SAND2000-1421 C

Open-Loop Adaptive Filtering for Speckle Reduction in Synthetic Aperture Radar Images

J. A. Rohwer, Sandia National Laboratories, Albuquerque, NM 87185-0986
N. Magotra, Texas Instruments, Houston, TX 77251-1443

Abstract

The Two-Dimensional Adaptive Correlation Enhancer Algorithm (2DACE) is an open-loop adaptive filtering technique that can be applied to Synthetic Aperture Radar (SAR) images for the purpose of reducing speckle. This paper includes the development of the 2DACE algorithm and the optimum filter parameters for this specific task. The unique implementation of 2DACE with a data amplitude pre-compression operation was proven to effectively reduce speckle, enhance fine features, and maintain image resolution.

1. Introduction

This work presents research into the application of the Two-Dimensional Adaptive Correlation Enhancer Algorithm (2DACE) [1], an open-loop adaptive filtering technique, to reduce speckle in SAR images. Open-loop filters are application specific and the key filter parameters must be optimized for the task. This paper presents a unique post-processing approach that combines nonlinear data amplitude compression and the 2DACE algorithm. The nonlinear compression is applied prior to the 2DACE to manage the gain control problems inherent with the open-loop architecture. This process maintains the initial image resolution. The optimum filter parameters are developed through testing with synthetic images and SAR images.

The objective was to determine if 2DACE could effectively reduce speckle without degrading the target resolution. The development of the optimal parameter combination are presented along with results that prove the expected performance. The filter was tested using two-dimensional Taylor Point Spread Functions. White Gaussian noise and actual speckle from a Synthetic Aperture Radar image were added to the test images to determine the efficacy of 2DACE. As a final test the filtering routine was applied to SAR point targets and SAR images.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

2. Speckle in SAR images

Objects viewed in highly coherent light can acquire a granular appearance and the granularity has no apparent relationship to the properties of the object. The irregular pattern is best described by the methods of probability and statistics. Characterization of speckle has been a research topic of many years, actually some of the most important work in speckle was performed in the 1970s and 1980s [2].

In general an object is very rough in relation to the wavelength of the radiating source. When coherent radiation is reflected from a rough surface the returned signal has different phases due to the surface properties. The combination of the coherent nature of the signal and dephased returns produces the granular pattern known as speckle. Speckle is undesirable in SAR images because it detracts from the fine details and degrades the image quality by reducing the resolution. Figure 1 is a three dimensional plot of speckle from a SAR image.

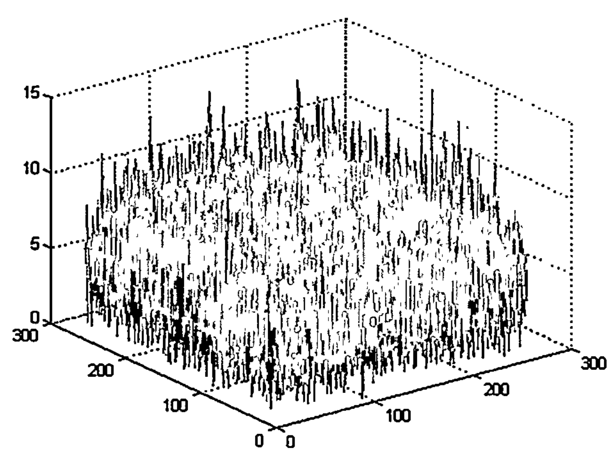

Figure 1. Mesh plot of speckle, 256x256 pixels. The speckle was cropped from a field in the SAR image F2_335493_308.

