NONLINEAR M-BAND WAVELET FILTER STRUCTURES FOR SAR IMAGE COMPRESSION

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ABSTRACT

Synthetic aperture radar (SAR) imaging systems generate vast quantities of data and hence efficient image compression is an essential step for reducing the cost of data storage and transmission. The compression performance achieved by wavelets based on linear filters is limited by the presence of speckle noise. In this paper a new compression scheme for SAR images that uses a nonlinear wavelet decomposition is proposed. Using the lifting framework, a 4-band filter bank and nonlinear filters are used to separate the underlying image features from the speckle noise. Experimental results show a compression performance that is much improved in comparison with JPEG.

1. INTRODUCTION

Image compression is widely used for reducing the storage and transmission cost of digital images. However, SAR images typically contain less inter-pixel redundancy than natural images because or their high level of multiplicative noise, termed speckle. When coupled with low contrast, speckle results in images that do not compress well. For example, at the JPEG 2000 meeting in Sydney 1998, the SAR test images had residual error an order of magnitude greater than for the other test images across all the algorithms submitted.

It is well known that images contain relevant features at different scales or resolutions. Multiscale approaches make use of this fact and have become well established in many image processing applications. In particular, the wavelet transform allows efficient image analysis and has been widely applied to image compression [1]. Within SAR imagery, wavelet techniques have been used for both image compression and noise reduction [2-3]. Lossy compression schemes work by removing some of the image information and it is therefore desirable to remove those image components corresponding to noise while retaining image features. However, as conventional wavelet filters are linear, they are not ideal for separating the underlying image signal from the speckle noise.

The advantages of non-linear filters for speckle noise suppression are well known. They are far better than linear filters at differentiating between image features and noise, and can successfully smooth images while preserving edges [4]. It would therefore be advantageous to incorporate a nonlinear filter element within the wavelet structure. The greater understanding of nonlinear multiscale techniques that has recently been developed [5-8] makes such an approach possible. In this paper we propose a wavelet filter structure for SAR images which provides a nonlinear decomposition with critical subsampling and perfect reconstruction.

The success of wavelets for image compression is primarily attributed to coding strategies for data organisation and representation. To achieve this Shapiro's embedded zerotree wavelet coder (EZW) [9] and Said and Pearlman's set partitioning in hierarchical trees (SPIHT) [10] exploit the inter-subband dependency of insignificant coefficients. In such schemes a transform that reduces the number of large wavelet coefficients is beneficial for achieving high compression. For SAR images the objective is not necessarily to obtain a small number of significant coefficients but instead is to construct a transform that attempts to separate the underlying image signal from the speckle noise. If this is successfully achieved, the quantization stage can then allocate more bits to the image features than to the noise components. One such transform is described below.

2. NONLINEAR WAVELET STRUCTURES

Wavelet analysis was originally based on the use of linear analysis and synthesis filters. This reliance on linear filters has recently been overcome by the lifting scheme that provides a mechanism for the construction of both linear and nonlinear wavelet transforms [11]. The lifting scheme provides a spatial interpretation of the wavelet transform and possesses enough flexibility and freedom to allow the inclusion of nonlinear structures. Perfect reconstruction is retained by imposing restrictions on the structure instead of the filter coefficients, enabling different methods of subsampling and various filter shapes and sizes to be incorporated within the lifting framework.

Initial approaches to nonlinear wavelet decompositions subsampled and then decomposed the signal using a nonlinear element as one part of the filter pair and the identity filter as the other [12]. However, since one part of the resulting signal is essentially only downsampled aliasing is inevitable. To overcome this problem subband coefficients can be predicted and updated from other subbands, reducing the effects of aliasing and producing a smother low pass subsampled image [13].

For image analysis, filtering needs to be performed in two dimensions. To extend the wavelet filter structure to two dimensions several techniques can be used, the simplest being to use separable filters in the horizontal and vertical directions. However, as nonlinear operators do not obey the law of superposition, the order of filter application affects the results. An alternative two-dimensional structure that overcomes this problem is multi-band (M-band) filtering in which a 4-band structure can be used to process two dimensions in one step of the transform. An additional advantage of this approach is that pixels from a more representative local region can be used to derive the coefficients in the subbands.

