Improved Multilook Techniques Applied to SAR and SCANSAR Imagery

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Abstract—Multilook processing is commonly used in SAR image formation in order to reduce the speckle noise. We propose two new multilook techniques for improving the radiometric resolution without altering the geometric resolution and characteristics of the impulse response. These techniques are based on the formation of looks with different bandwidths. The final image is formed by giving each look a proper size and weighting and by adding them incoherently. The looks with wide bandwidth contribute to an improvement of the overall geometric resolution, while the looks with narrow bandwidth improve the overall radiometric resolution. The equivalent number of looks is more than 2.3 times the number of independent looks and is superior to conventional multilook processing with overlapping. Finally, using the proposed techniques, we present an algorithm for efficient SAR and ScanSAR processing and prove its validity by image comparison and analysis.

I. INTRODUCTION

Speckle appears in SAR images due to the coherent processing of radar echoes of distributed target scatterers. The statistical properties of speckle are well known [4], [11] and its presence in SAR images reduces the detectability of objects in the image and also the capability to separate and classify distributed targets.

Traditional digital multilook processing consists of an incoherent addition of independent images (looks) of the same scene. The looks can be obtained by partitioning the available signal bandwidth (range and/or azimuth) and processing each look independently. The final image is produced by adding the looks incoherently, pixel by pixel. The direct trade-off between geometric and radiometric resolution must be considered when choosing the number of looks for the processing. One look processing means a fully coherent use of the bandwidth (best geometric resolution), and in this case the speckle noise will obey an exponential distribution where the standard deviation is equal to the mean value in the intensity image (multiplicative characteristic). For multilook processing, the geometric resolution will degrade as the number of looks increases and the speckle statistics of the intensity image obey a gamma distribution, where the standard deviation decreases with the square root of the number of independent looks. Some simulation results concerning azimuth multilook processing can be found in [13].

If no look overlapping is used, similar results to multilook processing (with the exception of the shape of the impulse response) are obtained by using a simple mean filter applied on the one-look processed image [8]. An adequate window size must be chosen to achieve the same resolution as in the multilook case. For example, if the pixels in a one-look image are not correlated, a mean filter with four points would decrease the standard deviation of the speckle noise in the same way as four-look processing. Better results than a simple mean filter are obtained, for example, with an adaptive filter which uses the local mean and local variance values of the image to control the local averaging process [7]. The use of multilook processing in this case is advantageous in terms of processing time because the data volume can be reduced directly in the processing as the looks are formed.

When weighting is applied at each look to improve the point target response, the looks can be overlapped up to a certain value in order to maximize the use of the available signal bandwidth while maintaining their statistical independence. Therefore the equivalent number of looks (as defined in the following) can be increased and the radiometric resolution of the image improved [1], [2]. This means that for a given geometric resolution, the reduction of the speckle noise using the multilook technique with overlap is greater than the reduction using the mean filter. The spatial filtering technique proposed by Li [8] using a \( \sin(\lambda)/\lambda \) squared or triangular weighted window and the technique of the continuous mixed integrator proposed by Zelenka [15] achieve results similar to the conventional multilook technique with overlap, so that we are going to use the conventional multilook technique as a reference for the performance comparisons.

In this paper, we assume that the available signal bandwidth and geometric resolution are defined by the system specification, so that an optimization of the radiometric resolution is desired. We assume also that the signal energy is constant within the available bandwidth, that the signal is not corrupted by thermal noise, and that equal weighting is used for each look. The influence of the latter two factors in the radiometric resolution can be found in [2]. We also use the equivalent number of looks (ENL) for evaluating the radiometric resolution. The ENL corresponds to the effective number of statistically independent looks and is given by:

\[
\text{ENL} = \frac{(E[P])^2}{\text{VAR}[P]} \tag{1}
\]
where \( P \) is equal to the intensity of a pixel in the multilook image, and \( \mu \) and \( \text{VAR} \) are the mean value and the variance of \( P \), respectively. When multilook processing is applied in the azimuth and range signal bandwidths, the total ENL is given by the product of each ENL \([2], [9]\). In the following development we only consider the one-dimensional case.

II. Analysis of the ENL

Using the assumptions made in the introduction (looks of equal power, no thermal noise), the ENL can be derived from (1) as a function of the fractional overlap and number of independent looks:

\[
\text{ENL} = \frac{L}{1 + 2 \sum_{j=1}^{L-1} \frac{L-j}{L} \cdot \rho_{j+1}^2 \cdot \rho_{j+1,1}^2(x)}
\]

with

\[
L = 1 + \frac{(L_0 - 1)}{(1 - x)}
\]

where \( L_0 \) is the number of independent looks, \( x \) is the fractional overlap, \( L \) is the actual number of overlapped looks, and \( \rho_{j+1,1} \) is the correlation factor between look \( j+1 \) and look 1 (\( \rho = 1 \): complete overlap; \( \rho = 0 \): complete separation).

