Rice Consortium for Computational Seismic Interpretation

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1 Executive Summary

1.1 Overview

This proposal details a multi-year, multi-sponsor University-Industry research initiative on the application of advanced signal analysis and processing techniques to problems in oil and gas exploration and production. One of the striking features of seismic signals is their highly non-stationary character — a property that is poorly dealt with by current analysis and processing tools. The central theme of the *Rice Consortium on Computational Seismic Interpretation* is the application of *time-frequency representations* and *wavelet transforms* to seismic and well-log signal analysis, interpretation, and processing. The initiative leverages 30+ years of leadership in signal processing research at Rice University towards two primary objectives: (1) systematic development of advanced time-frequency-based seismic attributes for enhanced feature extraction from multi-dimensional seismic data, and (2) application of wavelet-based signal processing tools to key problems in seismic and well-log data preprocessing. Technology transfer to the industrial sponsors will be achieved through software libraries (Seismic UNIX modules and Matlab code), interactive research meetings, focused collaborative work sessions, and technical reports, preprints and publications.

1.2 Motivation and Significance

Seismic imagery of the earth's subsurface is critical to all aspects of the oil and gas exploration and production process — from the location of fields to their appraisal, development, and subsequent monitoring. In exploration, seismic images of the earth's subsurface are scrutinized by interpreters who search for patterns correlated to possible hydrocarbon reservoirs. Recently, 3D imaging technology has become a standard exploration tool, particularly in mature hydrocarbon provinces like the Gulf of Mexico and the North Sea. The seismic interpretation process has changed radically as a result. While previously interpreters dealt with large plots of 2D cross-sections of the earth, they now work on computers with 3D volumes comprising Gbytes of data. There exists a great need for advanced tools for sifting through these mountains of data for features indicative of hydrocarbons.

One of the most striking features of seismic and well-log signals is their *highly non-stationary character.* This non-stationarity confounds traditional data analysis and processing tools, such as time-invariant filtering and Fourier transform techniques. As a result, these tools offer less than optimal performance. Clearly, non-stationary signals dictate matched, non-stationary analysis and processing techniques.

The central theme of this research effort is the application of *time-frequency representations* and *wavelet transforms* to seismic data analysis, interpretation, and processing. Time-frequency and wavelet representations measure local (in time and/or space) changes in frequency and scale content of a signal. Representations like the wavelet transform, the short-time Fourier transform, and the Wigner distribution figure prominently in a host of different application areas, including data compression; image coding and analysis; communications; speech and acoustic signal processing; and modeling and understanding of the human hearing and vision systems.

Time-frequency and wavelet representations map signals to a time-frequency/scale domain that acts like a generalized (time-varying) Fourier domain. Thus, in addition to analyzing seismic data, time-frequency/scale representations have natural applications in data processing. The time-frequency signal representation in terms of transient wavelets rather than long duration plane waves will enable high-performance *non-stationary signal and image processing* for detection, classification, compression, denoising, deconvolution, etc.

Seismic attributes aid the quantitative interpretation of seismic data by extracting information on the nature of its non-stationarity. The increased quality and resolution of seismic data, allows the deployment of quantitative signal analysis and feature extraction algorithms. Robust and automated seismic attribute extraction is becoming increasingly important for information extraction. Many of the currently used attributes lack the robustness and geological/physical significance to live up to this task. We will develop new seismic attributes based on a set of sophisticated high resolution time-frequency analysis tools developed over the past number of years at Rice.

1.3 Objectives

Our multidisciplinary approach to computational seismic interpretation and processing is unique in that it builds a bridge between advanced digital signal processing techniques and their application in geophysics. Our primary objectives are twofold:

Advanced time-frequency representations for seismic data: Using the time-frequency paradigm, we will derive novel attributes particularly suited for extracting features and highlighting anomalies in modern 3D and 4D seismic data sets. Measures to be investigated include volume attributes (dip, azimuth, continuity, correlation) and event-based attributes (extracted along or perpendicular to the prevailing dip).

We will develop improved variants of the classical complex trace attributes (such as instantaneous frequency, bandwidth, Q-factor, etc.) based on a suite of powerful new time-frequency representations developed at Rice. The high performance of these representations will naturally lead to attributes that are more accurate, indicative, robust, and rapid to compute than their classical counterparts.

Wavelet-based seismic data processing: We do not propose to simply apply existing wavelet processing techniques to seismic and well-log data, but rather to develop fundamentally new seismic processing algorithms based on wavelets. We will develop wavelet systems that are tailor-made for seismic processing tasks, in the sense that they are designed to take the specific properties of seismic and well-log signals into account.

In the near term, we aim to leverage 30+ years of signal processing experience at Rice (including 8 years of time-frequency and wavelet analysis experience) into seismic interpretation and processing. In the long term, we will expand our effort to address the challenges associated with analysis and processing of 3D, 4D and 4C seismic data. In particular, we will concentrate on fast and robust algorithms for dealing with the huge data volumes involved.

A detailed description of our promising preliminary results, research objectives, and plans are included in Appendices A–C.

1.4 Impact

Expensive to acquire and often impossible to reacquire, seismic and well data is perhaps the most important asset of any oil company. Effective hydrocarbon exploration and production depends heavily on signal processing algorithms to extract the maximum possible amount of information from each data set. However, current tools for information extraction do not match the fundamental non-stationary character of seismic data, and information extraction performance suffers as a result. High resolution time-frequency representations provide a natural domain for analyzing and processing non-stationary seismic data. Our new seismic attributes have the potential to revolutionize seismic data interpretation, enabling human seismic interpreters to search effectively and efficiently through mountains of data for the critical non-stationarities that indicate potential hydrocarbons. Furthermore, non-stationary processing techniques will provide geophysicists with new opportunities for improving on traditional seismic signal preprocessing algorithms.

It could be said that up to the present wavelets and time-frequency methods have not delivered as promised and have, to a large degree, been a disappointment in geophysics applications. While a huge body of advanced time-frequency research has been developed in the signal processing community, the link with geophysics has not been made directly. Only an interdisciplinary team made up of both signal processing and geophysics researchers in collaboration with industry can realize the true potential of time-frequency methods in geophysics. Here at Rice we have assembled the core of such an interdisciplinary team; in conjunction with industry we can indeed deliver revolutionizing interpretation tools using advanced signal processing.

1.5 Consortium Fee

The proposed annual fee is $25,000. The consortium will become active when five sponsors have committed themselves, with a target start date of January 1, 1998. After an initial period of two years, new sponsors joining the consortium or sponsors not actively participating in the preceding program year will be asked to pay an initiation fee to join the consortium. In the initial phase of the consortium, personnel supported by other research funds will play an active role. Graduate fellowships will be identified explicitly as industrially-sponsored; this will be a significant factor in attracting good students to our interdisciplinary team.

2 Management Plan

The core research staff of the consortium will consist of Dr. Jan E. Odegard, Dr. Philippe Steeghs, Prof. Richard G. Baraniuk, Prof. C. Sidney Burrus, and Prof. Raymond O. Wells, Jr. (see curricula vitae in the Appendices). We plan to add one or two full-time postdoctoral research scientists, a number of graduate students, as well as a part-time administrative assistant. Additional faculty members might be invited to join the consortium based on interests and future research activities. Funding obtained for the project will be used to leverage additional research funding from government agencies and the University. Current federal and industrial research funding related to the proposed project will also be leveraged towards the consortium by the participating faculty members.

1. **Project Director:** In collaboration with faculty members, research staff, and consortium members, develop the overall scientific research objectives and maintain the overall administrative and budgetary activities of the project. Supervise and approve plans for annual meetings and maintain communication with industry collaborators and sponsors. Develop new interactions and generate additional and complementary funding through leveraging of consortium funds.

2. **Faculty:** Work with the Director in developing the scientific objectives and goals of the research program. Advise graduate and undergraduate students and work extensively with graduate students who are well into their thesis research; suggest and approve topics for thesis research. Supervise and help plan annual meetings. Collaborate with industrial partners and develop new research directions. Develop an interdisciplinary introductory graduate course/seminar on material related to the research effort as well as maintain other teaching and professional duties.

3. **Postdoctoral Research Scientists:** Carry out independent focused collaborative work supporting the over-arching goals of the research program. Interact with individual company researchers on a regular basis for effective technology transfer and research objective tuning. Manage weekly research seminars and assist in directing graduate and undergraduate students on various projects and research activities. Plan and arrange annual review meeting as well as organize intermittent research meetings as needed. Report and document research results; develop and document pilot code to be shared with the participating companies. Ideally, we expect each research scientist to remain with the project for a minimum of two years.

4. **Graduate Students:** Perform research and complete basic requirements for the Ph.D. degree in their respective departments. Take appropriate advanced course work in signal processing, spectrum estimation, wavelet theory, geophysics, and applied mathematics to strengthen theoretical skills and develop understanding of the physics underlying the research effort.

5. **Undergraduate Students:** A number of undergraduate students will be involved in the project through summer employment and honors class projects.

6. **Administrative Assistant:** Serve as a contact for routine business with sponsors, funding agencies, and the University. Maintain records; arrange travel; schedule research meetings; coordinate the logistics of annual review meetings; maintain publication database, bibliography, and consortium web pages. Assist the Director, faculty and research scientists in budgetary and editorial responsibilities.

3 Technology Transfer

The consortium will implement several parallel mechanisms for transferring research results to the individual members. We will exploit the internet to the fullest by providing a secure, members-only web interface for the consortium. Through this internet connection we will provide pre-publication technical reports, software and miscellaneous information of importance to the consortium members. Furthermore, the consortium will host an annual meeting at Rice University for joint discussions, technology presentations, and demonstrations. The goals of the annual meeting will be twofold:

1. formally report on the past year's research activities
2. provide a common forum for open discussions and company input.

While the internet link will be central in facilitating technology transfer the primary method for transferring research results will be through the development of software and library modules (C, C++, Java, and Matlab). The consortium will use seismic UNIX as the platform for developing seismic processing modules. Core processing modules will be provided as independent library modules written in C and/or C++. For the purpose of rapid research development, testing and prototyping of new ideas, the MATLAB programming environment will be used extensively by the consortium. Our focus on writing portable software modules in C and/or C++ will expedite technology transfer by eliminating the necessity for each participating company to code algorithms from scratch for basic prototyping and testing in-house.

In addition to software, technology transfer will also be facilitated through publications, technical reports, education, and close collaboration with researchers from the participating companies.

To enhance the value of the material provided at the annual meeting the annual report, appropriate technology demonstrations, technical reports and publications as well as software developed by and for the consortium will be provided on a CD-ROM. The CD-ROM will be organized as web pages and will permit the individual member companies to enhance the consortium exposure by publishing the CD-ROM as web pages on their intranets.

