AFRL-SR-AR-TR-04-

0440

REPORT DOCUMENTATION PAGE

1. REPORT DATE 01-09-2002	**2. REPORT TYPE** Final Report	**3. DATES COVERED** from 1 June 01 to 31 Dec 03

4. TITLE AND SUBTITLE

Multiscale statistical models for signal and image processing

5a. CONTRACT NUMBER

5b. GRANT NUMBER F49620-01-1-0378

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Richard G. Baraniuk

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Rice University
6100 Main Street
Houston, TX 77005

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Sponsored Research (AFOSR)
Jon Sjogren
801 North Randolph Street
Room 732
Arlington VA 22203-1977

10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We are developing a general theory for multiscale signal and image modeling, processing, and analysis that i matched to singularity-rich data, such as transients and images with edges. Using a linguistic analogy, our model can be interpreted as *grammars* that constrain the wavelet *vocabulary*. Our investigation focuses on probabilisti graph models (tree-based hidden Markov models) that can accurately, realistically, and efficiently represer singularity structure in the wavelet domain. Grammar design is being guided by a detailed study of the fin structure of singularities using Besov spaces and multifractal analysis.

20040810 022

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

8-4-04

BEST AVAILABLE COPY

AFOSR Grant # F49620-01-1-0378

Final Report
June 2004

Multiscale Statistical Models for Signal and Image Processing

Richard Baraniuk
Rice University

Department of Electrical & Computer Engineering
6100 Main Street
Houston, TX 77005

Tel: 713-348-5132
Email: richb@rice.edu
Web: dsp.rice.edu

1. Objectives

This project developed a new set of tools for multiscale signal and image modeling, processing, and analysis that are matched to singularity-rich data, such as transients and images with edges. Using a linguistic analogy, our models can be interpreted as *grammars* that constrain the wavelet *vocabulary*. Our investigation focused on probabilistic graph models (tree-based hidden Markov models) that accurately, realistically, and efficiently represent singularity structure in the wavelet domain. Grammar design was guided by a detailed study of the fine structure of singularities using Besov spaces and multifractal analysis.

2. Research Findings

Complex wavelet vocabulary

Signal and image processing algorithms based on the fully decimated wavelet transform suffer from *shift-variance*, reducing their power considerably. Shift variance dilutes the power of any model for the wavelet coefficients because the model must tolerate the strong changes in wavelet coefficient structure as the signal is shifted. Hence, we developed models for the *complex wavelet transform* (CWT). The dual-tree CWT analyzes a signal or image in terms of two wavelets that are close to a Hilbert transform pair (90 degrees out of phase, like a cosine and sine). The complex magnitude of the CWT is very nearly shift-invariant and in 2-d also features improved angular resolution (six oriented subbands at multiples of 15 degrees over the standard wavelet transform's three).

We extended our wavelet hidden Markov tree (HMT) modeling framework to the magnitude of the CWT. The complex HMT model is computationally efficient (with linear-time computation and processing algorithms) and applicable to general Bayesian inference problems as a prior density for images. (See the Figures at the end of this report.)

Modeling both the magnitude and phase of the complex wavelet transform enables us to perform *coherent processing* in the wavelet domain analogous to coherent processing in the Fourier domain. Our experiments indicate that large gains in denoising, classification, and compression performance should result.

Edge geometry modeling

The magnitude and phase of the complex wavelet transform have natural interpretations in terms of image edges. Given an edge passing through a complex wavelet's support, the magnitudes of the six complex wavelet coefficients at that scale and position can be interpolated to accurately indicate the *angle* of the edge. The *phase* of the largest magnitude coefficient indicates the edge's offset from center. This relationship has allowed us to build Markov models to describe the evolution of image edges in a multiscale fashion. (See the Figures at the end of this report.)

Orthogonal complex wavelets

The dual-tree CWT analyzes in terms of a tight frame of redundancy 2 in 1-d and 4 in 2-d. For maximum efficiency, it is reasonable to ask whether it is possible to construct useful complex wavelets with no redundancy. By "useful" we mean complex wavelets whose coefficients have easily modeled structure. Working in a 3-band (rather than the classical 2-band) filterbank structure, we have developed a new non-redundant CWT whose coefficients reflect the attractive properties of the redundant 2-band CWT.

3. Accomplishments

Complex HMT denoising

We successfully applied the complex wavelet HMT model in two relevant problems. In estimation ("*denoising*"), the complex wavelet HMT model outperformed all known wavelet denoising algorithms, including redundant wavelet thresholding (cycle spinning). A multiscale maximum likelihood *texture classification algorithm* produces fewer errors with the new model than with a traditional real wavelet HMT. (See the Figures at the end of this report.)