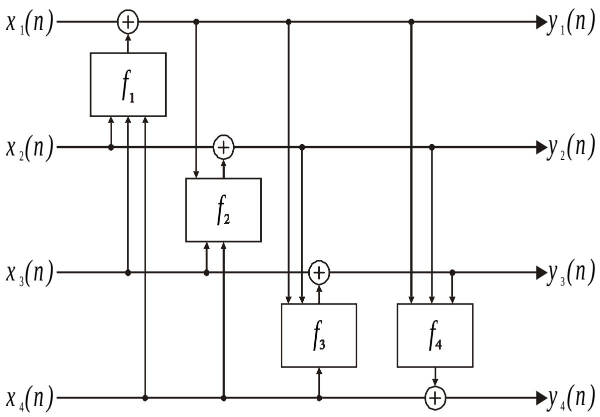


Figure 1: Four-band filter structure.

The proposed nonlinear wavelet transform is based on a multiscale filterbank, using a nonlinear filter for both the prediction of the high pass and update of the low pass parts of the filter, see Figure 1. It uses integer coefficients and allows for both lossy and lossless coding.

Whereas traditional linear lifting approaches only use odd and even samples to predict and update the subbands our 4-band structure allows for different two-dimensional regions of support. The image is split into non-overlapping highly correlated regions which are more suitable for distinguishing between the underlying image features and noise than the odd/even case. In addition, the nonlinear update allows the low pass image to be smoothed. This compares with [12] which formed the low pass band by downsampling only.

Figure 1 shows an implementation of the analysis stage of a four channel filter bank. The components of the original image are denoted by the subsets of pixels $x_1(n)$, $x_2(n)$, $x_3(n)$ and $x_4(n)$. The resulting transformed signal for one level of decomposition is given by $y_i(n)$ for $i=1,2,\ldots,4$ where $y_1(n)$, $y_2(n)$ and $y_3(n)$ are the high pass subbands and $y_4(n)$ is the low pass subband. To obtain the high pass coefficient $y_1(n)$ the subset of pixels $x_1(n)$ is predicted by a function f_1 of the subsets $x_2(n)$, $x_3(n)$ and $x_4(n)$. Similarly, the high pass coefficient $y_2(n)$ (resp. $y_3(n)$) is predicted by a function f_2 (resp. f_3) of the subsets $y_1(n)$, $x_3(n)$ and $x_4(n)$ (resp. $y_1(n)$, $y_2(n)$ and $x_4(n)$). These resulting high pass coefficients are then reused to update $x_4(n)$ to obtain the low pass coefficient $y_4(n)$. The transform for one level of decomposition is thus given by

$$\begin{aligned} y_1 &= x_1 - f_1(x_2, x_3, x_4) \\ y_2 &= x_2 - f_2(y_1, x_3, x_4) \\ y_3 &= x_3 - f_3(y_1, y_2, x_4) \\ y_4 &= x_4 - f_4(y_1, y_2, y_3) \end{aligned} \qquad (1)$$