The consortium and its research faculty and staff will also offer individual companies and/or groups of companies one-on-one tutorials and workshops that draw on the experience gained from the consortium research. While these types of extensive educational efforts will be individually arranged and negotiated, they will be at reduced cost and more in-depth. Seminars and lectures can be arranged with individuals at the expense of the company and any standard honorary fee will be waived for consortium members. While the educational aspects of the consortium are optional, they will be extremely efficient for technology transfer. Tutorials, workshops, and lectures can be used to educate a larger group within the company about the technology developed by the consortium. The in-house knowledge acquired through these educational efforts can then be applied to research problems outside the scope of the consortium.

Active participation and industrial input and collaboration will ensure a focused research consortium. In addition to the annual meeting, less formal interactions will take place throughout the year as appropriate. A number of open seminars will be given and/or hosted by the project team on relevant technologies in an effort to enhance interest and foster interactions with industry.

In addition to the technical contributions, the consortium will have a significant impact on the education and training of scientists and engineers at Rice University. The consortium will allow the group to train a larger number of graduate students as well as attract highly qualified postdocs and visiting research faculty.

Undergraduate students will be pulled in and the consortium will be an integral part in their training for a future career in the booming energy industry. In fact, the promising preliminary results of [70] were developed in the course of a senior honors project.

Since we began working with oil companies two years ago, Rice faculty incorporated examples from geophysics into their signal processing course materials. As a result, students graduating with a strong background in signal processing have had an increased desire in pursue a career in the oil and oil-service industry.

Finally, the Department of Electrical Engineering at Rice has recently launched a summer intership program for undergraduate and graduate students. As a member of the consortium, your company will an automatic member of this program, greatly enhancing your recruiting abilities as well as further improving technology transfer.

4 Institutional Commitment and Support

Eighty-five years ago, Rice's founding president, Edgar Odell Lovett, assembled a remarkable community of scholars dedicated to excellence in education and research [10]. Today, Rice is recognized as a top-ranked undergraduate college and a premier research university. Rice's modest size (approximately 450 faculty, 2700 undergraduates, and 1400 graduate students) has not prevented it from becoming a top 20 University. In remaining true to its founding principles, Rice has leveraged its size to foster a strong and growing collaborative environment for both education and research. In this way, faculty in small departments have worked together to integrate individual expertise and talents into multidisciplinary teams to address complex challenges in research areas of national importance.

Through the leadership of President Malcolm Gillis and Provost David Auston, several bold initiatives are underway that are reflected in strategic faculty hiring and major new buildings to house research in computational and information engineering, nanoscale science, biosciences and bioengineering, and public policy. Rice has also embarked on a bold program to apply information technologies in imaginative approaches to teaching and learning.

Rice organizes its research through both its academic departments and a group of strategic institutes. The institutes provide the opportunity for collaborative research efforts, graduate student training, enhance undergraduate programs, and industrial partnering across disciplines, departments and schools. Today, Rice's research institutes include:

CITI Computer and Information Technology Institute

CRPC Center for Research on Parallel Computation

EESI Environmental and Energy Science Institute

CNST Center for Research in Nanoscale Science and Technology

RQI Rice Quantum Institute

IBB Institute for Biosciences and Bioengineering

BIPP Baker Institute for Public Policy.

The *Computer and Information Technology Institute* (CITI) is a research institution composed of faculty, research scientists, staff, and graduate students dedicated to the advancement of applied interdisciplinary research in the areas of computer and information technology. CITI's goal is to support, foster, and develop research and education across a wide area of computing technologies, computational engineering, and information processing and theory. Faculty, research scientists, staff and students associated with CITI are primarily from the departments of Electrical and Computer Engineering, Computational and Applied Mathematics, Computer Science, and Statistics, although Mathematics, Biochemistry and Cell Biology, Chemical Engineering, Physics, Geophysics, Chemistry, Space Physics, and Mechanical and Civil Engineering are also represented. Over eighty Ph.D. faculty and research scientists and over 120 graduate students are affiliated with CITI.

Founded in 1987, CITI has grown to achieve an annual research funding level of approximately $8 million. In addition, CITI sponsors several major centers and laboratories, including the Center for Research in Parallel Computation (CRPC), the Rice Inversion Project (TRIP), the Center for Technology in Teaching and Learning (CTTL), the Center for Computational Discrete Optimization (CCDO), the Center for Multimedia Communications (CMC), the Computational Mathematics Laboratory (CML), the Distributed Computing Laboratory (DCL), and the Statistics Consulting Lab (SCL). It is Rice's intention to have CITI act as an interdisciplinary catalyst to foster research projects across the campus.

Rice University has established a reputation as a high-quality engineering educational and research institution. However, Rice is a small university and does not attempt to address all engineering research areas or disciplines. Likewise, CITI does not attempt to address all aspects of information technology and computational engineering; it primary areas of research are:

- digital signal and image processing
- seismic data processing and analysis

- data modeling and analysis
- parallel computation
- distributing computing
- telecommunications (including wireless)
- optimization (discrete, continuous and multidisciplinary design)
- technologies in education (including collaborative environments)

Consistent with Rice's philosophy to invest heavily in the Institutes and the Centers, this consortium draws heavily on strengths created through interdisciplinary collaboration.

5 Computational Resources

Our current computer infrastructure consists of a mixture of Sun workstations and mid-range compute servers running Solaris. Through various internal efforts the group is today using as the main compute server a 250MHz, 4 processor Sun Ultra Enterprise 3000 with 1Gb of RAM and 24Gb disk space. In addition to the dedicated resources, the consortium team has regular access to a 250MHz, 8 processor Sun Ultra Enterprise 4000 server with 1Gb of RAM and 9Gb disk space.

In addition to the Sun server/workstation precesses, the core members participating in the proposed consortium were recently awarded, as part of a 3-year $2 million Intel grant to Rice University, a large number of Intel based compute servers and NT development stations. The Intel equipment will provide the consortium and its members an opportunity to port and benchmark seismic processing modules developed by the team. Traditional supercomputers have, until very recently, dominated the market for computation- and I/O-intensive applications. These applications are beginning to migrate to clusters, currently largely dominated by Unix platforms. Similarly, the high-end visualization area has been dominated primarily by Silicon Graphics equipment. The Intel offers Rice and our consortium the opportunity to work with industry and Intel to break new ground.

In addition to the local resources, the group, through various collaborations, has access to researchers exploring a number of different computing platforms and paradigms. Rice has been at the forefront of parallel computing for many years, most notably through the Center for Research in Parallel Computation (CRPC), a Science and Technology Center funded by the National Science Foundation. Furthermore, we have been among the first advocates of clusters of commodity workstations for parallel computing, leading on early results in fault tolerance and computational support tools for clusters. Through these various efforts, we have presently on campus a number of such clusters, including a HIPPI network of 4 Silicon Graphics 4-way SMPs (funded by NSF), a Memory Channel network of 4 DEC Alpha 4-way SMPs (funded by DEC and Rice), an 8 node IBM RS/6000 SP2 (funded by NASA in conjunction with Boeing), and a number of lower-end networks, including two PC networks, one running Linux and one running WindowsNT. Furthermore, we also have on campus a 16-node Convex SPP-2000, and through our involvement with the

NCSA Partnership for Advanced Computational Infrastructure (PACI), we have access to a very large Silicon Graphics Origin 2000 and a larger Convex SPP-2000 at NCSA. In short, we have access to the entire gamma of parallel computing equipment, from the low end to the very high end.

Rice have a strong track record of successful collaboration between computer scientists and researchers in the scientific and engineering disciplines using high performance computing in respective research areas. Examples include: The Rice Inversion Project (TRIP), in its sixth year of support from the petrochemical and geophysical industry; the Keck Center for Computational Discrete Optimization; and the Distributed Computing Lab, which supports a variety of clustered computational projects involving Chemistry, Nanotechnology, and Biosciences, and Bioengineering.

6 Financial Plan

The fee of participating in the consortium is $25,000/year (subject to future revisions) with a start date of January 1, 1998. A minimum of 5 companies will be required to start the consortium. After an initial period of two years, new sponsors joining the consortium or sponsors not actively participating in the preceding program year will be asked to pay an initiation fee of 50% of the current annual fee to join the consortium.

During the open enrollment period, individual research interactions will be pursued aggressively and developed prior to a commitment from 5 companies. However, such interactions will be formed with the expressed understanding that when 5 or more companies have signed on to participate in the research effort, the outlined consortium agreement , its infrastructure and associated goals will become the primary vehicle for collaboration.

Funding will be devoted to the support of the research goals set forth by the project as outlined in this proposal in close collaboration with representatives from the participating companies. Such support includes salary, fringe benefits, equipment, travel, indirect costs, and other expenses related to the overall goals of the project.

In the initial phase of the consortium, personnel supported by other research funds will play an active role. Graduate fellowships will be identified explicitly as industrially-sponsored; this will be a significant factor in attracting good students to our interdisciplinary team.

7 Terms of Sponsorship

An agreement for joining the Rice Consortium for Computational Seismic Interpretation is enclosed.

APPENDICES: PROPOSED RESEARCH

A Time-Frequency, Time-Scale, and Wavelet Representations

The sinusoidal decomposition of the Fourier transform plays a fundamental role in a broad range of disciplines, including geophysics. Given a time/space signal $x(t)$,[1] the Fourier transform

$$\widehat{x}(f) \;=\; \int x(t)\, e^{-i2\pi f t}\, dt, \tag{1}$$

performs an analysis in terms of infinite-length sinusoids. In Figure 1(b) we plot the power spectrum $|\widehat{x}(f)|^2$ of the seismic trace of Figure 1(a).

The power spectrum provides information on the distribution of global cyclicities in the signal $x(t)$. In particular, it measures the average energy content of the signal at sinusoidal frequency f. However, the power spectrum provides no explicit information on the *time variation* of cyclicities. (This information is hidden in the phase of $\widehat{x}(f)$). In any application involving transients or time-varying signals — geophysics included — this timing information is crucial for effective signal analysis and processing.

The fundamental theme of this research effort is the representation of seismic data in terms of joint time and frequency coordinates. The resulting *time-frequency representations* (TFRs) [17, 51] play the role of *local power spectra* that measure how the frequency content of a signal changes over time.[2] A TFR of the signal, $P_x(t, f)$, measures the content of x around time t and frequency f, and so can be interpreted as a mathematical generalization of the musical score. As we see in Figure 1(c), TFRs elicit and display the fine structures that result from nonstationarity in signals. Thus, the joint time-frequency domain provides a new domain for seismic signal analysis and processing.

While the Fourier power spectrum of a signal is unique, there are an infinite number of different TFRs for analyzing time-varying frequency content. The key is picking the right tool for the job at hand. Here we give a brief outline of the key concepts and representations. More information is available in the papers [5, 4, 17, 51, 79] and on the Rice signal processing internet site located at www.dsp.rice.edu.

