NONLINEAR WAVELET PROCESSING FOR ENHANCEMENT OF IMAGES

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Abstract

In this note we address some recent results on nonlinear wavelet processing. In particular we illustrate how the soft thresholding algorithm due to Donoho [2] can successfully be used to remove speckle in SAR imagery. Furthermore, more surprisingly we also show that transform coding artifacts, such as blocking in the JPEG algorithm, can be removed to achieve a perceptually improved image by post processing the decompressed image.

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1 Introduction

We consider the problem of noise reduction by nonlinear wavelet processing. In particular we focus on two applications of the recently developed theory related to wavelet (soft) thresholding [2]. The model for the problems we consider is as follows. Let $y = x + e$ be the observed image of the ideal image x corrupted by some noise e. Most observed images typically suffer from artifacts due to the process associated with formation/processing/compression. The objective is then to remove as much of the corruption as possible without destroying relevant information.

In particular we consider two examples. The first example illustrates how postprocessing with the wavelet thresholding algorithm is able to remove speckle from a synthetic aperture radar (SAR) image [5, 7]. In this case the noise can be modeled by a white Gaussian noise (WGN) process and hence according to the algorithm proposed by Donoho [2] is a perfect candidate problem. The second problem involves post-processing of low bit rate decompressed JPEG images [4]. In this case the noise is due to the blocking associated with the DCT. This noise is clearly not a WGN process. However, as we will see, applying wavelet thresholding still results in a perceptually superior image without introducing unwanted image artifacts.

2 Denoising Algorithm

If the error e is Gaussian and uncorrelated (both spatially and with x), then finding x from y is a classical statistical estimation problem. Since the procedure $\hat{x}(y)$ should work for a variety of images $x \in X$ the goal is to solve

$$\inf_{\hat{x}} \sup_{x \in X} \|\hat{x}(y) - x\| . \tag{1}$$

This classical problem has solutions which are asymptotically near optimal (simultaneously) for a wide variety of classes X [2]. The procedure $\hat{x}(y)$ is based on soft-thresholding in the wavelet domain where the threshold depends on the variance of e. Let W and W^{-1} denote the wavelet and inverse wavelet transform operators respectively. Then the nonlinear wavelet procedure is given by

$$\hat{x}(y) = W^{-1} T_\delta(Wy) \tag{2}$$

and

$$T_\delta(s) = \mathrm{sgn}(s)(|s| - \delta)_+, \tag{3}$$

where $(x)_+$ takes the value x for positive x and zero otherwise. The threshold δ is obtained through an estimation from the observed image y.

Two important qualitative features of the method are: (i) the reconstruction is noise-free in the sense that no spurious oscillations are introduced (other than in the data y) and (ii) relatively sharp features in y are maintained.

3 Speckle Removal in SAR images

Speckle can be found in SAR, acoustic imagery such as sonar and laser range data. When an object is illuminated by a coherent source and the object has a surface structure that is roughly on the order of a wavelength of the incident radiation, the wave reflected from such a surface consists of contributions from many independent scattering points. Interference of these dephased but coherent waves result in the granular pattern known as *speckle*. Thus speckle tends to obscure image details and hence speckle reduction is important in most detection and recognition systems. It can be shown and simply verified by measurement that the WGN model is a good approximation for speckle [3].

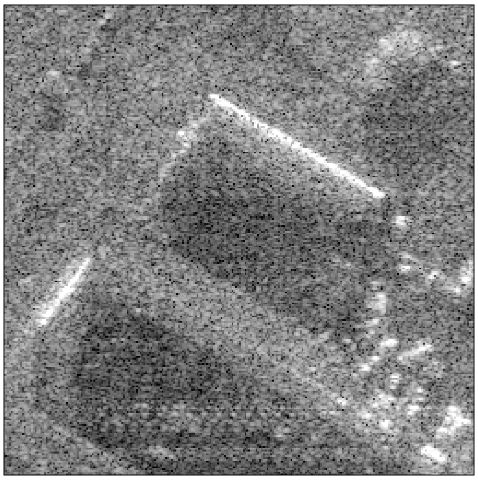
The goal is to minimize the effects of speckle when the observed image y is a digitized SAR image. There are several algorithms for removing speckle in SAR images [1, 6]. However, no single method has been found that does a good job of removing speckle without a significant loss of image resolution.

A classic measure of speckle is the standard-deviation-to-mean (s/m) ratio [3, 1] and log standard deviation [6]. Table 1 shows those two values for original and processed images for two typical regions. In Fig. 1 we have plotted the original and the processed version of a SAR image

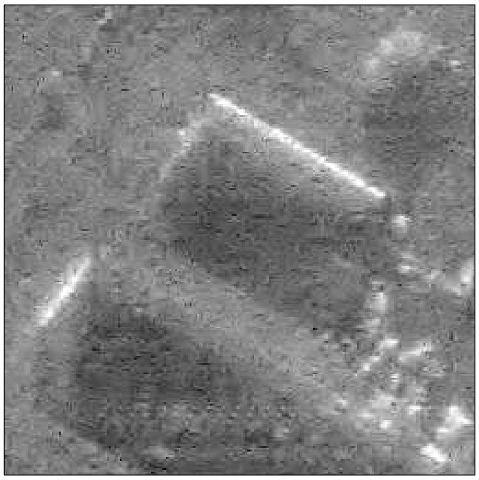
Table 1: Standard deviation to mean (std/m) and log standard deviation (log-std) for SAR HH clutter data. The table givs a comparison between original unprocessed HH SAR image and the wavelet despeckled HH SAR image.

	std/m		log-std (dB)	
	Original	Wavelet despeckled	Original	Wavelet despeckled
Trees	1.7639	0.8995	6.8750	3.6006
Grass	1.2061	0.3933	5.8213	1.6358

scene (HH horizontal-horizontal polarization). We can see from the image that speckle is greatly reduced while sharp features are kept.