DISCLAIMER

DISCLAIMER

3. 2DACE algorithm development

The 2DACE algorithm is a two-dimensional open loop architecture for updating the FIR filter weights. The algorithm is implemented by convolving the input image, a (j,k) matrix, with the 2D filter coefficients, $w[m,n]$. Each input pixel, element of the (j,k) matrix, is multiplied with each filter coefficient from $w[m,n]$ and then summed to produce $y[j,k]$ as given by

$$y[j,k]=\sum_{m=j-L}^{j+L}\sum_{n=k-L}^{k+L}x[j,k]\cdot w[m,n] \quad (1)$$

The FIR filter size is proportional to the lag of the update equation described below in (2).

$$w[m,n]=\beta w[m,n-1]+(1-\beta)\frac{x[m,n]x[m,n]}{2L^2p[m,n]} \quad (2)$$

β is referred to the adaptation constant, and L is the maximum lag of two-dimensional filter. The filter coefficients $w[m,n]$ are written in matrix form as

$$w[m,n]=\begin{bmatrix} w_{0,0}[m,n] & \cdots & w_{0,2L}[m,n] \\ w_{1,0}[m,n] & \cdots & w_{1,2L}[m,n] \\ \vdots & \ddots & \vdots \\ w_{2L,0}[m,n] & \cdots & w_{2L,2L}[m,n] \end{bmatrix} \quad (3)$$

The subscript 2L,2L refers to the element in the filter weight matrix and m,n refers to the index of the input image matrix $x[m,n]$. The input matrix to the filter is of the form shown in equation (4) where m,n is the element index.

$$x[m,n]=\begin{bmatrix} x[m-L,n-L] & \cdots & x[m-L,n+L] \\ x[m-L+1,n-L] & \cdots & x[m-L+1,n+L] \\ \vdots & \ddots & \vdots \\ x[m+L,n-L] & \cdots & x[m+L,n+L] \end{bmatrix} \quad (4)$$

In equation (2) the present value of the input data is divided by a recursive estimate of the input signal power, $p[n,m]$.

$$p[m,n]=\beta p[m,n-1]+(1-\beta)x^2[m,n] \quad (5)$$

3.1 Stability of 2DACE algorithm

The stability of the 2DACE algorithm is apparent after taking the Z transform of equation (2). The two dimensional convolution is denoted by $*$ and the Z transform of the input matrix, $x[m,n]$, is $X[z_1,z_2]$. The Z transform is shown below in equations (6) and (7).

$$W[z_1,z_2]=\frac{k}{(1-\beta z_1^{-1})}X[z_1,z_2]*X[z_1,z_2] \quad (6)$$

$$X[z_1,z_2]=\begin{bmatrix} z_1^{-L}z_2^{-L} & \cdots & z_1^{-L}z_2^{L} \\ z_1^{-L+1}z_2^{-L} & \cdots & z_1^{-L+1}z_2^{L} \\ \vdots & \ddots & \vdots \\ z_1^{L}z_2^{-L} & \cdots & z_1^{L}z_2^{L} \end{bmatrix}X[z_1,z_2] \quad (7)$$

In equation (6) it is seen that the filter is stable and causal for $|z_1|>\beta$ as long as $\beta<1$.

3.2 Adaptation constant

The smaller the magnitude of β, the less "memory" the recursive system has. This can be seen by inspecting equation (2). For $\beta<0.5$, $w[m,n]$ has more of a dependence on the current input data and less of a dependence on previous histories of the filtering coefficients.

Within the Z transform equation of the filter coefficients the term $\frac{1}{(1-\beta z^{-1})}$ can be approximated by the geometric series with ratio β in the time domain. The time constant of the 2DACE algorithm is defined as $\tau\approx\frac{1}{1-\beta}$. By fitting τ to the geometric series and showing that $\beta=e^{\frac{-1}{\tau}}$ it is evident that β controls the rate of adaptation. As $\beta\rightarrow 1$ τ rapidly increases. β is also referred to the smoothing parameter. This is a good explanation for the effect that β has on the input data. For larger values of β the processed SAR image has significant smearing, caused by the smoothing effect of β.