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[1] For clarity of explanation, we will base our development in terms of one-dimensional time signals. However, the time-frequency concept generalizes in a straightforward manner to multi-dimensional spatial signals (images).

[2] Time-frequency techniques are not new to geophysics. In fact, many of the early developments in this area were made by geophysics researchers (see [64, 42], for example). However, this project builds on new TFRs that have not yet been applied to seismic data.

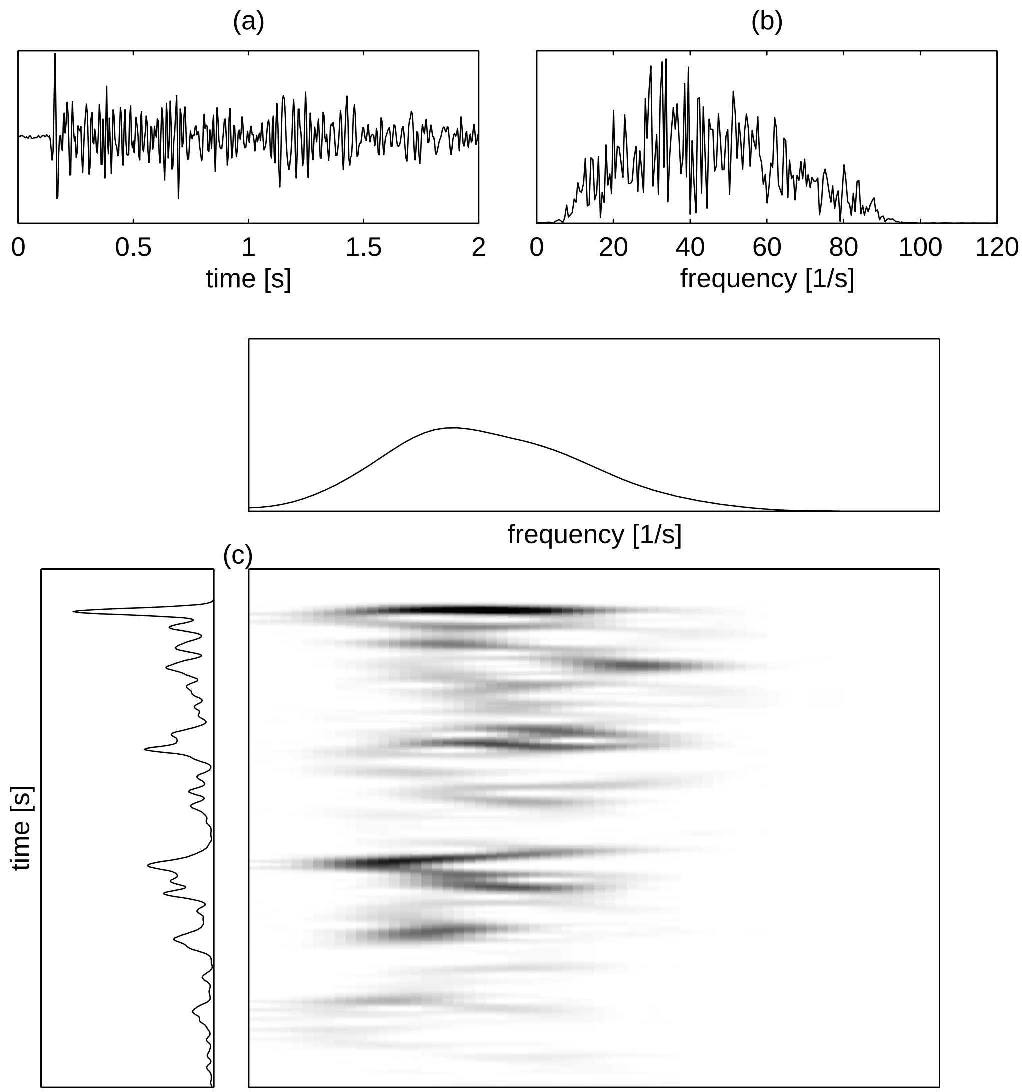


Figure 1: *Time-frequency representations (TFRs) of a seismic time trace (a). The Fourier power spectrum (b) provides only global frequency information. The short-time Fourier transform (c) localizes frequency information in time.*

A.1 Time-frequency representations

Short-time Fourier transform. The simplest way to measure the local frequency content of a signal is to compute the Fourier transform of a windowed portion of the signal. The result is the windowed Fourier transform or short-time Fourier transform

$$S_x(t,f) \;=\; \int x(\tau)\, w^*(\tau - t)\, e^{-i2\pi f\tau}\, d\tau, \tag{2}$$

with w the sliding window function. The squared magnitude $|S_x(t,f)|^2$ is known as the spectrogram. The short-time Fourier transform can also be interpreted in terms of projecting the signal onto a set of overcomplete basis elements. Defining

$$\theta_{t,f}(\tau) \;=\; w(\tau - t)\, e^{i2\pi f\tau}, \qquad t, f \in \mathbb{R}, \tag{3}$$

we have

$$S_x(t,f) \;=\; \langle x, \theta_{t,f} \rangle\,, \tag{4}$$

with the inner product $\langle g, h\rangle \;=\; \int g(\tau)\, h^*(\tau)\, d\tau$. The *time-frequency atoms* $\theta_{t,f}$ are formed by translating and modulating the window function and thus are concentrated at different points in time-frequency. Contrast this situation to that of the Fourier transform, which projects onto the frequency-localized but infinite-length sinusoidal basis elements $e^{i2\pi f\tau}$.

The time-frequency representation of the short-time Fourier transform is sensitive to the length of the window function w. Figure 2(a) and (b) depict short-time Fourier transforms of the seismic trace using windows of two different lengths to illustrate the fundamental time-frequency resolution tradeoff of this TFR: Short windows provide good time resolution at the expense of frequency resolution, while long windows provide good frequency resolution at the expense of time resolution.

Wigner distribution. Since the "best" short-time window will depend on the signal under analysis, a short-time Fourier transform "matched" to the signal should provide a more accurate rendering of the time-frequency content. The Wigner distribution — a rescaled short-time Fourier transform using the time-reversed signal as window — in fact provides an optimal time-frequency resolution tradeoff. The Wigner distribution is a quadratic function of the signal

$$W_x(t,f) \;=\; \int x\Big(t + \frac{\tau}{2}\Big)\, x^*\Big(t - \frac{\tau}{2}\Big)\, e^{-i2\pi f\tau}\, d\tau. \tag{5}$$

It satisfies the marginal properties

$$\int W_x(t,f)\, df = |x(t)|^2, \qquad \int W_x(t,f)\, dt = |\widehat{x}(t)|^2 \tag{6}$$

that make it interpretable as a time-frequency energy density.

The excellent time-frequency localization properties of the Wigner distribution result from its quadratic matched filter structure. Unfortunately, this nonlinear structure also results in oscillatory

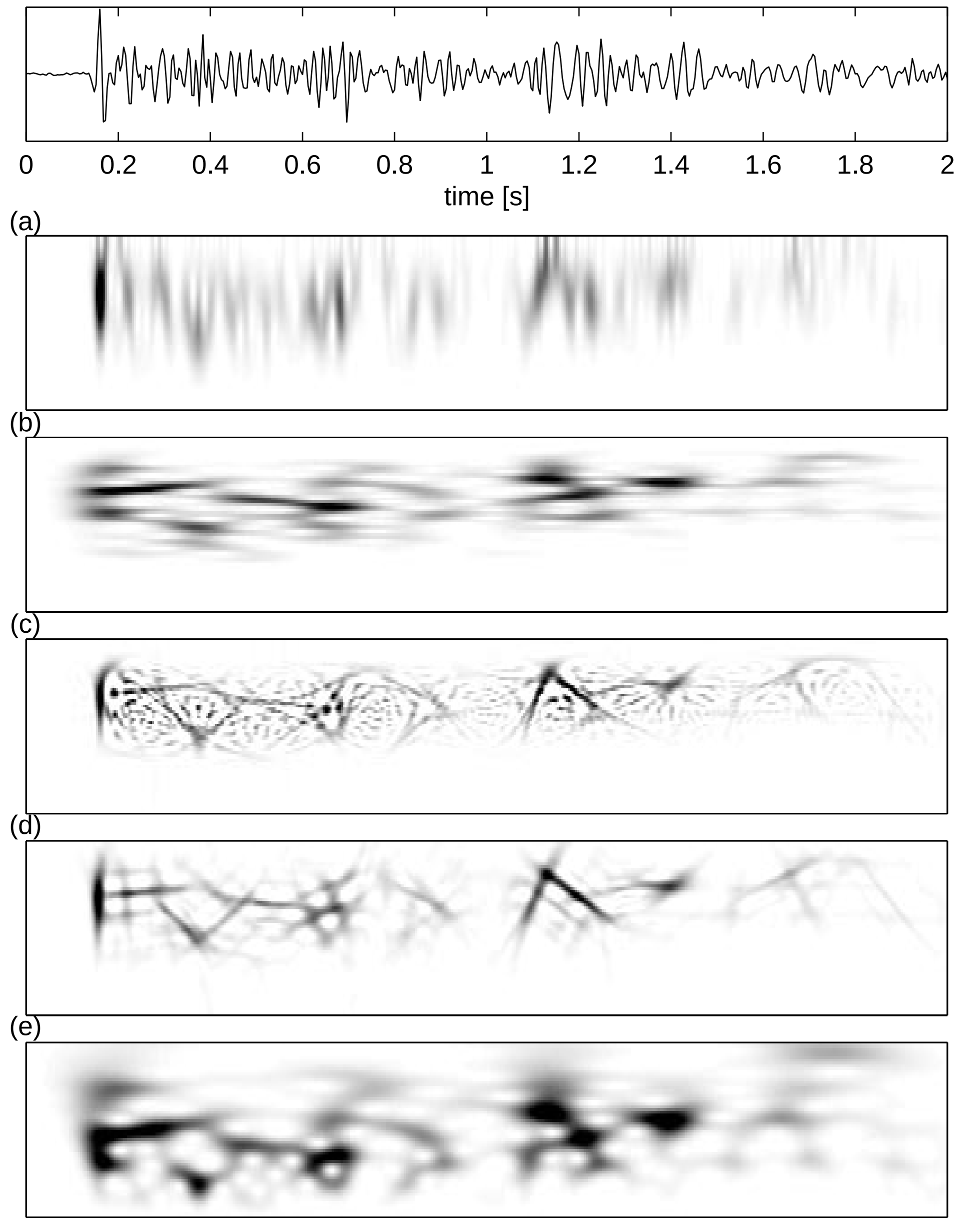


Figure 2: *Time-frequency representations of a seismic trace. (a) Spectrogram (short window), (b) spectrogram (long window), (c) pseudo Wigner distribution, (d) optimum kernel time-frequency representation, and (e) scalogram (Morlet wavelet).*

interference components, which impair its representation of real-world, multi-component signals (see Figure 2(c)).