Edge geometry compression

We developed a prototype *image compression algorithm* based on this framework that encodes the image geometry description and the residual texture information jointly in a rate/distortion optimal fashion. The algorithm outperforms the new JPEG2000 by a fairly significant margin (up to 1-2dB in PSNR for "edgy" images). Indeed, we have proved that for a simple class of "piecewise smooth" cartoon images consisting of smooth (C^2) regions delineated by smooth (C^2) edges, that this algorithms is *near-optimal in a rate/distortion sense*. That is, the mean-squared error D of image approximation decays with the number of bits R as $D(R) \sim C\ (N/\log N)^{-2}$.

Finally, since the compressed bit stream contains explicit geometry information regarding edges, it could prove very useful for efficient image classification and data base searching. This new framework demands further investigation. (See the Figures at the end of this report.)

Both of these innovations have been transferred to Texas Instruments for possible incorporation into next-generation wavelet-based image processing systems.

4. Personnel Supported

Richard Baraniuk (PI)
Hyeokho Choi (senior researcher; equivalent to postdoc)
Justin Romberg (graduate student)

In addition NSF Graduate Fellow Michael Wakin contributed significantly to this effort at no charge to the grant.

5. Technical Publications

All papers are available at the Rice DSP web site at *dsp.rice.edu/publications*

5.1 Journal Publications

M. Wakin, J. K. Romberg, H. Choi, and R. G. Baraniuk, "Wavelet-domain Approximation and Compression of Piecewise Smooth Images," submitted to IEEE Transactions on Signal Processing, 2004.

H. Choi and R. G. Baraniuk, "Multiple Wavelet Basis Image Denoising using Besov Ball Projections," to appear in IEEE Signal Processing Letters, 2004.

R. V. Gaikwad and R. G. Baraniuk, "Optimal Signaling Strategies for Communication in the Presence of Cross-talk," IEEE Transactions on Communications, July 2004.

R. Neelamani, H. Choi, and R. G. Baraniuk, "ForWaRD: Fourier-Wavelet Regularized Deconvolution for Ill-Conditioned Systems," IEEE Transactions on Signal Processing, 2003.

R. L. Claypoole, G. Davis, W. Sweldens, and R. G. Baraniuk, "Adaptive Wavelet Transforms for Image Coding using Lifting," IEEE Transactions on Image Processing, December 2003.

R. G. Baraniuk, R. A. DeVore, G. Kyriazis, and X. M. Yu, "Near Best Tree Approximation," Advances in Computational Mathematics, vol. 16, pp. 357–373, 2002.

T. D. Dorney, W. W. Symes, R. G. Baraniuk, D. M. Mittleman, "Terhertz Multistatic Reflection Imaging," Journal of the Optical Society of America, Vol. 19, No. 7, July 2002.

5.2 Reviewed Conference Proceedings

M. Wakin, J. Romberg, H. Choi, and R. G. Baraniuk, "Image Compression using a Cartoon+Texture Image Model," *Digital Compression Conference*, Snowbird, Utah, 2002.

M. Wakin, J. Romberg, H. Choi, and R. G. Baraniuk, "Rate-Distortion Optimized Image Compression using Wedgelets," *IEEE ICIP* 2002.

M. Wakin, J. Romberg, and R. G. Baraniuk, "Multiscale Wedgelet Image Analysis: Fast Decompositions and Modeling," *IEEE ICIP* 2002.

35 more – see *dsp.rice.edu/publications* and *dsp.rice.edu/~richb/bio.html*

6. Interactions / Transitions

6.1 Conference Presentations

See above Conference Proceedings.

6.2 Transitions

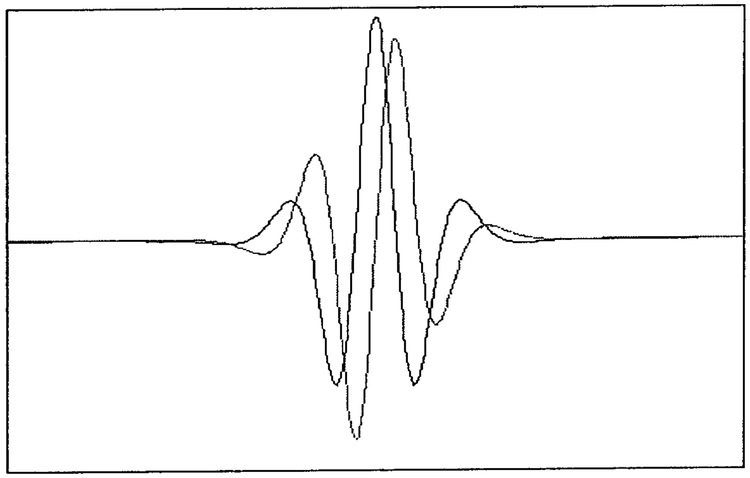
Transitioned complex wavelet algorithms to Texas Instruments (Dr. Felix Fernandes, felixf@ti.com) and to Raytheon (Dr. Harry Schmidt). We also have posted software for many of these new algorithms on our web site at dsp.rice.edu/software