4. 2DACE algorithm implementation

The post-processing speckle reduction routine developed has a series of six operations. Refer to Figure 2. First data amplitude compression is applied to the image to reduce the dynamic range. The compression process controls the gain and maintains the image resolution. The second step is data padding of the input image with reflected pixel values. This allows the filter coefficients to converge to the statistics of the image before the convolution is performed with pixels on the border of the image. The third step is to filter the compressed and padded image with the 2DACE algorithm. The fourth step is to crop the image to remove the data padding and the fifth step is to restore the dynamic range of the image. Restoring the dynamic range is an expansion process that is effectively the inverse process of the initial data amplitude compression. Step six is nonlinear data compression routine. This final data compression routine is optional and is applied after the 2DACE filtering to improve the contrast of the image. The data compression reduces the magnitude of the high intensity pixels and increases the magnitude of the low intensity pixels.

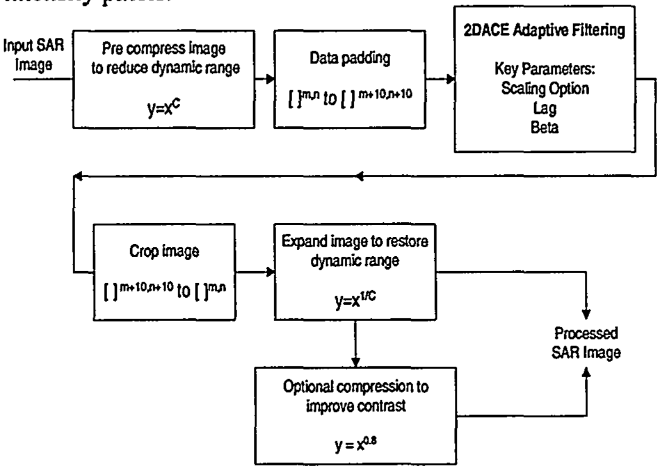

Figure 2. Block diagram showing the series of operations involved in speckle reduction with the 2DACE algorithm.

5. 2DACE filter parameters

Implementing the 2DACE filter algorithm to best filter the SAR images required finding the optimum filter parameters and developing pre and post-processing routines. Tuning the filter design to achieve the best balance between reducing speckle and maintaining image resolution involved filtering synthetic data and actual SAR images with many variations of the filter parameters. Referring to equation (2) the parameters affecting the speckle reduction and resolution are 1) scaling option $k = \frac{(1-\beta)}{2L^2 p[m,n]}$ 2) adaptation constant, β, 3) filter lag, L. The optimum adaptation constant was determined to be $\beta = 0.72$ and the filter lag $L = 1$.

6. Results

A two-dimensional low pass filter was used as the benchmark to test the performance of the 2DACE algorithm. The 3x3 LPF was easy to implement, provided a satisfactory degree of speckle reduction, and has been routinely used at Sandia National Laboratories as a quick means to improve the image quality. The drawback to the 2D LPF was the degradation in resolution and the blurring of the SAR image. Results presented in this paper prove that the 2DACE has superior performance over the 2D LPF.

6.1 SNR measurements - 2D Taylor PSF versus the 2D 3x3 LPF

The performance of the 2DACE algorithm is quantified through signal-to-noise ratio calculations and resolution measurements. The SNR is calculated with the variance of the clean ideal image divided by the least squares error calculation of the filtered image and the clear image [3].

$$SNR_{dB} = 10\log_{10}\frac{\sigma^2}{\sigma_{ls}^2} \quad (8)$$

$$\sigma_{ls}^2 = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}\left|x(m,n) - x'(m,n)\right|^2 \quad (9)$$

A two-dimensional Taylor PSF with zero mean additive white Gaussian noise (AWGN) and a variance of 0.02 is used the test image for SNR and resolution measurements. The SNR increase, after applying the 2DACE filtering algorithm with the optimum parameters, is 10.8dB. The SNR increase is 3.61dB when the 3×3 2D LPF is applied to the same test image.