Cohen's class TFRs. Typically, Wigner distribution interference components are suppressed via lowpass smoothing over the time-frequency plane. Two-dimensional convolution yields a distribution in Cohen's class of quadratic TFRs [17]

$$C_x(t,f) \;=\; \iint W_x(u,v)\,\Pi(u-t,v-f)\,du\,dv. \tag{7}$$

The smoothing function Π is called the *kernel* of the TFR. Since the properties of a particular quadratic TFR are completely determined by its kernel function, operation within Cohen's class reduces TFR design to kernel design [17, 5, 4]. Examples of Cohen's class TFRs are the Choi-Williams [14] and cone-kernel [99] distributions. The spectrogram is obtained using $\Pi = W_w$.

Optimal-kernel TFRs. Traditionally, Cohen's class TFRs have employed fixed kernels. However, specification of a fixed kernel limits the class of signals for which the corresponding TFR performs well — much like specification of a fixed window limits the performance of the short-time Fourier transform.

At Rice, we have developed a number of powerful *adaptive TFRs* that adjust the TFR kernel to optimally suppress the Wigner distribution interference components while preserving its time-frequency localization [5, 6, 4, 55, 54]. These TFRs employ performance measures based on concentration, peakiness, and entropy that relate closely to those in deconvolution [97, 25]. The optimal 1/0 kernel TFR [5, 6] and the optimal radially Gaussian kernel method [4] choose one kernel for the entire signal. The adaptive optimal kernel (AOK) TFR [55], on-line optimal TFR [54], and on-line optimal 1/0 kernel TFR [79] allow the kernel to change over time to better match complex signal structure. In Figure 1(d) we plot the adaptive optimal kernel TFR of [79] for the seismic trace. Optimal-kernel TFRs represent the current state of the art of high-resolution time-frequency analysis.

A.2 Time-scale representations

The TFRs of Cohen's class are *time-frequency shift covariant*. That is, time shifts and frequency shifts of the signal simply translate the TFR:

$$\begin{array}{ccc} x(t) & \longrightarrow & x(t-t_0)\,e^{-i2\pi f_0 t} \\ \downarrow & & \downarrow \\ C_x(t,f) & \longrightarrow & C_x(t-t_0,f-f_0). \end{array}$$

Time-scale representations (TSRs) are joint signal representations that are *time-scale covariant*. Time shifts and scale changes of the signal translate and scale a TSR $\Omega_x(t,f)$ [9, 77]:

$$\begin{array}{ccc} x(t) & \longrightarrow & \frac{1}{\sqrt{\alpha}}\,x\left(\frac{t-t_0}{\alpha}\right) \\ \downarrow & & \downarrow \\ \Omega_x(t,f) & \longrightarrow & \Omega_x\left(\frac{t-t_0}{\alpha},\alpha f\right). \end{array}$$

Like a TFR, a TSR measures the joint time-frequency content in a signal. We use the terminology TSR/TFR merely to differentiate between time-scale covariance and time-frequency shift covariance.

Continuous wavelet transform. The continuous wavelet transform results from projecting the signal onto the set of overcomplete basis elements

$$\psi_{t,f}(\tau) \;=\; \sqrt{f}\,\psi(f(\tau-t)), \qquad t,f \in \mathbb{R}, \tag{8}$$

formed by translating and scaling a basic bandpass wavelet function ψ (with center frequency 1Hz):

$$Q_x(t,f) \;=\; \langle x, \psi_{t,f}\rangle \;=\; \sqrt{f}\int x(\tau)\,\psi^*\left(f(\tau-t)\right)\,d\tau. \tag{9}$$

Unlike the short-time Fourier transform, the resolution of the continuous wavelet transform changes with frequency: at low analysis frequencies f the transform offers good frequency resolution at the expense of poor time resolution, while at high frequencies f the transform offers good time resolution at the expense of poor frequency resolution. The squared magnitude $|Q_x(t,f)|^2$ is referred to as the scalogram. Figure 2(e) (above) depicts the time-scale analysis of the scalogram.

Affine class TSRs. In order to more effectively time-scale analyze signals, quadratic "matched" wavelet transforms have been developed. The affine Wigner distributions [9, 35, 36] generalize the Wigner distribution, but marginalize to the Fourier transform and the Mellin transform, an important tool for dealing with compressed and dilated signals. Being quadratic, the affine Wigner distributions suffer from interference components. However, these can be suppressed using a wideband, proportional-bandwidth smoothing (an affine convolution [77, 35, 36]).

A.3 Discrete TFRs and TSRs: Frames and Bases

The short-time Fourier transform and continuous wavelet transform have discrete analogues, in which we discretize the values t and f that determine the time-frequency locations of the basis atoms used in (3) and (8). For TFRs, we use $(t,f) = (nt_0, mf_0)$; for TSRs, we use $(t,f) = (2^m nt_0, 2^{-m} f_0)$, $m,n \in \mathbb{Z}$. The resulting atoms can be made to form a *frame* (basically, a well behaved basis set) for almost arbitrary choices of the window or wavelet function [20, 76]. To form an orthonormal basis using time-frequency or time-scale atoms requires special windows/wavelets [20]. Discrete TFR/TSRs can be implemented using filter banks in $O(N)$ complexity for TSRs (wavelets) and $O(N \log N)$ for TFRs.

Discrete transforms have the advantage of speed and parsimony over their continuous counterparts. However, they typically have poorer time-frequency resolution and potentially aliased coefficients.

Additional approaches to TFRs include matching pursuit [63] and the hybrid linear/nonlinear distributions [76].

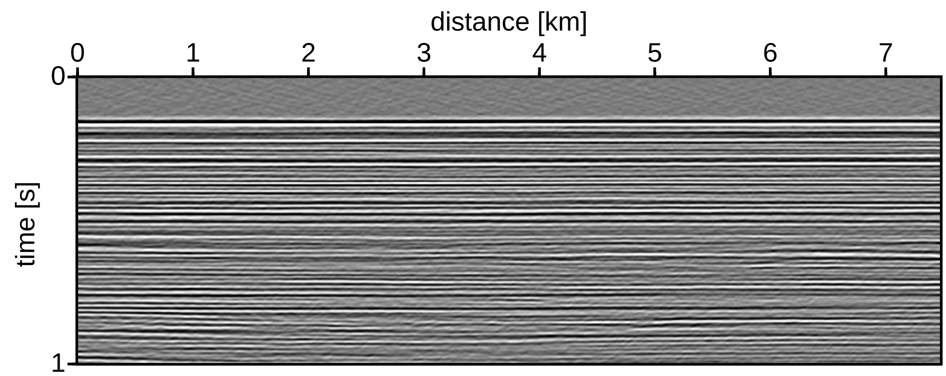
B Seismic signal analysis and attribute extraction

The demand for more detailed, but less time-consuming interpretation of seismic data calls for an increased effort to develop more effective methods for seismic attribute extraction and analysis. Seismic interpretation nowadays involves the inspection of a large number of cross-sections of 3D seismic data on a seismic interpretation work-station. There exists a great need for advanced tools for sifting through these mountains of data for features that are indicative of hydrocarbon reservoirs. For this, the application of coherence analysis [2, 33] and volume attribute analysis techniques [53] have proven successful. Recent results in [79, 88, 81, 82] show that with time-frequency techniques significant improvements can be achieved with respect to state-of-the-art attribute extraction techniques.

In addition to the issue of reducing seismic interpretation time, the decrease of the average size of new oil and gas fields demands a more detailed interpretation of small scale features in seismic data. Seismic attribute maps, such as horizon dip and azimuth maps have been very successful in finding and interpreting structures that are not easily recognized in the original data [19, 52, 56]. Seismic attribute extraction is not only a tool for seismic interpretation; it also plays a key role in the prediction of reservoir quality from seismic data as well. The correlation of seismic attributes with petrophysical properties that are measured in a borehole is used to guide the geostatistical prediction of reservoir properties away from the well location. Currently, there are literally hundreds of attributes in use in geostatistical applications [13]. It is rather remarkable that so few studies have been carried out in relation to the significance and quality of seismic attributes. Many geostatistical studies are based on complex-trace attributes, which have little geological significance and are highly susceptible to noise in the data. Heedless application of attributes in geostatistical reservoir prediction can result in grossly wrong estimates of reservoir properties [57].

Time-frequency representations (TFRs) such as wavelet transforms, short-time Fourier transforms and Wigner distributions all provide potential domains for extraction of more robust and meaningful signal attributes. The relation between TFRs and the instantaneous frequency has already been exploited to improve instantaneous frequency estimation of seismic data [79, 88]. For example, Figure 3 shows the instantaneous frequency that is obtained from an adaptively smoothed Wigner distribution. The figure shows how much better the instantaneous frequency estimate based on the time-frequency representation captures the detail that is hidden in the data compared tot the instantaneous frequency that is obtained by complex-trace analysis [84].