We analyze in the following the behavior of the ENL as a function of the fractional overlap \( x \) by substituting (3) and the values of the correlation factor \( \rho \) in (2). Fig. 1 shows the ENL as a function of the fractional overlap for a generalized Hamming weighting with \( \alpha \) from 0.54 up to 1 and for \( L_0 = 4 \) and \( L_0 = 2 \). The interpretation of this figure leads to a well-known result. For the case without weighting, we observe a small improvement of the ENL due to overlapping, since the overlapped looks are strongly correlated. For the case with strong weighting \( (\alpha = 0.54) \) and large overlap, the ENL is increased by more than 50% above the number of independent looks.

A more interesting analysis of Fig. 1 can be done for \( \alpha \), ranging from 0.54 to 0.75, which corresponds to most of the practical cases. In this case a decrease of the ENL for a fractional overlap greater than a certain value (between 0.4 and 0.6) is observed. This decrease has already been observed by Brooks \([2]\). We find the explanation in the fact that the traditional multilook technique does not make an efficient use of the signal energy at the extremities of the available signal bandwidth. For example, with an overlap of 50% \((x = 0.5)\), we observe that the halves of the looks located at the left and right extremity of the signal bandwidth are not correlated with the others. As the overlap increases, the missing contribution of the looks at the extremities of the signal bandwidth causes a small decrease of the ENL. We propose therefore two new, improved multilook techniques (IML techniques) that achieve a better radiometric resolution using the same available bandwidth.

III. The First IML Technique

In order to better use the signal energy we form additional looks with half the desired bandwidth at the extremities of the available signal bandwidth. Hereafter, we call the looks with half the desired bandwidth as "small looks." The small looks are added incoherently to the looks of the traditional multilook technique with 50% overlap (see Fig. 2 and consider the small looks only at the extremities). We can foresee that the radiometric resolution will be improved, since the small looks are correlated only with the outer halves of the original looks located at the left and right extremities of the signal bandwidth. On the other hand, the final geometric resolution will deteriorate due to the contribution of the small looks. This deterioration can be compensated for by increasing the bandwidth of the looks, which will lead to a decrease of the total number of looks (the available signal bandwidth is limited). Hence the net increase of the ENL, considering a compensated geometric resolution, is reduced.

We propose therefore a way to make this configuration more efficient. Increasing the number of small looks will give a greater contribution to the overall radiometric resolution; the looks with greater bandwidth (denoted here as "large looks") contribute to an improvement of the overall geometric resolution. The basic configuration of the improved multilook technique (IML technique) is shown on Fig. 2, where an overlapping of 50% is used for both look sizes. A scalar weighting value can be given for the small and large looks so that an optimum compromise between radiometric and geometric resolution is achieved. Analyzing several simulation results, we found that a scalar weighting value which provides an equal gain for the sum of the impulse responses of both the small and large looks is satisfactory. If \( f(t) \) is the final impulse response, this operation can be formulated as follows:

\[
|f(t)| = \alpha_L \cdot \sum_{i=1}^{L_L} |f_L(t)| + \alpha_S \cdot \sum_{i=1}^{L_S} |f_S(t)|
\]

where \( f_L \) and \( f_S \) are the impulse responses of the large and small looks, respectively, \( \alpha_L \) and \( \alpha_S \) are the scalar weight-
ing values, $L_L$ and $L_S$ are the number of large and small looks with overlap, and $L_T$ is the total number of overlapped looks. The number of overlapped looks is given by:

$$L_T = 2 \cdot L_0 - 1$$

$$L_S = 4 \cdot L_0 - 1$$

$$L_L = 6 \cdot L_0 - 2.$$  \hfill (5)

Assuming equal gain for the first and second term of (4), we obtain:

$$\frac{L_S \cdot \alpha_S}{2} = L_L \cdot \alpha_L.$$  \hfill (6)

The factor 2 arises from the fact that the gain of $f_L$ is twice the gain of $f_S$. With (5) and (6) and normalizing the values of $\alpha_L$ and $\alpha_S$, so that $\alpha_L \cdot L_L + \alpha_S \cdot L_S = L_T$, we obtain:

$$\alpha_L = \frac{6 \cdot L_0 - 2}{3 \cdot (2 \cdot L_0 - 1)}$$  \hfill (7)

and

$$\alpha_S = \frac{2 \cdot (6 \cdot L_0 - 2)}{3 \cdot (4 \cdot L_0 - 1)}.$$  \hfill (8)

The final impulse response of the IML technique using the scalar weighting values and a Hamming weighting ($\alpha = 0.54$) is shown in Fig. 3. The achieved ISLR (integrated sidelobe ratio) is 14.6 dB, the PSLR (peak sidelobe ratio) 43 dB, and the geometric resolution is 1.25 (normalized by the geometric resolution of the large look). The values of PSLR and ISLR are considered to be good enough to meet the specifications of image quality for all typical SAR systems. To compensate for the deterioration of the geometric resolution, we increase the bandwidth of the large and small looks by 25% and substitute $L_0$ by 0.85 $L_0$ in (5), (7), and (8) so that the geometric resolution is maintained.