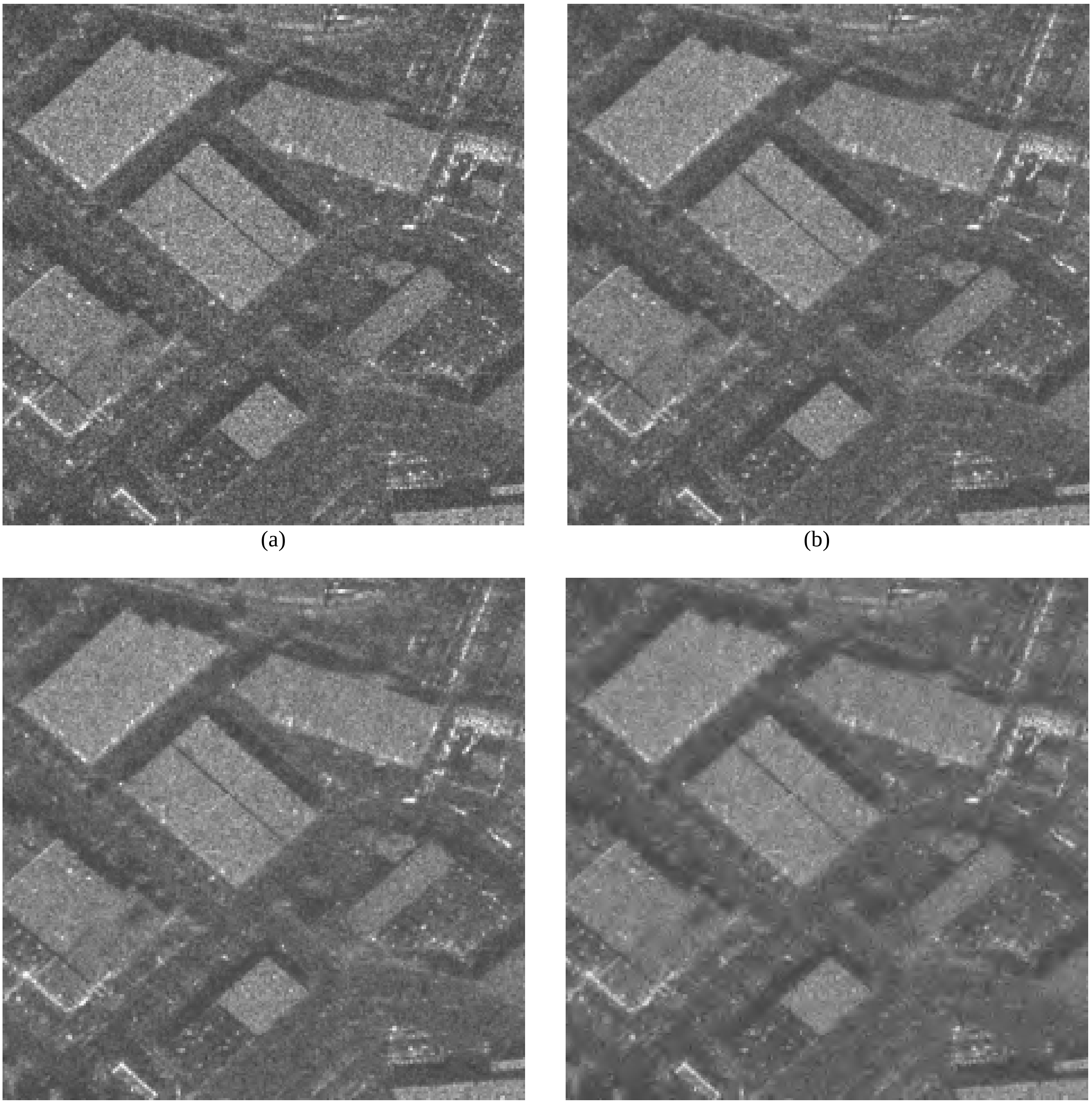
where the operation f_i can be either linear or nonlinear. For the synthesis stage, it can be shown that each $x_i(n)$ can be perfectly reconstructed from the set of $y_i(n)$ by performing the inverse equations in reverse order.

In addition to the advantage of nonlinear operations, the filterbank structure of Figure 1 also provides a more representative local region of support than conventional structures. For example, Figure 2 shows a section of an image with a filter structure of size 7×7. To predict the centre pixel x_1, shown in black, all the points in the region of support can be used except other x_1 points; these are shown shaded grey. It is clear that with this filter structure 40 out of a possible 49 pixels are available to update or predict the centre pixel.

x_1	x_2	x_1	x_2	x_1	x_2	x_1	x_2	x_1
x_3	x_4	x_3	x_4	x_3	x_4	x_3	x_4	x_3
x_1	x_2	x_1	x_2	x_1	x_2	x_1	x_2	x_1
x_3	x_4	x_3	x_4	x_3	x_4	x_3	x_4	x_3
x_1	x_2	x_1	x_2	x_1	x_2	x_1	x_2	x_1
x_3	x_4	x_3	x_4	x_3	x_4	x_3	x_4	x_3
x_1	x_2	x_1	x_2	x_1	x_2	x_1	x_2	x_1
x_3	x_4	x_3	x_4	x_3	x_4	x_3	x_4	x_3
x_1	x_2	x_1	x_2	x_1	x_2	x_1	x_2	x_1

Figure 2: 7×7 region of support.