The time-frequency and the time-scale planes are extremely rich feature spaces for enhancing existing or developing new seismic attributes. The TFR of a signal allows the definition of attributes such as instantaneous bandwidth, dispersion, and attenuation (Q-factor). The scale space provides a new point of attack for developments in seismic attribute extraction. The parameters used to characterize frequency content have their equivalent in the scale domain. For instance, attributes, such as mean frequency or bandwidth, have their counterpart in mean scale and scale bandwidth. The analysis of seismic data in terms of scaling properties may contribute to issues that are related to measurement scale and resolution, such as seismic to well ties and matching surface seismic and VSP data. The continuous wavelet transform has been proposed in the past as a feature space for seismic attribute extraction. However, similarly to the short-time Fourier transform in the



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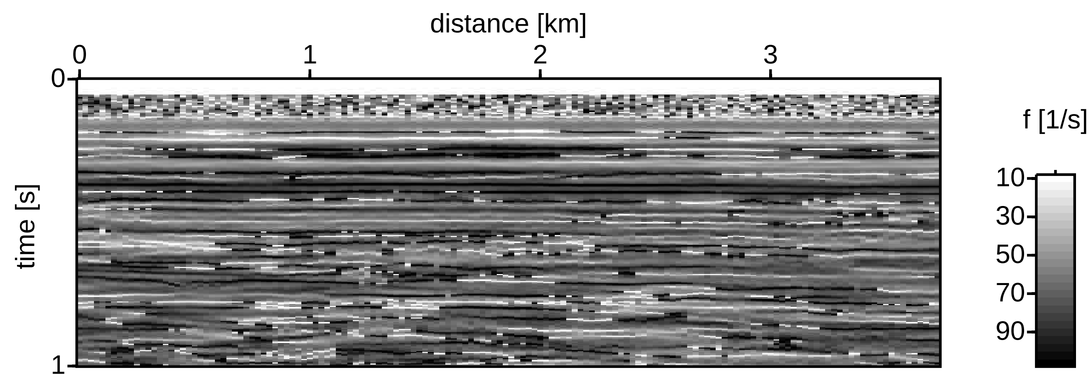

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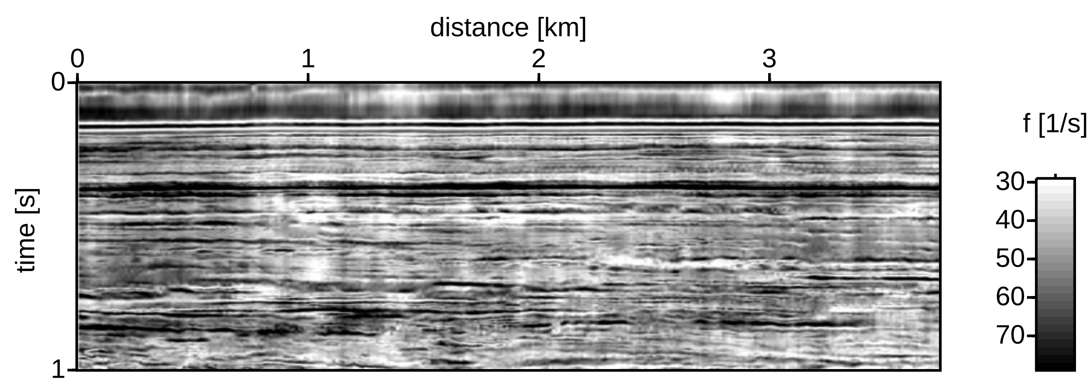


(c)

Figure 3: *(a) Seismic section, (b) complex-trace instantaneous frequency, and (c) instantaneous frequency obtained from an adaptively smoothed time-frequency representation (TFR) [88, 79]. For every trace of the seismic section, a TFR is computed. The instantaneous frequency is then extracted as the mean frequency of this TFR as a function of time.*

time-frequency case, the wavelet transform suffers from poor resolution. Recently, a number of novel high-resolution time-frequency and time-scale representations have been developed at Rice [35, 36]. The improved resolution of these representations will result in attributes that are more informative than those obtained using existing methods.

The extension of the time-frequency framework to higher-dimensional local frequency analysis has resulted in a method for volume attribute extraction from 3D seismic data [81]. Figure 4 illustrates a new *dip* measure applied to a 3D data set. The dip is extracted from a 3D local slant-stack power spectrum. It has already been shown that with local slant-stack good results can be obtained for dip and azimuth extraction [81]. However, in the local *angle-temporal frequency/scale* or *slowness-temporal frequency/scale* spectrum a number of other attributes can be devised. The local slant-stack enables the extraction of attributes along or perpendicular to the prevailing reflector dip. This reflector-based signal analysis will result in attributes with more geological significance than those in current use.

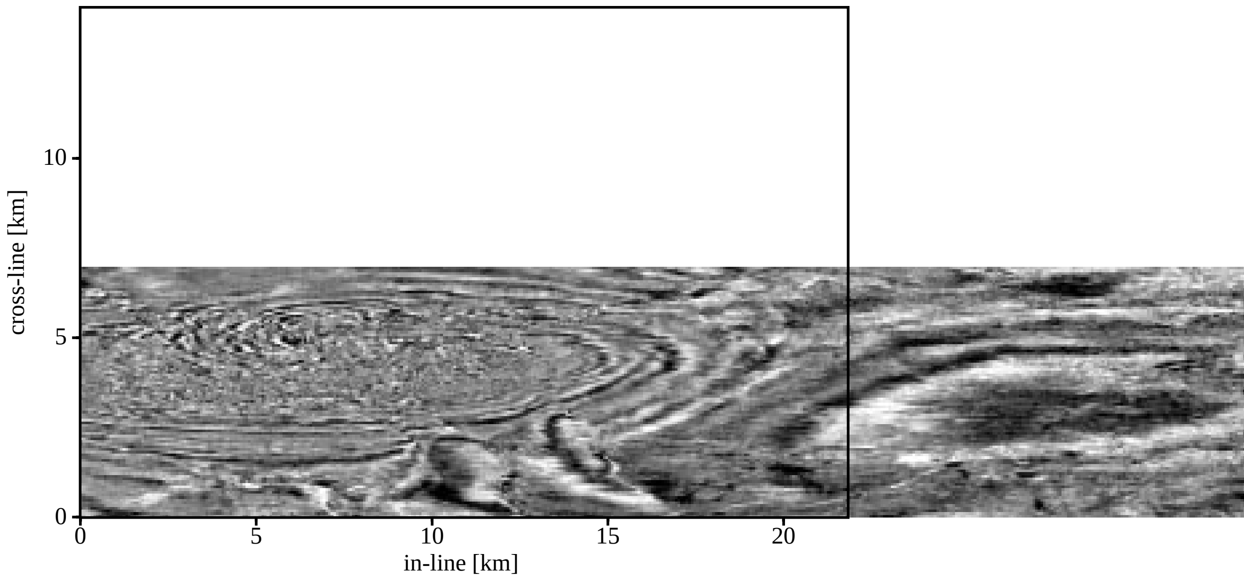
Local spectral analysis has the potential to become an extremely effective tool for automated pre-stack data analysis and feature extraction. The development of fast and robust algorithms will be critical for the success of transferring applications from the post-stack to the pre-stack domain. There exists a great need for signal analysis methods that can aid velocity model building for 3D pre-stack imaging, which is currently a very time consuming process. Automated velocity analysis based on high-resolution local slant stacks is currently under investigation. In addition, the local spectral analysis tools that have been developed at Rice are better able to cope than existing attribute extraction methods with the low signal-to-noise-ratios involved. As a result, pre-stack attribute extraction and processing should be feasible. A potential application of local spectral analysis methods in the pre-stack domain is robust estimation of offset dependent parameters as an extension of AVA/AVO analysis.

Recent developments in time-frequency and time-scale analysis have created exciting possibilities for improvements and new directions in quantitative seismic signal interpretation. We propose to conduct research in the following areas: time-frequency based attribute extraction, multi-dimensional local spectrum analysis, seismic sequence analysis and event characterization, pre-stack seismic attribute analysis, and scale analysis of seismic reflection data.

B.1 Time-frequency based attributes

Seismic attribute extraction based on TFRs has several advantages. Besides the fact that the TFR provides a theoretical foundation for attribute extraction, it is also advantageous to extract attributes in the time-frequency domain on practical grounds. Noise in the attribute section can be suppressed by either processing in the time-frequency domain or the use of signal adaptive kernels in the computation of the TFRs. TFR-based seismic attributes are considerably more robust than complex-trace attributes. In Figure 3 we showed how a signal adaptive kernel time-frequency representation result in a robust high-resolution instantaneous frequency measurement.

However, besides mean frequency there are a number of other parameters that characterize a signal. The time-frequency or time-scale representation of a seismic signal or a well log consists



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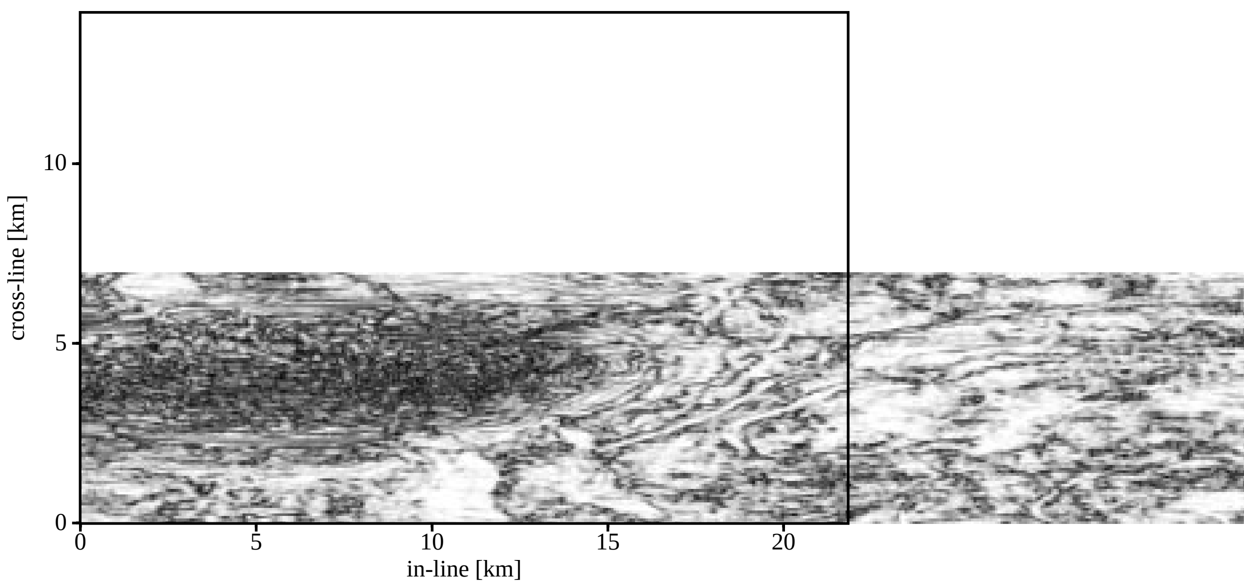


(b)

Figure 4: *Multi-dimensional seismic attributes. (a) Time slice image from a 3D seismic data set from the Gulf of Mexico. (b) "Local dip" slice obtained from a 3D local slant-stack of the seismic data [79, 81]. A salt dome (at left), several faults (extending radially from the salt dome), and several channels (to the right of the salt dome) are distinctly visible.*

of sets of ridges. The orientations and widths of these ridges are characteristic for the signal. Once computed, the TFR can be processed using edge detection and other image processing algorithms to extract ridge orientations and widths. In this respect, the *reassignment* method has provided very promising results [70]. Another fruitful approach is to regard the TFR as a two-dimensional statistical distribution. Hence, we can use higher order statistical moments, such as local bandwidths (proportional to $1/Q$), skewness and kurtosis to characterize seismic waveforms [79, 88].

- Aim: development of new seismic attributes based on TFRs.
- Short-term goals: implementation and further testing of new algorithms.
- Mid-term goals: development of robust and geological meaningful attributes.
- Status: a great number of algorithms are already available, including reassignment [70], ridge tracking and higher order attributes [79].