7. Patent Disclosures

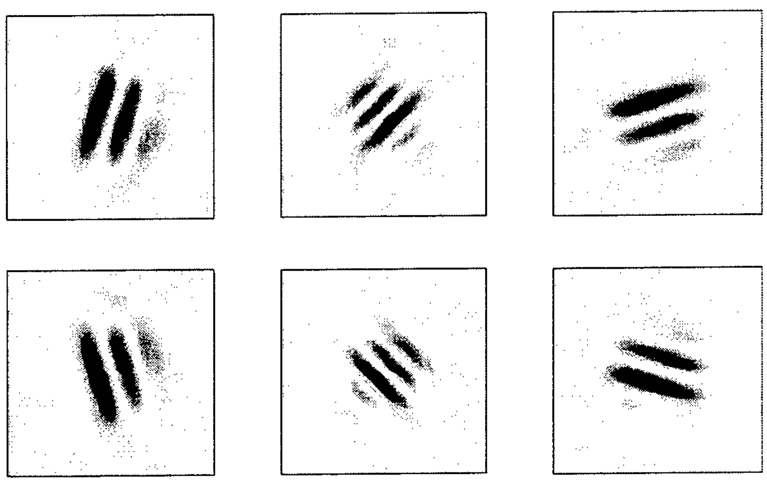
None.

8. Honors

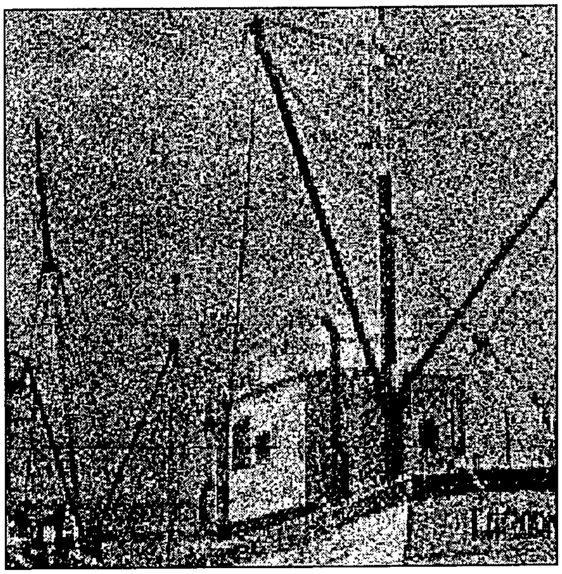
- Elected Fellow of the IEEE
- Co-Author on *Passive and Active Network Measurement Workshop* Student Paper Award
- Co-Author on *IEEE Signal Processing Society* Junior Paper Award (with M. S. Crouse and R. D. Nowak)
- *IEEE NORSIG* Best Paper Award (with E. Monsen, J. Odegard, H. Choi, J. Romberg), 2001
- George R. Brown Award for Superior Teaching (Rice, twice)
- ECE Young Alumni Achievement Award (University of Illinois)
- Charles Duncan Junior Faculty Achievement Award (Rice)



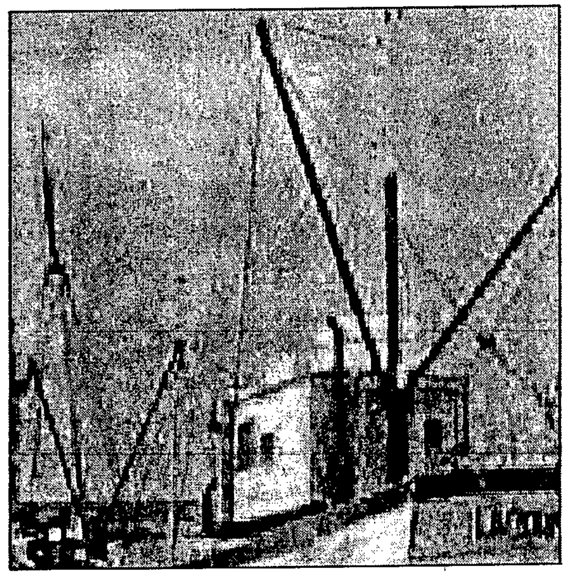
1-d complex biorthogonal wavelet, with even-symmetric real part (blue) and odd-symmetric imaginary part (red).