The correlation factor $\rho$ for each look related to its neighborhood is a function of the weighting function, look size, and overlapping value. In fact, six values of $\rho$ can occur with the proposed configuration: (a) The looks are not coincident, $\rho = 0$; (b) the small looks are correlated $\rho_L$; (c) the large looks are correlated $\rho_L$; (d) the large and small looks are slightly correlated $\rho_{SL}$ (see the correlation on Fig. 4 between the second small look from the left and the second large look from the left); (e) the large and small looks are correlated $\rho_{SL}$ (correlation between the first small and large look); and (f) the large and small looks are strongly correlated $\rho_{SL}$ (correlation between the second small look and the first large look from the left). Considering the above values and also the scalar weighting values $\alpha_S$ and $\alpha_L$, we obtain a modified form of (2) for the first IML technique:

$$ENL = \frac{L_T^2}{\sum_{i=1}^{L_T} \alpha_L^2 + \sum_{i=1}^{L_T} \alpha_S^2 + 2 \cdot (L_T - 1) \cdot \alpha_L^2 \cdot \rho_{SL}^2 \cdot \alpha_S + 2 \cdot \alpha_S \cdot \alpha_L \cdot \sum_{i=1}^{L_T} \rho_{SL}^2} + \frac{L_T^2}{2 \cdot \alpha_L \cdot \sum_{i=1}^{L_T} \rho_{SL}^2}$$

$$+ \frac{2 \cdot \alpha_S \cdot \alpha_L \cdot \rho_{SL}^2 + 2 \cdot \alpha_S \cdot \alpha_L \cdot \rho_{SL}^2}{2 \cdot \rho_{SL}^2}.$$  \hfill (9)

Calculating the values of the correlation factors for a Hamming weighting ($\rho_{SL}^2 = 0.055$, $\rho_{SL}^2 = 0.055$, $\rho_{SL}^2 = 0.055$).
0.065, $\rho^2_{052} = 0.27$, and $\rho^2_{053} = 0.77$) and substituting (5), (7), and (8) in (9), we obtain the final expression of the ENL:

$$ENL = \frac{26 \cdot L_0^4 - 49 \cdot L_0^3 + 33.3 \cdot L_0^2 - 9.6 \cdot L_0 + 1}{11.3 \cdot L_0^3 - 17.6 \cdot L_0^2 + 8.8 \cdot L_0 - 1.4}.$$  

(10)

IV. THE SECOND IML TECHNIQUE

For a small number of independent looks ($1 \leq L_0 \leq 2$) we show that a further improvement of the ENL can be achieved by decreasing the number of small looks. We consider then the look configuration of Fig. 2 with the same overlap for the large looks and with no overlap for the small looks. The elimination of the overlap of the small looks has the effect of giving more emphasis for the small looks at extremities of the signal bandwidth, which have a smaller correlation with the large looks. This leads to an effective reduction of the small looks for improving the radiometric resolution.

To compensate for the deterioration of the geometric resolution we alter again the values of $\alpha_2$ and $\alpha_3$ and also increase the bandwidth of the large and small looks by 25%, so that the same geometric resolution is obtained as in the case of the traditional multitlook technique. Similarly to the first IML technique, we can calculate the final expression of the ENL for the second IML technique:

$$ENL = \frac{L_0 \cdot (2.6 \cdot L_0^2 - 3.2 \cdot L_0 + 1)}{1.29 \cdot L_0^3 - 1.5 \cdot L_0 + 0.43}.$$  

(11)

Fig. 4 compares the ENL achieved by the traditional multitlook technique with 50% overlap and by the two IML techniques applied in one signal spectrum (azimuth or range). For a large number of independent looks ($L_0 \geq 4$), the first IML technique achieves an ENL of $2.3 \cdot L_0$ and is superior to conventional multitlook processing with 50% overlap, which achieves $1.6 \cdot L_0$. An interesting result is obtained by the second IML technique when the full signal bandwidth is used coherently ($L_0 = 1$). The IML configuration consists in this case of one large look and two small looks and achieves an ENL of 1.65 or 2.72 when applied to both the range and azimuth processing. In this case ($L_0 = 1$) the second IML technique is more advantageous than the first because it reaches a higher ENL with a lower number of look; i.e., with less computational effort. This result is especially interesting for ScanSAR, where the bandwidth restrictions are severe [12]. In this case there is not necessarily a decrease in the azimuth power spectrum for a given point target at both edges of its bandwidth, which is produced during the illumination time of a subswath. This occurs because the azimuth bandwidth of each subswath corresponds to a subpart of the total azimuth bandwidth. If there is no decrease at both edges, then the contribution of the small looks of the second IML technique increases because they make efficient use of the signal energy at the extremities of each subswath bandwidth.