B.2 Multi-dimensional local spectrum analysis

Three-dimensional local slant stack analysis has already resulted in very high resolution 3D dip and azimuth attributes, as shown in Figure 4. The local slant stack is based on the extension of time-frequency analysis to multi-dimensional local wavenumber-frequency analysis. The slant stack in a three-dimensional geometry, where $\boldsymbol{x} = \{x_1, x_2, x_3\}$, is given by

$$\mathcal{R}\{u\} \;=\; \breve{u}(\boldsymbol{p}, \tau) = \int_{\boldsymbol{x}^3 \in \mathbb{R}^3} u(\boldsymbol{x}, \tau + p_i x_i) d\boldsymbol{x}, \tag{10}$$

where $\boldsymbol{p} = \{p_1, p_2, p_3\}$ is a 3D slowness vector and τ is the intercept time. The relation between the wavenumber vector $\boldsymbol{k} = \{k_1, k_2, k_3\}$, slowness vector $\boldsymbol{p}$,and temporal frequency f is given by

$$\boldsymbol{k} \;=\; f\boldsymbol{p}. \tag{11}$$

Hence, there is an intimate relation between the temporal Fourier transformation of the slant stack and the wavenumber-frequency spectrum $\tilde{u}(\boldsymbol{k}, f)$:

$$\tilde{u}(\boldsymbol{k}, f) \;=\; \tilde{u}(f\boldsymbol{p}, f) \;=\; \breve{u}(\boldsymbol{p}, f), \;\; f \geq 0. \tag{12}$$

With this relation in mind, a local slant stack power spectrum has been defined in [79], based on the multi-dimensional Wigner distribution $W(\boldsymbol{x}, t; \boldsymbol{k}, f)$. The local slowness-frequency power spectrum is obtained by interpolation of the local wavenumber-frequency representation on a (p, f) grid

$$S(\boldsymbol{x}, t; \boldsymbol{p}, f) \;=\; W(\boldsymbol{x}, t; f\boldsymbol{p}, f) \;=\; W(\boldsymbol{x}, t; \boldsymbol{k}, f). \tag{13}$$

The local slant stack is then obtained by an inverse Fourier transformation of (13) with respect to the frequency f

$$\breve{S}(\boldsymbol{x}, t; \boldsymbol{p}, \tau) \;=\; \int_{f \in \mathbb{R}} \exp(j2\pi f\tau) W(\boldsymbol{x}, t; \boldsymbol{p}, f) df. \tag{14}$$

With this definition, the theory of Cohen's class time-frequency analysis applies to the local slant-stack and time-frequency analysis techniques can be readily transferred to multi-dimensional analysis.

In [81] volume dip and azimuth attributes have been developed, based on a local slant stack analysis of 3D seismic data. A data example of such a volume dip map is shown in Figure 4 (above). However, presently the algorithms are computationally too intensive for routine implementation. A short term goal of the research is the development of faster algorithms for the computation of the local slant-stack power spectrum. A possible way to speed up the computation of the global Radon transform is to perform the slant-stack operation in the wavelet domain [32]. By using only a few significant wavelet coefficients for the computation of the Radon transform considerable reduction of computation time can be attained. More efficient algorithms may also bring pre-stack 3D local spectral data analysis within reach.

The volume dip and azimuth developed in [81] are only two of many more attributes that can be derived from a local slant-stack analysis. Local dip-frequency spectra can be used to extract frequency attributes along or perpendicular to prevailing event dips. Taking structural dips into account in the attribute extraction procedure will result in attributes that are more informative on stratigraphic features in the data.

Seismic volume attributes can also be used to guide fault and event tracking in 3D seismic data. The volume dip attribute can be used to delineate faults and other discontinuities. The capability of the volume dip measurement for bringing forward faults and at the same time reducing coherent reflections is illustrated in Figure 5. The result that is shown on this cross-section indicates that further research aimed at automatic feature extraction using local slant-stacks may turn out to be be very rewarding.

- Aim: 3D local spectrum analysis and processing of 3D seismic data.
- Short-term goals: faster algorithms and kernels for multi-D local spectral analysis.
- Long-term goals: event-based seismic attribute analysis, geological feature extraction, and tracking guided by volume attributes.
- Status: Theoretical development of Wigner-Radon transformations complete [79]. Volume dip and azimuth extraction algorithms have been developed [79, 88]. Many 1D algorithms can be extended to the multi-dimensional case, for example, optimum kernel techniques [5, 4] and reassignment [70].

B.3 Sequence analysis and event characterization

Local Fourier analysis is widely applied in various seismic data analysis problems (see [8, 24, 41], for example). In many of these applications the difficulty of choosing an analysis window and the multi-component nature of seismic signals leads to severe complications. Within the framework of Cohen's class TFRs, many of the these type of problems can be resolved or at least be better understood.

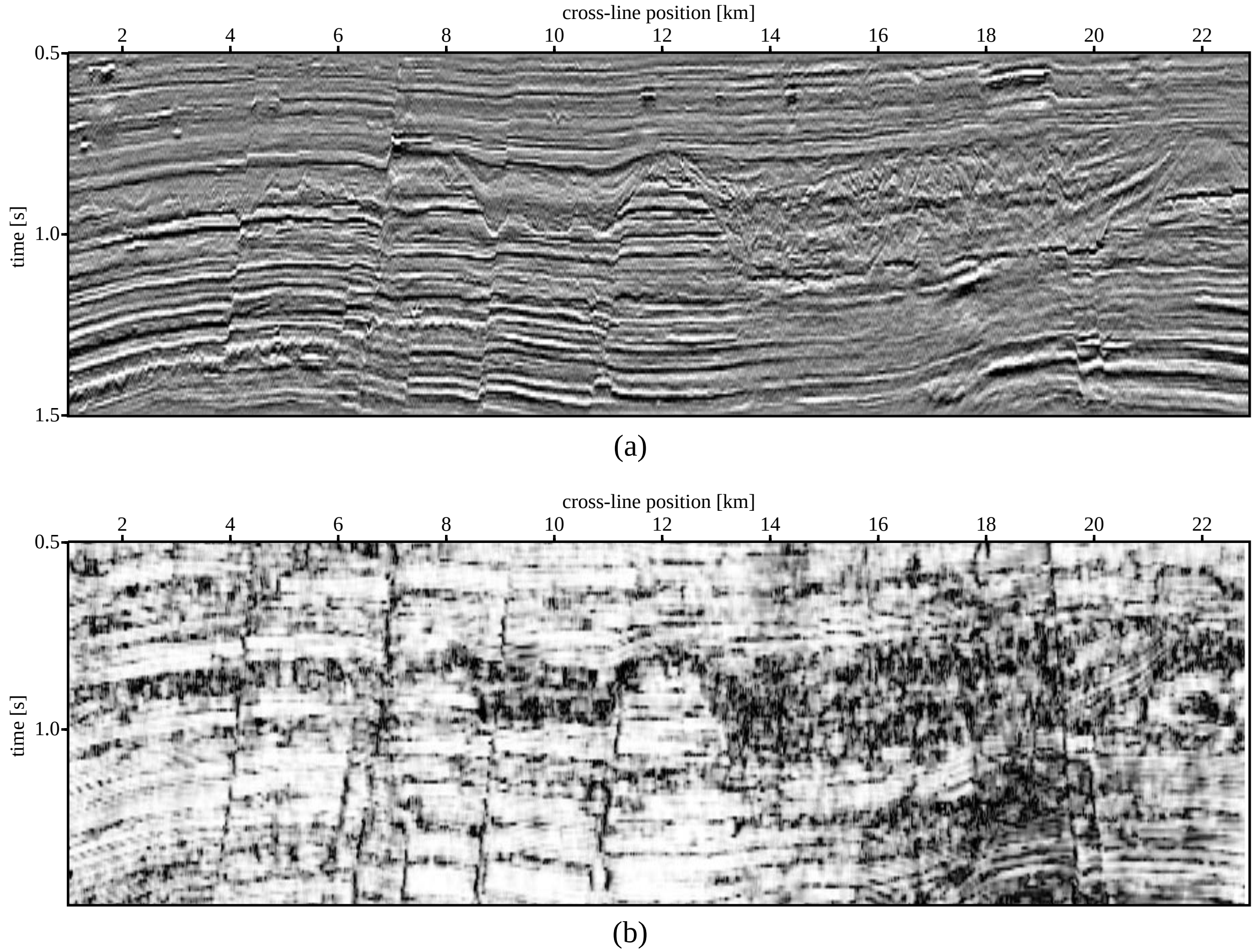


Figure 5: *(a) Inline from a 3D seismic data set and (b) local 3D dip attribute. Faults clearly stand out in the dip image, a property that can be exploited to guide fault recognition and tracking in 3D seismic data.*

The goal of seismic processing and imaging is to extract the (band-limited) reflectivity function of the subsurface from the seismic data. Once this band-limited reflectivity is obtained, it is the task of the seismic interpreter to infer the geological significance of a certain reflectivity pattern. The local frequency content of the data can serve as an indicator of the nature of subsurface stratification. For instance, frequency tuning effects indicate layer thickness and phase changes can be related to the nature of the reflecting boundary.

Seismic facies analysis is largely an assessment of the distribution of amplitude and frequency characteristics in the seismic image: sudden transitions in signal amplitude mark important geological boundaries, whereas the frequency characteristics of the interfering events between the major boundaries indicate geological facies. Hence, a seismic facies description involves the appraisal of non-stationary features in seismic data. Consequently, analysis methods that can handle data non-stationarity will be most effective for studying and quantifying seismic facies. It is shown in [80] that the nature of subsurface stratification can be deduced from the TFR of reflection patterns. Results of synthetic models are shown in Figure 6. Note how well the TFR elicits the tuning of the signal to subsurface stratification, which is not easily observed in the seismic images.

An example of how the observations in the synthetic models can be used to design new seismic attributes is given in Figure 7. The signal is classified according to the type of tuning that is observed in the TFR. The result is a subdivision into sequences of the seismic image that confirms an earlier sequence stratigraphic interpretation of the data [79].

- Aim: quantitative seismic sequence analysis and event characterization.
- Short-term goals: model-based time-frequency and time-scale analysis of seismic sequences and events.
- Mid-term goals: seismic event characterization in terms of time-frequency patterns, seismic sequence characterization and classification.
- Status: preliminary results of time-frequency analysis are given in [80, 79]. Wavelet transform analysis of seismic events is described in [22].

B.4 Pre-stack seismic data analysis and attribute extraction

The trend towards the pre-stack imaging and analysis of 3D seismic data has created a demand for effective data analysis and feature extraction tools. The development of fast algorithms for feature extraction will be a critical component in the development of more efficient velocity model building methods for pre-stack migration. In addition, the advent of 3D AVO analysis and the search for additional pre-stack direct hydrocarbon indicators has created a need for robust parameter estimation algorithms. Amplitude versus angle analysis is generally based on a model in which the impedance contrast can be represented by a step function. However, for impedance contrasts other than step functions, such as gradual changes or in the presence of thin layers, there is not only a change of amplitude as a function of angle, but phase or frequency changes may occur as well. These changes of phase are not readily dealt with [12].

