \gamma \), together with the well known baseline \( \gamma_B \), temporal \( \gamma_T \) and volume \( \gamma_V \) decorrelation terms. Thus, the coherence of a ScanSAR interferometric pair can be expressed as follows:

\[
\gamma = \gamma_B \cdot \gamma_T \cdot \gamma_V \cdot \gamma_{ASD}. \tag{18}
\]
The last coherence term $\gamma_{ASD}$, which is due to the Asynchronous Scanning Decorrelation (ASD), has the following expression (for $\Delta T_D \leq T_D$):

$$\gamma_{ASD} = \frac{W_i}{W} = 1 - \frac{\Delta T_D}{T_D}. \quad (19)$$

Since $\gamma_{ASD}$ might be dominant with respect to the other terms (especially when the number of subswaths used is large) it should be eliminated by synchronizing the repeated scans or, whenever possible, by filtering out the noise, as described in the following section. For example, 2-beam and 4-beam (1-look) ScanSAR interferograms have been simulated by exploiting two ERS-1 interferometric passes (see Section II-B). Fig. 10 shows the interferometric fringes for synchronized scans, and for scan misalignment $\Delta T_D = 0.8 T_D$ (e.g., $\gamma_{ASD} = 0.2$). Notice the azimuth variant SNR, that gives an almost uncorrelated vertical strip in the figures (e.g., the contribution of the targets located at the edges of the antenna beamwidth during the scan interval).

Besides the decorrelation, the scan misregistration introduces a loss of resolution in the complex interferogram. The increase in the interferogram resolution can be expressed by the ratio between the common bandwidth for synchronized acquisitions and the common bandwidth for misaligned acquisitions, e.g., $(W/W_i) = (1/\gamma_{ASD})$. The size of a resolution cell (a pixel) on the ground also increases by the same factor, and decorrelation may result as the contribution of non stationarities, like slope changes within the same pixel.

Up to now, we assumed the same Doppler centroid for the two interferometric images. However, if the two images were acquired with a different Doppler centroid, $\Delta f_{dc}$ (e.g., due to a different antenna pointing), the expression (17) of the overlapped bandwidth becomes

$$W_i = (T_D - \Delta T_D) f_R + \Delta f_{dc}. \quad (20)$$

Therefore, a change in the Doppler centroid of $\Delta f_{dc}$ can be regarded as an equivalent scan misalignment $\Delta T'_D = \Delta f_{dc}/f_R$.

B. Eliminating the ASD Term

The decorrelation term created by the scan misregistration $\gamma_{ASD}$ can be avoided by filtering out the uncorrelated part of the images' spectra. It is clear from Fig. 9 that the central frequency of the band-pass filters, which allows the taking of only the common part of the spectra has the same linear variation of the filters used in the focusing step. Once $\Delta T_D$ is known, the first image should be band-pass filtered with a bandwidth $W_i$ and with the following central frequency:

$$f_{o1} = (\xi' + \Delta T_D) f_R \quad (21)$$

$\xi'$ being the azimuth coordinate of the first image (again the reference azimuth has been chosen in the middle of the dwell time $T_D$). The central frequency used to filter the second image has the following expression:

$$f_{o2} = (\xi'' - \Delta T_D) f_R \quad (22)$$

$\xi''$ being the azimuth coordinate of the second image.

If the effect of terrain slopes—detailed in the next section—is not relevant, the ASD can be easily cancelled by windowing the two raw datasets by the product of the two scan patterns $w_{o1}, w_{o2}$ in order to keep only the common spectral contributions (the mid grey areas in Fig. 9) [8].

The decorrelation reduction achieved with the proposed data processing can be clearly appreciated by comparing Figs. 11 and 12. In the cases illustrated, two interferometric ScanSAR acquisitions with a $\Delta T_D$ that is half the dwell time $T_D$ were simulated. As a result the coherence histogram derived from the misaligned ScanSAR acquisitions is scaled with respect to the one derived for SAR (e.g., for aligned ScanSAR acquisitions) of the factor given in (18) and (19).
The position of the coherence histogram peak, for example, is approximately halved. However notice that most of the decorrelation is recovered by performing the azimuth varying filtering.

The ASD can be theoretically removed whenever there is a common band $W_i > 0$ i.e., $\gamma_{ASD} > 0$ in (19). This condition implies

$$\Delta T_D < T_D \quad \text{or} \quad \Delta T_D > T_R - T_D \quad \Rightarrow \quad \Delta T_D > T_R \left(1 - \frac{T_R}{N_{\text{lw}}}\right)$$

for $0 \leq T_D \leq T_R$. (23)

derived from (19), taking into consideration the periodicity of the acquisition. Notice that for the 2-beam-1-look ScanSAR ($N_{\text{lw}} = 2$), condition (23) is met with $\sim 100\%$ of the times for random acquisitions, and $50\%$ of the times for a 4-beam-2-look system. The first system seems to be a good candidate for ScanSAR interferometry. When the beam-look product is large, stringent constraints on the scan acquisition synchronizations should be assumed. For example, the 5-beam-3-look ASAR requires an along track synchronization error of $< 140$ m to obtain a common bandwidth, $W_i > 0$. However, that limit should be reduced to obtain an acceptable interferogram resolution.