V. SAR PROCESSING WITH THE IML TECHNIQUE

A conventional SAR processor can easily be altered to implement the new techniques in both range and azimuth processing. We use the basic configuration in the frequency domain proposed by Wu [14] with the Fast Fourier Transform (FFT) to perform the two one-dimensional correlation process. Fig. 5 shows the basic block diagram for processing with the IML technique. The generation of the $L_0$ large looks and $L_0$ small looks as well as the introduction of the weighting function is performed in the frequency domain. The bandwidth $B_0$ of the large looks is set 25% greater than the bandwidth for the desired geometric resolution (including the decrease of the geometric resolution by the weighting function) in order to compensate for the influence of the small looks. The bandwidth $B_0$ of the small looks is $B_0/2$. For a time bandwidth product lower than 20 for the small looks the generation of the looks must be performed in the time domain to avoid a mismatch of the reference function with the input signal. A number of $L_0 + L_0$ IFFT’s (inverse FFT) is executed with the results of the multiplications between the Fourier-transformed input signal and each created look in the frequency domain. Finally, look detection and incoherent summation is performed with the appropriate scalar weighting factors ($\alpha_2$ and $\alpha_3$).

VI. RESULTS WITH THE E-SAR SYSTEM OR DLR

The DLR Institute for Radio Frequency Technology has developed an experimental airborne L/C/X-band SAR system [6]. Designed for operation onboard a small aircraft flying at low altitudes, the E-SAR system is able to produce high-resolution images. A flight over the airfield at Oberpfaffenhofen in West Germany was used to test the IML technique. This area, with several agricultural fields in its vicinity, was equipped with four groups of corner reflectors for calibration purposes.
The software for the SAR image processing was developed on a MicroVAX II computer. The software of the IML techniques was also implemented (in the azimuth spectrum) so that both methods could be compared to show the improvement of the new approach. In both cases (IML and traditional technique) the image was processed with a range resolution of 3 m and 1 independent look, and an azimuth resolution of 4 m and 4.5 independent looks. Both methods used a Hamming weighting, with $\alpha = 0.54$. For the processing with the traditional multilook technique, a fractional overlap of 0.5 was chosen. Fig. 6 shows an image processed with the first IML technique. The surface plots compare a group of corner reflectors of this scene processed with both the IML and traditional multilook techniques. A more effective reduction of the speckle noise by the IML technique is observed at the grass area surrounding the corner reflectors (compare the surface plots in Fig. 6).

The measured values of the ENL in Table I were obtained by evaluating (1) over several agricultural fields of the processed image. The measured value of the geometric resolution corresponds to the measured 3 dB width of the corner reflectors.

The E-SAR raw data were also used to simulate an ScanSAR system. In this case the trade-off between geometric and radiometric resolution is critical, due to data rate limitations. The available swath width of the E-SAR system was divided into two subswaths and the illumination time for each subswath was set to achieve a 3-m azimuth resolution (one look) at the middle of the subswath. Adequate processing was performed by cancelling the quadratic phase variation and applying an FFT to obtain the final image. A single-look configuration (fully coherent utilization of the available bandwidth) was used in the traditional technique and no improvement of the equivalent number of looks is possible (ENL = 1). Using the second IML technique with $L_0 = 1$ in range and azimuth processing, we obtained a measured ENL of about 2.5 with a slightly reduced geometric resolution (see Table I).

The practical results in Table I show good agreement with theoretical values. There are only slight differences due to the shape of the azimuth and range signal power spec-
trum that was considered constant in our theoretical derivations.

VII. CONCLUSIONS

We have developed two IML techniques that are suitable and easy to implement for all SAR systems that use a digital image-formation process. A better radiometric resolution is achieved with the same bandwidth (data rate).

In our case, the IML technique requires approximately 50% more computational time than the traditional multilook approach. We are currently developing an SAR processing algorithm based on a time-domain subaperture configuration [10]. The computational requirements for the SAR processing are reduced considerably by using an optimized approximation for the reference function of each subaperture. Like other conventional subaperture approaches, this method offers great flexibility with respect to multilook processing. The IML technique is easily implemented by adding coherently the necessary number of subapertures to form the small and large looks and then adding all the created looks incoherently. With a dedicated hardware for the subaperture approach, the IML technique can be implemented efficiently in real-time or near real-time with current MOS technology.

REFERENCES