6.2 Resolution measurements - 2D Taylor PSF versus the 2D 3x3 LPF

Typically resolution is the most important characteristic of a SAR image. A two-dimensional Taylor Point Spread Function with AWGN and SAR speckle was used to determine the 2DACE effects on point target resolution. Measurements of the –3dB and –14dB pulse widths of the 2D Taylor PSF are documented to quantify the effects of the 2DACE filter and the filter parameters on the resolution.

The results show that the resolution increased as β increased. For β equal to 0.72 the percent difference in -3dB pixel width, when compared to the clear noise free image, is -1.0% in the horizontal and vertical directions. The percent difference in –14dB pixel width is -1.3% in the horizontal direction and -7.1% in the vertical direction. When compared to the pulse widths of the noisy Taylor PSF the 2DACE algorithm reduces the pulse width and actually improves the resolution. The results show that initial image resolution is maintained.

The data proves that the 2DACE algorithm outperforms the 3×3 2D LPF. The percent difference in the -3dB pixel width for 3×3 2D LPF image and the clear image is +18.6% in the horizontal direction and +8.6% in the vertical direction. The percent difference in −14dB pixel width is close to +20% in the horizontal and vertical directions. It is evident that the 2DACE outperforms the 3×3 2D LPF.

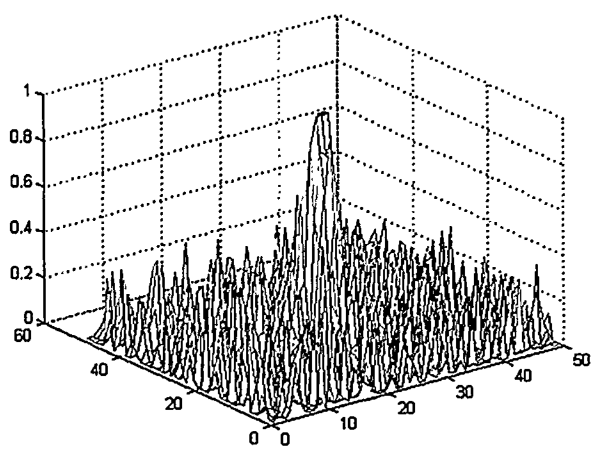

Figure 3. A 50x50 mesh plot of 2D Taylor PSF and AWGN with variance 0.02.

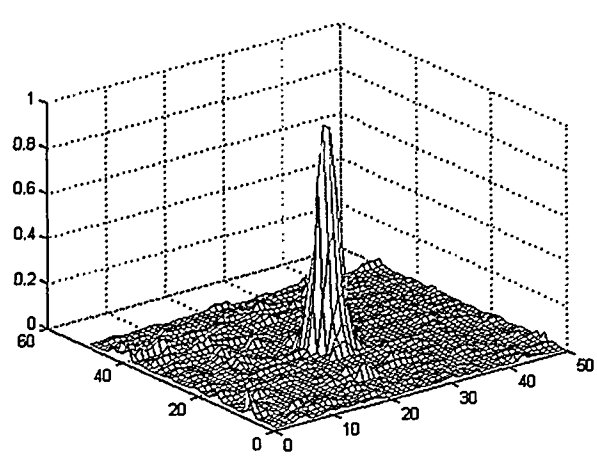

Figure 4. A 50x50 mesh plot of the filtered 2D Taylor PSF and AWGN. The optimum filter parameters were used, $\beta = 0.72$ and the filter lag $L = 1$.

6.3 Results with a SAR point target

Tests performed with a SAR point target, Figure 5, show that the 2DACE filtering process did not affect the resolution in the horizontal or vertical dimensions, as long as the image was compressed before the 2DACE filtering process.

6.3.1 Data compression. Data Compression is useful when the low intensity pixels of the filtered image need to be enhanced while the high intensity pixels need to be suppressed. Nonlinear compression is applied to the input image to enhances the low intensity pixels. The compression technique is of the form $y = x^C$ where x is the input data, C is the compression constant, and y is the output data.