2-d complex wavelets analyze at 6 different orientations, all multiples of 15 degrees noisy, 20.2 dB

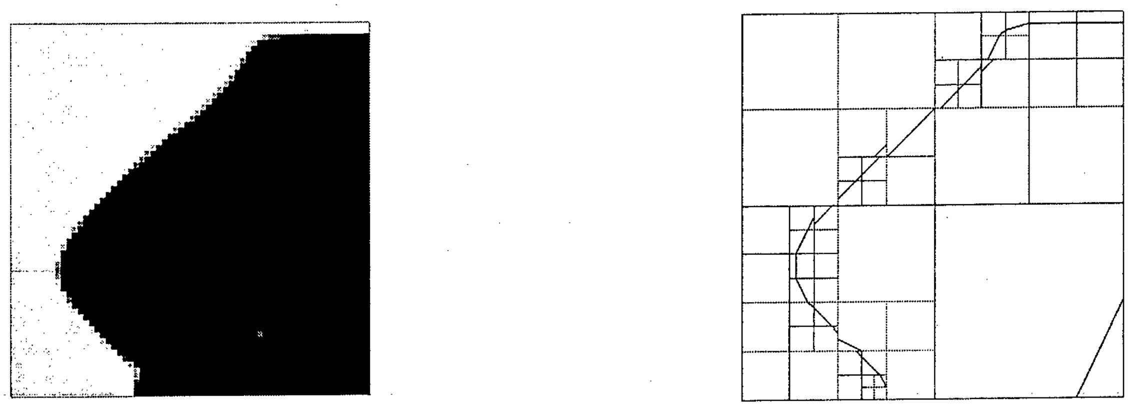


HMT, 28.6 dB

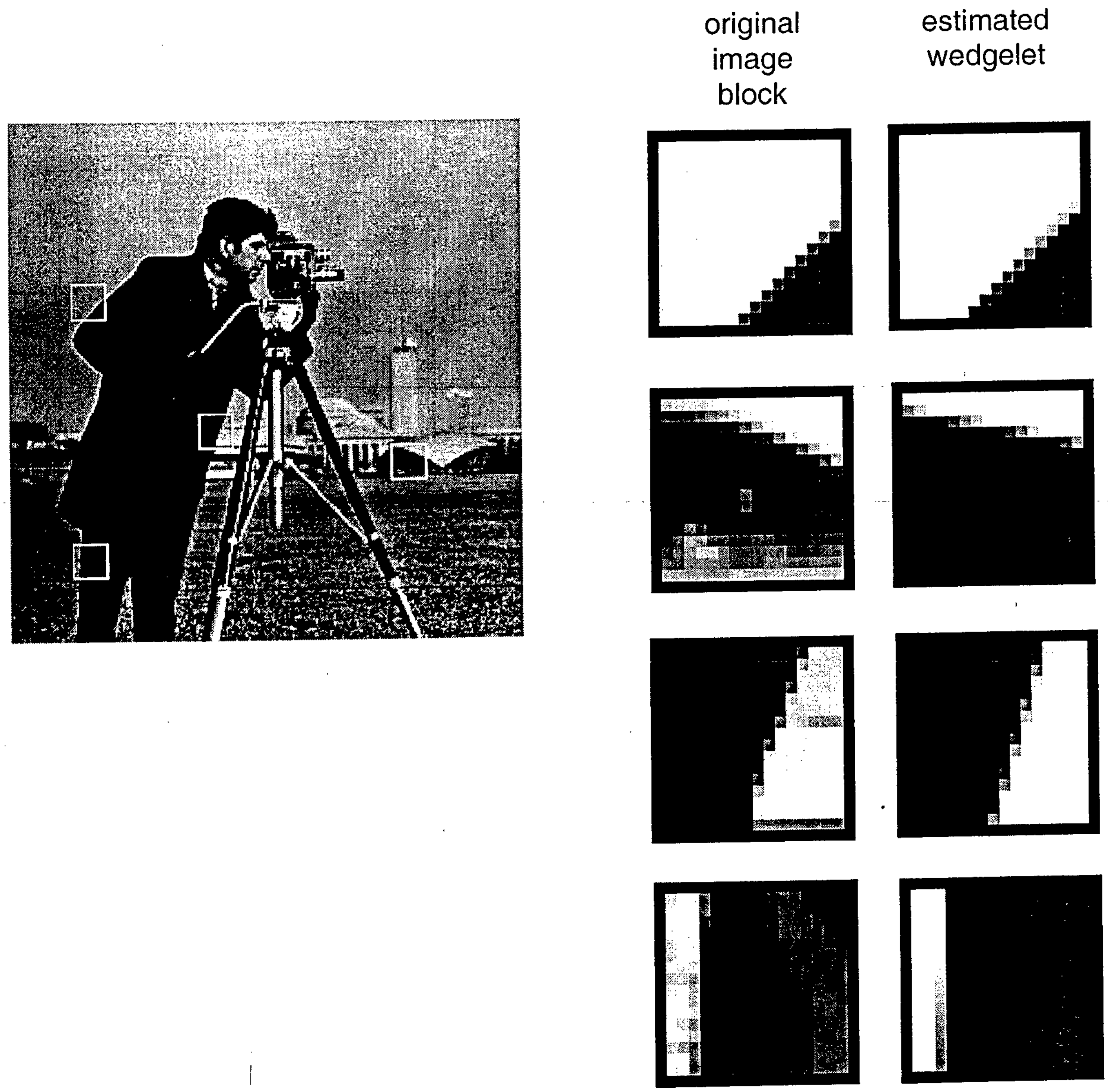


CHMT, 29.3 dB

Our complex wavelet HMT denoising algorithm outperforms all other wavelet denoising algorithms in the literature (figures are PSNR). Note especially the clean edges and ridges in the complex wavelet HMT (CHMT) estimate.



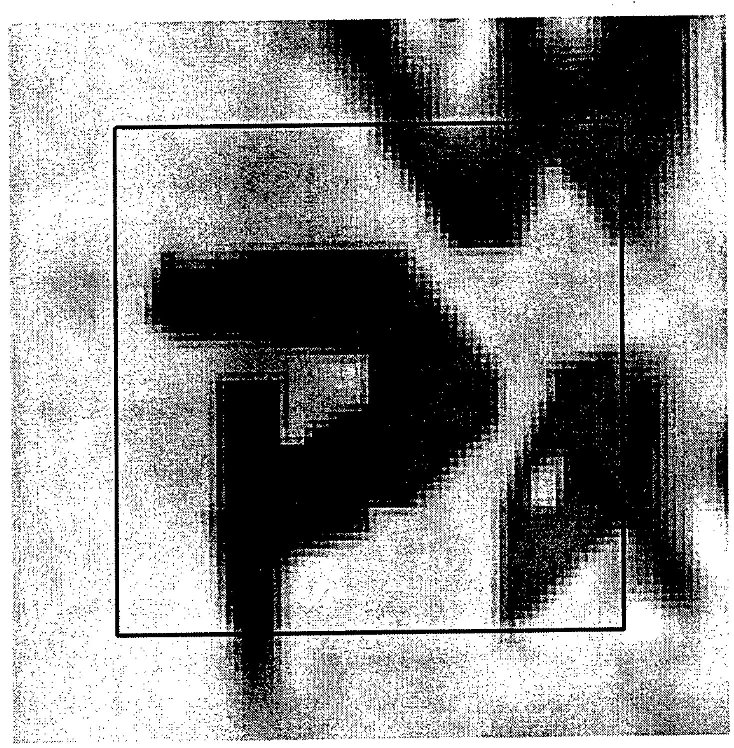
Our multiscale edge geometry model builds up smooth image edges from straight line segments (a la Donoho's wedgelets). A multiscale Markov model on the segments enables a fast dynamic program on the wedgelet quad-tree to find the optical balance between the sparsity of the representation (a few large edge segments) and accuracy (requiring many small segments). Due to the Markov probability model, this method significantly outperforms Donoho's CART-based representation.



The CWT enables accurate and efficient algorithms for identifying edges and estimating their parameters. In this example, four square blocks from the image on the left have been analyzed in terms of their CWT coefficients. Using the CWT magnitudes to estimate the edge orientations and the phases to estimate the offsets, we approximate these blocks by piecewise constant wedgelets at right.

state-of-the-art
SFQ
wavelet image
coder
(zoom)

new
WSFQ
wavelet/wedgelet
image coder
(zoom)



Comparison of state-of-the-art SFQ wavelet-based image coder versus the new WSFQ coder based on wavelets and wedglets (zoom).