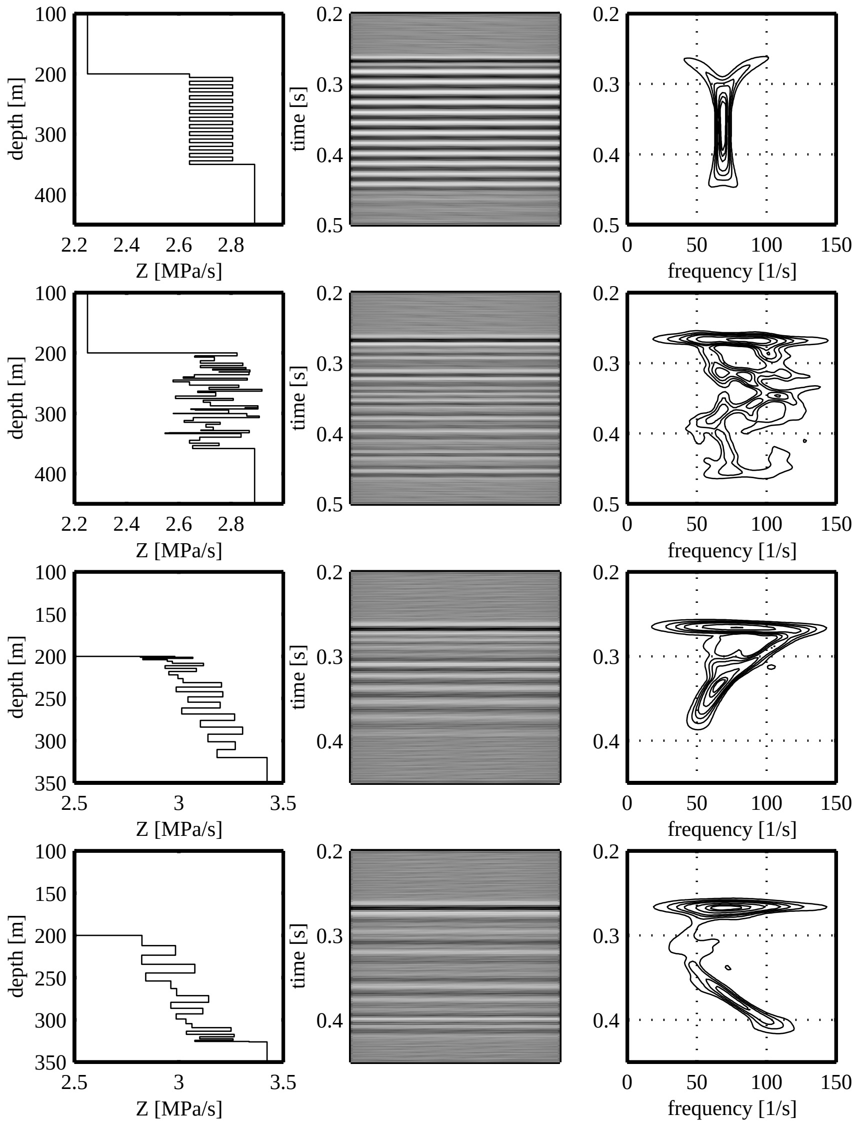


Figure 6: *Time-frequency analysis of seismic sequences. The first sequence is a alternation of high and low velocity layers, resulting in frequency tuning of the seismic response to the frequency of the layering. The second sequence is a randomly stratified velocity. No clear pattern can be observed in the TFR. The third and the fourth sequence are models for a thickening upward and thinning upward layered sequence.*

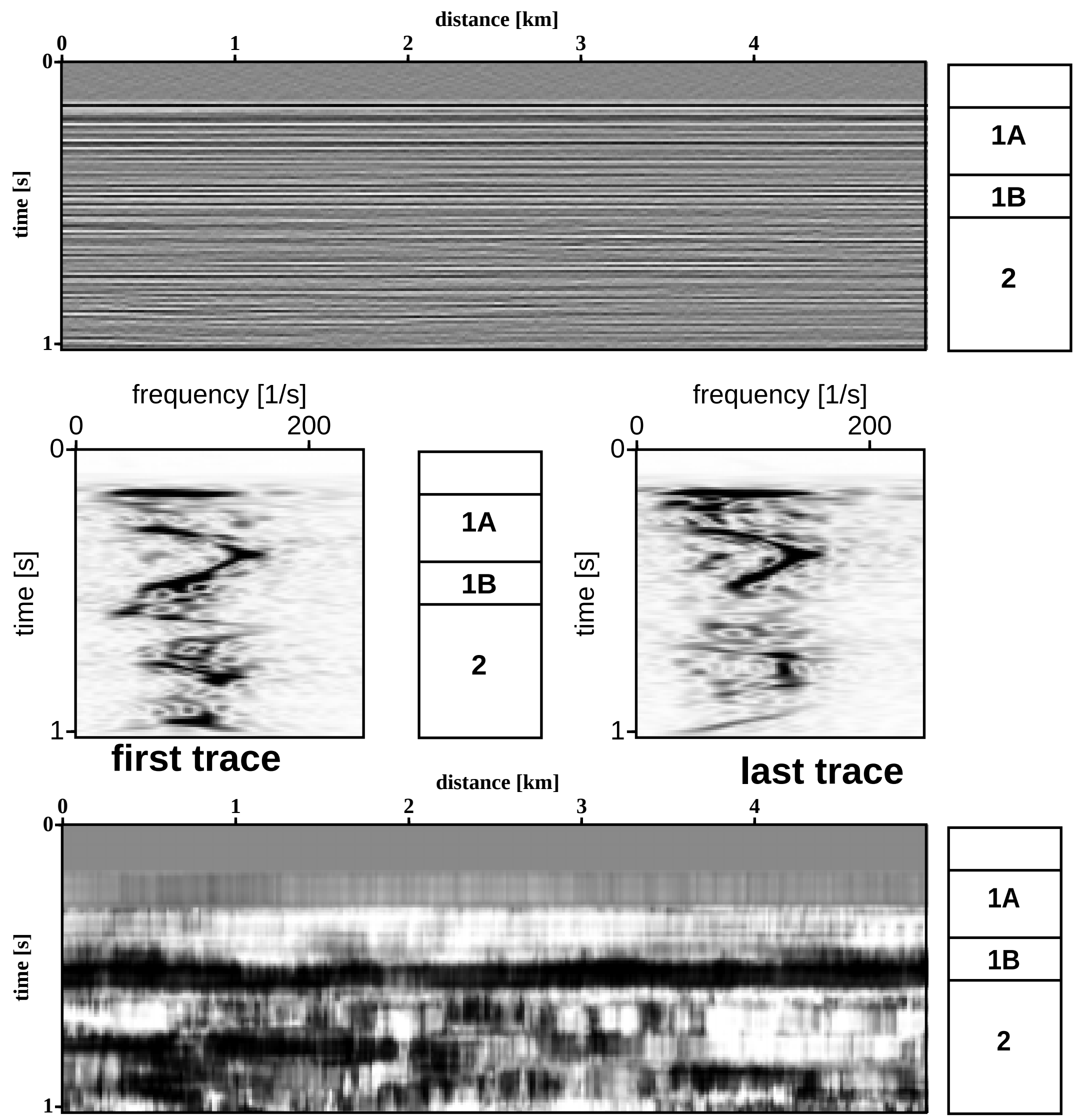


Figure 7: *Sequence classification [79]. The TFR of each trace in the seismic section is computed. The angle of the ridges in the time-frequency plane is computed and plotted as an attribute (lower section). Increasing frequency with seismic travel time is white, decreasing frequency is black. Three sequences can be recognized. The upper sequence is characterized by increase of frequency with seismic travel time (sequence 1A). The second sequence shows a decrease of frequency with time (sequence 1B). Below sequence 1, a more random laterally varying time-frequency pattern is observed (sequence 2). Compare with the synthetic models of Figure 6.*

Pre-stack local frequency and scale analysis can provide the tools for robust extraction of frequency and phase versus angle parameters. Our aim is to develop new AVA-like attributes that are better able to deal with different types of impedance models. Some interesting preliminary results of scale versus amplitude analysis can be found in [90, 22]. Other interesting pre-stack attributes that can be derived from TFRs are dispersion and attenuation characteristics (see [32] for example). Rice has developed techniques for matching signal representations to dispersion characteristics of signals [7]. These representations will be very well suited for instantaneous Q analysis of seismic data.

The multi-dimensional local slowness spectra that have been developed in [79], can find an application for automatic moveout or velocity analysis of pre-stack data. A local slant stack analysis of a pre-stack data gather results in a slowness-frequency decomposition of signal energy in each space-time sample. From this local slowness-frequency spectrum a velocity spectrum can be derived, which can be used in 3D velocity model building. One of the short-term research goals of the consortium is to further address the implementation of high-resolution local slant stack analysis for this application.

- Aim: pre-stack attribute extraction and processing. Fully automatic velocity analysis.
- Short-term goals: tests of local slant-stack analysis on pre-stack data, application to velocity analysis on synthetic and real data.
- Long-term goals: development of new AVA-like and “dispersion” attributes.
- Status: analysis tools are available. Promising results with regard to scale versus angle analysis are given in [90, 22].

B.5 Seismic scale analysis

The role of scale in seismic wave propagation has only recently emerged as an important topic of research. The scaling properties of geological media have been under investigation, for instance, in [50]. However, the interaction of seismic waves with scaling media is little understood. An empirical analysis of the scale content of seismic and well data is needed to assess the importance of scale-based seismic analysis and processing techniques. Rice has developed several high-resolution time-scale representations that are excellent tools to carry out such an analysis [35, 36]. The short term goal of this research is the application of scale analysis techniques to a wide range of well-log and seismic data, in order to understand and quantify the scaling behavior seismic signals. One of the aims of our research is the extension of the traditional frequency analysis techniques to scale-based analysis and attribute extraction procedures for seismic data characterization. In addition, the results of the analysis will enable us to tune wavelet analysis and processing techniques to the scale characteristics of seismic data, thus increasing the effectiveness of wavelet and scale based signal processing and analysis.

- Aim: appraisal of the scaling properties of seismic and well-log data.

- Short-term goals: development of seismic data analysis in the local scale domain, development of scale-based seismic attributes.
- Mid-term goal: experimental analysis of seismic and well log data to assess the importance and role of scaling properties.
- Long-term goal: introduction of scale as a parameter for seismic data analysis and processing.
- Status: new time-scale representations have been developed at Rice [35, 36], preliminary results of scaling analysis of well logs are reported in [50], and seismic time-scale analysis is described in [22].