Initial tests revealed that the filtered SAR point target has a degradation in −3dB and −14dB resolution. The change is resolution of the SAR point target is due to the large dynamic range. The SAR point target has a peak amplitude of 150, which is very large compared to the speckle mean. Therefore the convolution process widens out the point target as it transitions from the base to the peak. To adjust for this problem the image is compressed before the 2DACE is applied, then the image is uncompressed after the filtering. Test results show that the compression reduces the dynamic range of the input image and as a result the resolution is not affected by the filtering process.

Another benefit of the pre-compression is that shadowing is removed. Without the pre-compression process the filter generates a shadow in the direction that the filter is shifted. Since the dynamic range between point targets and the image mean is reduced, the filter doesn't clamp to a low value when transitioning from the peak.

6.3.1 Resolution of a SAR point target. The data shows that with a compression of $y = x^c$, the resolution of the point target is maintained after filtering. The resolution results are best for $c = 0.10$. For β equal to 0.72, $L = 1$, and $c = 0.10$ the percent difference in −3dB resolution, when compared to SAR point target, is -2.2% in the horizontal direction and +6.1% in the vertical direction. The percent difference in −14dB resolution is less than -13% in the horizontal direction and -1.6% in the vertical direction. Refer to Figures 5 and 6 for the SAR point target before and after filtering with 2DACE.

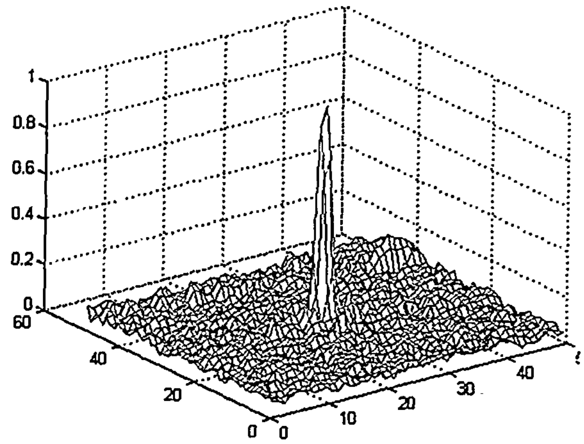

Figure 5. A 50x50 mesh plot of a SAR point target cropped from the SAR image F1_501442_217.

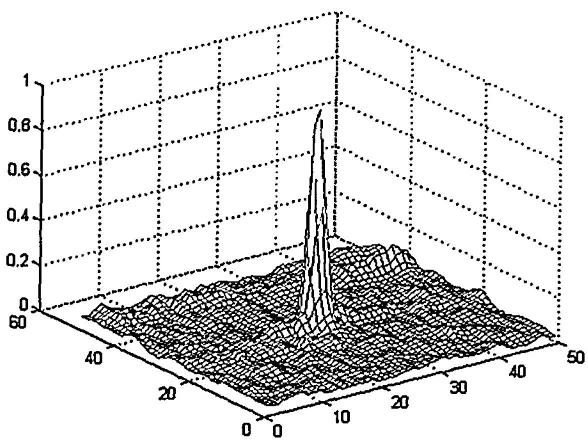

Figure 6. A 50x50 mesh plot of the filtered SAR point target. The optimum filter parameters were used, $\beta = 0.72$ the filter lag $L = 1$, and the pre-compression was $y = x^{0.1}$.

7. SAR images

A speckled SAR image and the image filtered with 2DACE are shown below. This section subjectively compares the different filtered images with the speckled SAR image. In Figure 7 the speckle can clearly be detected, especially around the high intensity targets. The granularity pattern of the speckle can also be seen in the areas of flat contrast. The image in Figure 8 is the output of the 2DACE filter with the optimal parameter settings. The speckle is removed from the entire image. The high intensity objects are not blurred, the objects are more defined than in the original image, and the fine details in the areas of flat contrast are more pronounced.