Nonlinear operations that can be used for each f_i range from straightforward median, min and max to more advanced adaptive methods. Furthermore, the shape and size of the region of support is flexible and could be cho-



(a) (b) (c) (d)

Figure 3: (a) original image at 8 bits per pixel (bpp), (b), (c) and (d) compressed to 1 bpp, 0.5 bpp and 0.2 bpp.

sen adaptively according to the local statistics. The ability to employ nonlinear methods, together with the well localised region of support results in a wavelet transform that separates image features from speckle noise at a range of scales.

3. EXPERIMENTAL RESULTS

Four scales of the nonlinear transform was applied to SAR image shown in Figure 3(a) and the result compressed to 1, 0.5 and 0.2 bits per pixel (bpp) using a modified Embedded Zerotree Wavelet (EZW) algorithm [9] with appropriately weighted subbands, see Figure 3(b), (c) and (d) respectively. These results were obtained by using a square 11×11 region of support, a median-type operator for the prediction stage and a pixel-wise update from the prediction. The results show a good subjective quality down to 0.5 bpp but at lower bitrates edge smearing and compression artefacts can be seen.

The PSNR against bpp is shown in Figure 4. For comparison the results for an optimal implementation of JPEG. The proposed nonlinear method performs better than JPEG for all bit rates, with an improvement ranging from 0.5dB at 2 bpp to 6dB 3 bpp. At lower bitrates the nonlinear M-band method still performs slightly better than JPEG but the difference is not so marked.

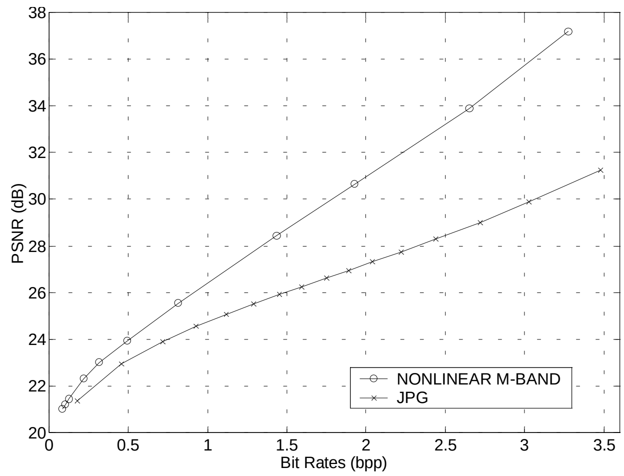


Figure 4: PSNR vs. bitrate for test image

4. CONCLUSIONS AND FURTHER WORK

A new 4-band nonlinear wavelet structure for SAR image compression has been presented. Experimental results show an improved performance in terms of PSNR compared with that of JPEG. Good subjective image quality has also been demonstrated.

The benefit of the outlined filter structure is its flexibility which permits other nonlinear filters and regions of support to be used in the prediction and updating stages. To further capitalise on these benefits an area of future work is to use an adaptive update of the low pass image to remove noise from the coefficients, producing a smoother low pass image or to enhance image features.

Furthermore, selectively targeting the noise in the high pass subbands can be used to reduce the overall image noise. This technique has been shown to improve the subjective and objective performance for other compression methods. As our filter structure can be used in a similar manner to conventional speckle filters, it has high potential for this type of noise reduction. One important issue that has been identified with this approach is that of the stability of the transform, especially at high compression ratios.

5. ACKNOWLEDGEMENTS

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