(a)

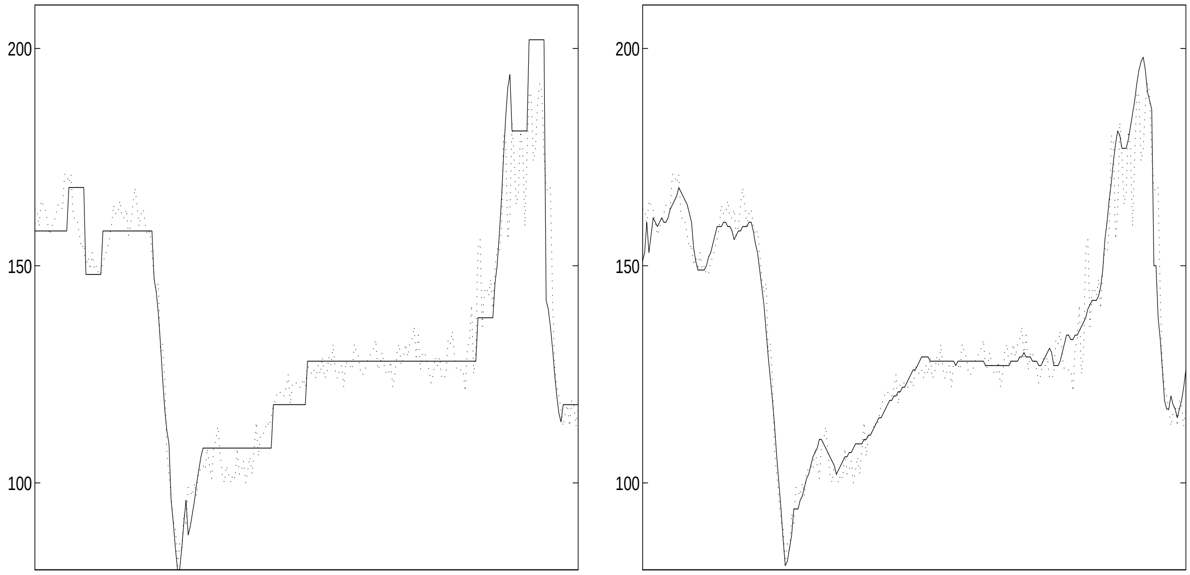


(b)

Figure 1: (a) Unprocessed SAR image (HH) of farm-supply store in Stockbridge, New York. (b) Wavelet despeckled SAR image using Daubechie's wavelets. The SAR image illustrates both natural clutter and man-made clutter discrete. The SAR image data was obtained from the Lincoln Lab clutter package 1 (M90P5F1-127).

4 Post-Processing of Decompressed JPEG Images

For this problem it is evident that e is correlated both spatially and with x, hence the stochastic assumptions on e are not valid. However, the method can be applied since the undesirable blocking artifacts can be removed while still exploiting property (ii) (see Section 2) of the algorithm. To see why, consider one of the rows of the image Lenna (see Fig. 2). In Fig. 2a we compare the original image data with the JPEG decompressed image with the characteristic blocking artifact. In Fig. 2b we have plotted the corresponding data obtained from the "denoised" image together with the original image data. Here we clearly see that while the original image features are preserved the image discontinuities due to the DCT blocking are removed. Notice that appropriate thresholding



(a) (b)

Figure 2: Threshold smoothing of step discontinuities. In both figures the dotted line represent the original image intensity. (a) solid line – a plot of image intensities for the decompressed JPEG image (b) solid line – a plot of image intensities for the post processed decompressed JPEG image.

removes jump discontinuities associated with blocking while yet maintaining the structure of the original signal. This intuition suggests that soft-thresholding can be used to enhance JPEG (or DCT) coded images. Our investigation supports this intuition both from a perceptual and mean-squared error point of view. Moreover, the method seems more promising than methods in the literature on enhancing JPEG compressed images [8, 9]. Besides, the method in [9] suggests using a novel decoder, while the method suggested in this paper can use a conventional decoder for which VLSI chips are available.

(a) (b)

Figure 3: (a) Decompressed Image (b) Postprocessed Image

5 Summary

In this note we have illustrated how the recently developed theory of (soft) thresholding might be used as a tool for noise removal in images. The first examples considered (speckle removal from SAR) was particularly suited for the given algorithm since speckle can be modeled as a AWGN process. However, the second example (postprocessing of decompressed JPEG images) did not satisfy the required noise model and yet it resulted in images perceptually superior to the original JPEG decompressed images at very low bit rates.

For the JPEG standard our work is of considerable significance since with computationally efficient non-linear processing (the complexity is $O(N)$ and hence faster than the Fast Fourier Transform which is $N\log(N)$) one can improve the visual quality of images and reduce the mean-squared reconstruction error. For wavelet subband coding too this might give rise to improved performance. In this context, even small performance improvements may justify soft-thresholding, since the wavelet transform is already available.

The authors are currently investigating algorithms that combine the advantages of the described wavelet denoising algorithm and the polarimetric whitening filter (PWF) for optimal speckle removal in SAR images. We are also pursuing a more robust approach to choosing the threshold for noise removal in JPEG images (robust with respect to compression ratios and a large collection of images).

Acknowledgments

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