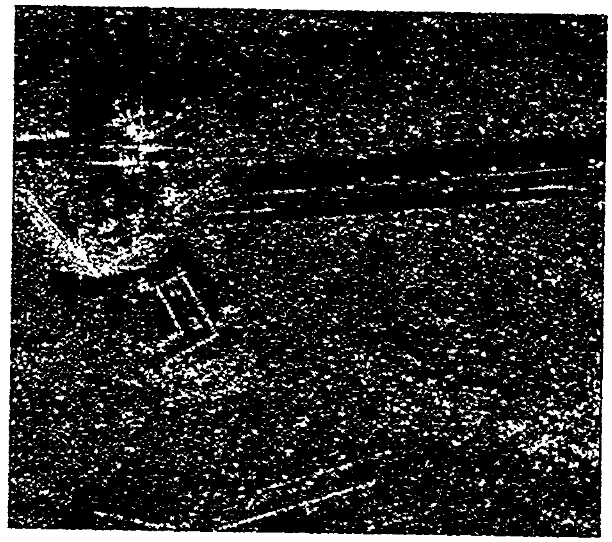

Figure 7. SAR Image F1_501422_217

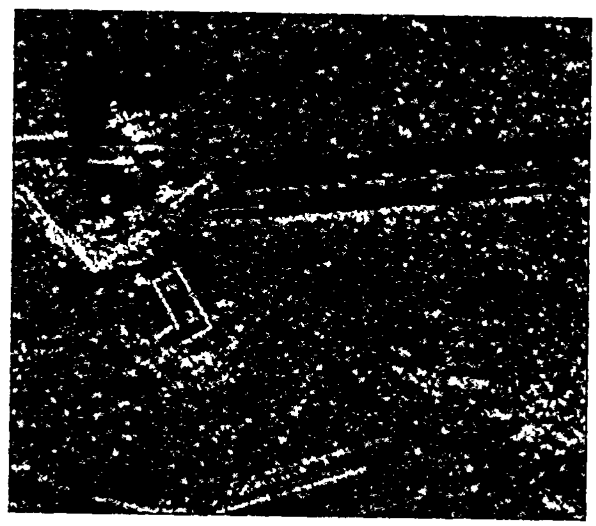

Figure 8. F1_501422_217 filtered with 2DACE and the optimum filter parameters.

8. Conclusion

This research presented a unique implementation of the 2DACE algorithm involving nonlinear compression to manage the gain control problems inherent with the open-loop architecture. 2DACE was implemented in MATLAB and proven to effectively reduce speckle in SAR images without adversely affecting the resolution.

Because of the wide dynamic range of the pixels in the SAR images, nonlinear data compression techniques were applied before and after the image processing. The compression techniques were required to control the open-loop gain of the filter, improve the resolution, and restore the contrast of the image. In addition the performance of open-loop adaptive algorithms is quite often application specific the filter parameters must be optimized for the task.

The 2DACE filter algorithm was applied to 2D Taylor PSF images to test the filter's performance and compared to results using the 3×3 2D LPF. As a final test the 2DACE filtering algorithm was applied to SAR images obtained from the Synthetic Aperture Radar Department 2345 at Sandia National Laboratories. A quantitative comparison of point targets and a subjective comparison between the original speckled image and the filtered image proves the expected performance of the algorithm.

References

1. C. Knittle and N. Magotra, "Two-Dimensional Adaptive Enhancement and Detection of Linear Features in Noisy Images," *25th Asilomar Conference*, November 1991.
2. J.W. Goodman, "Statistical Properties of Laser Speckle Patterns," Topics in Applied Physics: Laser Speckle and Related Phenomena, ed. J.C. Dainty, Springer-Verlay, 1984.
3. A.K. Jain, Fundamentals of Digital Image Processing, Prentice Hall, Englewood Cliffs, NJ, 1989.