C. Effect of the Azimuth Slopes

The effect of the azimuth slopes of the terrain on the image reflectivity spectrum can be studied using the geometry shown in Fig. 13: there a constant sloped terrain with an azimuth slant angle $\alpha$ is represented. For squint angles $\approx 0$, the transmitted wavelength $\lambda$ is projected on the terrain scaled by a factor $1/(\sin \alpha \cos \theta)$, $\theta$ being the look angle. The corresponding azimuth ground wavenumber (i.e., in the direction $L$ in the figure) is: $k_L = 4\pi/\lambda L = 4\pi \sin \alpha \cos \theta / \lambda$. The second interferometric image is gathered with a look angle $\theta + \Delta \theta$, the ground terrain spectrum is thus shifted by

$$\Delta k_L \approx \frac{\partial k_L}{\partial \theta} \Delta \theta = -\frac{4\pi f_0}{c} \Delta \theta \sin \theta \sin \alpha$$

$$= \frac{4\pi f_0 B_n}{c} \sin \theta \sin \alpha$$

$B_n$ being the normal baseline. The corresponding azimuth spectrum shift is

$$\Delta k_c \approx \frac{\Delta k_L}{\cos \alpha} = \frac{4\pi f_0 B_n}{c} \frac{r_0}{r_0} \sin \theta \tan \alpha.$$ (25)

If we define $\rho_B$ to be the ratio between the current baseline, and the “critical” baseline, fixed by the system range bandwidth, $B_R$:

$$\rho_B = \frac{B_{n_{\text{max}}}}{B_n} = \frac{B_R}{f_0} \frac{r_0}{B_n} \tan \theta.$$ (26)
then the following expression of the azimuth spectral shift (given in hertz) holds

$$\Delta f_a = \frac{\Delta k_x}{2\pi} v = -\frac{2B_R}{c} \nu_B \sin \theta \tan \theta \tan \alpha. \quad (27)$$

The azimuth spectral shift in (27) is usually ignored in SAR interferometry, since it is much smaller than the azimuth bandwidth. Yet, it can be significant in ScanSAR system, where the azimuth bandwidth is reduced proportionally to the beams-looks product, $N_{\text{sw}}$. Take, for example, the ASAR case. If we assume a look angle of $\theta = 40^\circ$ and a normal baseline $B_\nu = \frac{1}{2} B_{\text{max}}$, from (27) we get a shift $\Delta f_a = 22$ Hz for an azimuth slope of $10^\circ$. This shift is indeed a small fraction of the SAR azimuth bandwidth (~1500 Hz), yet it is approximately 45% of the ScanSAR azimuth bandwidth (50 Hz, [9]). For perfectly aligned scans, that shift contributes to the image coherence (in (18)), with a factor $\gamma_{\text{ASD}} = 0.45$, and the resolution is more than doubled.

In the case of misaligned acquisitions, the common bandwidth $W_i$ can be increased or reduced on a sloped terrain, depending on the signs of the scan error $\Delta T_D$ and of the shift $\Delta f_a$, induced by the azimuth slope. The coherence coefficient $\gamma_{\text{ASD}}$ is then modified as predicted by (19), but uses $W_i + \Delta f_a$ instead of $W_i$ for the common bandwidth. The slope dependent decorrelation can be cancelled out by tuning the central frequency of the filters, in (21) and (22), and the filter bandwidth, according to (27). Yet, the possible resolution loss cannot be recovered.

**D. ScanSAR-SAR Interferometry**

The decorrelation due to asynchronous scanning and terrain slopes and the resolution loss can be avoided if one ScanSAR survey is combined with a SAR survey got from the same mission, under a sufficiently close view angle. In that case, the decorrelation that comes from the non overlapped bandwidth can be removed by filtering the SAR data with the azimuth varying filter specified in the previous section. If the effect of slopes is minimal, it is sufficient to apply the scanning pattern $w_{3a}(f)$ used by the ScanSAR acquisition to the SAR raw data. The mixed SAR-ScanSAR interferometry is particularly helpful for those missions where scanning alignment requirements would be barely met, like for ASAR.

**V. CONCLUSION**

An efficient focusing technique for ScanSAR images has been presented. This technique operates on one small data set at a time (i.e., the data collected during the dwell time), thus allowing real-time implementation possibilities. Repeat pass ScanSAR interferometry has been analyzed. Due to the azimuth varying nature of the ScanSAR images spectrum, an accurate synchronization of the repeated scanning cycles is necessary to generate low noise interferograms. However, it has been shown that even if the scanning cycles show just a partial overlap, the Asynchronous Scanning Decorrelation term can be eliminated by means of an azimuth varying band pass filter. Furthermore, that filter can be designed to reduce the decorrelation due to the azimuth slope of the terrain, which can be noticed particularly with low-resolution ScanSAR systems. The same technique can be exploited to generate interferograms between SAR and ScanSAR images.

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**REFERENCES**


Andrea Monti Guarnieri, for a photograph and biography, see p. 210 of the January 1996 issue of this TRANSACTIONS.

Claudio Prati, photograph and biography not available at the time of publication.