C Wavelet-Based Seismic Data Processing

The wavelet transform has become a standard tool in many areas of signal and image processing, because a broad range of functions and operators can be concisely represented in the wavelet domain. For this reason, the wavelet transform is an excellent tool for data compression, signal estimation (denoising), and feature detection for a wide class of signals. It is rather remarkable that although the wavelet concept originated in seismic signal analysis [64], only a few cases have been reported where the wavelet transformation significantly outperforms classical methods for seismic data processing (see [32], for example).

One of the striking features of seismic and well-log signals is their *highly non-stationary character.* Because of this property, one would expect that a non-stationary processing technique based on wavelets could outperform Fourier-based techniques in many areas of seismic data processing. Our goal is not simply to apply existing wavelet processing techniques to seismic data, but rather to develop fundamentally new seismic processing algorithms based on wavelets. We propose to develop wavelet-based algorithms that are tailor-made for seismic processing tasks, in the sense that they take the specific properties of seismic signals into account. Based on our experience at Rice with regard to wavelet design, optimization and processing, we expect that our effort in this direction will result in effective and efficient wavelet-based processing algorithms.

For many types of signals, such as radar, sonar and medical imagery, Rice has successfully applied wavelet techniques for non-stationary filtering and analysis [68, 73, 71, 72, 75, 74, 58, 59, 60, 46, 48, 47, 44]. Adaptation of these techniques to seismic signal processing will certainly result in effective algorithms for signal denoising and feature extraction.

Since the early 1980s, the theory of wavelet transforms has been continuously under development. Recently, some important theoretical advances have been made that have important practical consequences, For example, the result that wavelets provide unconditional bases for a wide class of signal smoothness spaces means that wavelet transforms of real-world signals (seismic and well-log signals included) will be sparse [26]. Results such as these justify a renewed effort towards an effective deployment of the wavelet transform in seismic data processing.

It is important to investigate the potential advantages that a multiresolution representation might provide for both processing and analysis of seismic data. Numerous aspects of wavelet theory (discrete wavelet representation, continuous wavelet representation, time-scale representations, frames, lifting, to name a few) will play roles here. We will systematically analyze the data in these various representations in order to learn about the peculiarities of the data that can be exploited using the wavelet framework. Results of this analysis will then be used to design optimal wavelet bases for data processing.

One of the reasons for the limited success to date of wavelet transforms in seismic signal processing may be the lack of multi-dimensional wavelet-based processing algorithms that take the trace-to-trace coherence of seismic reflections into account. For instance, it is expected that multi-dimensional wavelet transformations that are specifically designed for seismic signals will be far more effective for the suppression of ground-roll and airblast in energy seismic shot-records than algorithms than existing methods [21].

Wavelet transformations decompose signals into their scale content. As a result, the wavelet transform is very well suited for multi-resolution signal analysis and processing. The multi-resolution decomposition of signals has applications in many areas of seismic signal analysis, ranging from analysis and fusion of data measured at different scales (well logs, VSP, and surface seismic, for example) to multi-scale migration [23].

- Aim: A comprehensive framework for non-stationary pre-processing of seismic data. Fast and effective (data- and problem-adaptive approach) algorithms.
- Short-term goal: Design and optimization of matched wavelet systems.
- Mid-term goal: design of non-stationary noise suppression algorithms, space/time-variant deconvolution, wavelet processing and reconstruction of irregular sampled data sets using the lifting paradigm.
- Long-Term goal: General framework for non-stationary signal processing.

The following sections highlight a number of areas in which the Rice team have made significant contributions to the theory and application of wavelets.

C.1 Denoising of seismic and well-log data

We have made considerable progress in nonlinear wavelet processing for denoising (signal estimation). Our early results were based on the work of Donoho and Johnstone's SureShrink algorithm [27, 29, 30] and involved nonlinear thresholding of the wavelet coefficients (see Figure 8). Applications investigated to date include: (1) speckle reduction in synthetic aperture radar (SAR) [47, 48, 72, 68], (2) noise suppression in time-frequency images [3], (3) reduction of artifacts from JPEG compressed images [39, 40, 68], and (4) reduction of speckle noise in TV holography images [74]. In addition, we have generalized SureShrink by introducing a robust shift-invariant (redundant/undecimated) wavelet transform [43, 59]. Redundant wavelet denoising has significantly enhanced noise reduction capabilities compared to the SureShrink.

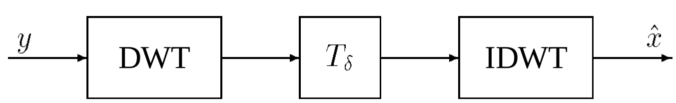


Figure 8: *Wavelet-based noise reduction algorithm. (DWT – discrete wavelet transform, IDWT – inverse DWT, and T_δ – nonlinear threshold function.)*

More recently, we have directed our attention towards wavelet-domain probability models for statistical signal processing. Wavelet-domain Hidden Markov Models (HMMs) improve signal processing in the wavelet-domain by characterizing both the properties of individual wavelet coefficients and the salient interactions *between* wavelet coefficients [18]. Applying these models to signal estimation, we have achieved significant performance improvements over SureShrink and other state-of-the-art denoising algorithms. Furthermore, using wavelet-domain HMMs, we can model both signal and noise in order to denoise in structured (correlated) noise environments.

C.2 Compression

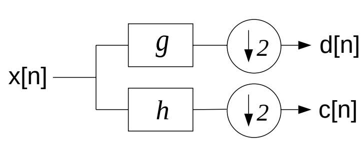
Over the past number of years, we have developed considerable expertise in wavelet-based signal, image, and video compression [45, 86, 87, 72, 92, 91, 94, 71, 72, 95, 93]. The challenges associated with compressing natural images and video are well known and extensively studied. In addition to working with natural images, we have also performed extensive research on wavelet-based compression algorithms for synthetic aperture radar (SAR), medical, and seismic data/images. Performance metrics are typically very different for these types of images.

Several groups have developed wavelet-based compression algorithms for seismic data suitable for limited usage in exploration [11, 98, 31, 89, 45, 1]). However, several key aspects of lossy compression of pre-stack seismic data have to a large degree been ignored in these early attempts. In [45] we demonstrated that lossy compression can render seismic data useless due to significant *phase distortion*, which causes later processing to introduce severe image artifacts (“phantom” data in locations where geology was not present).

While we do not foresee that this consortium will dedicate substantial effort towards developing new seismic data compression algorithms, we do intend to keep the consortium members abreast of developments in compression technology. We strongly believe that much additional research is required before compression technology will be optimally matched to the seismic data application. However, the experiments in [45] give us confidence that good solutions exist and are within reach. Rice University has been elected as an Associate Member of the Seismic Compression Diagnostic Initiative (SCDI), an industrially sponsored consortium for developing metrics for evaluating compression algorithms on seismic data.

C.3 Lifting: Adaptive wavelets for non-uniformly spaced data

Lifting, a space-domain construction of wavelets [83, 16, 15], is based on a prediction-error decomposition of the signal rather than the traditional filter bank (see Figure 9). This alternative architecture results in two primary advantages: (1) the predictor P and update U can be arbitrary (time-varying/nonlinear) operators and the transform remains invertible, and (2) the predictor and update can work with non-uniformly sampled data. In concert, these two properties enable flexible nonlinear and adaptive mulitscale signal and image decompositions on potentially non-uniformly sampled grids. Such algorithms are ideally suited for adapting to the non-stationary, oft-non-uniformly sampled seismic data.



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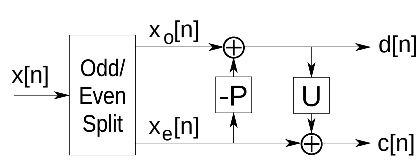

(b)

Figure 9: *(a) Wavelet filter bank stage, with h and g low and high pass filters, respectively. (b) Equivalent lifting stage, with* P *the predictor and* U *the update.*

Promising preliminary results on lifting-based denoising and compression can be found in [16, 15]. In these papers, we investigate the capabilities of the lifting approach for adaptive wavelet transforms that optimize (minimize) data-based prediction errors to match the characteristics of a given signal. The motivation behind these transforms is that better predictors lead to a transform that provides a more efficient representation of the signal. Since the compression property of signal transformations is the key to successful signal processing, the adaptive transforms derived here have the potential to improve transform-based processing.

C.4 Design and optimization of wavelet bases

Rice is leader in wavelet design and optimization [69, 85, 38, 37, 49, 61, 96, 62, 78]. Three complementary approaches have been investigated: (1) signal dependent wavelet optimization (given a signal or set of signal, find the optimal wavelet basis for representation and processing), (2) optimal design with respect to the wavelet filters (filter design), and (3) optimal design with respect to the wavelet basis functions (function design). Using these design approaches, we have developed new wavelet systems having more vanishing moments, extra smoothness, better frequency characteristics, more symmetry, and better approximation capabilities compared to conventional systems.

C.5 Frames

In conventional orthogonal and biorthogonal wavelet systems, the basis functions are tightly constrained and resemble anything but seisic waveforms [20]. Clearly, matching the basis to the seismic wavelet could improve the performance of wavelet-based analysis and processing algorithms. In order to do this, we propose to expand signals onto a *frame*, a (slightly) overcomplete basis set. In a frame, the redundancy provides added flexibility in the choice of analysis functions as well as added robustness to noise, coefficient quantization, numerical errors [20, 76].

C.6 Deconvolution

By working in the wavelet domain, we can trade off between Fourier-domain division and time-domain techniques such as minimum entropy deconvolution [97, 25]. Wavelet-domain deconvolution techniques with potential for geophysical applications include wavelet-domain Wiener filters [67, 65, 66, 34] and the "wavelet-vaguelette" deconvolution technique of Donoho [28].

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Reviewed Journal Publications

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[25] J. E. Odegard. Image enhancement by nonlinear wavelet processing. In *Proceedings Wavelets and Large Scale Image Processing*, International Press, Argonne National Laboratory, Invited lecture, October 1994.

[26] M. Lang, I. W. Selesnick, J. E. Odegard, and C. S. Burrus, "Constrained FIR filter design for 2-band filter banks and orthonormal wavelets. In *Proceedings IEEE Sixth Digital Signal Processing Workshop*, pp. 211–214, Yosemite, CA, October 1994.

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[30] H. Guo, J. E. Odegard, M. Lang, R. A. Gopinath, I. W. Selesnick, and C. S. Burrus, “Speckle reduction via wavelet shrinkage with application to SAR based ATD/R,” In *SPIE Math. Imaging: Wavelet Applications in Signal and Image Processing*, Vol. 2303, pp. 333–344, San Diego, CA, July 1994.

[31] R. A. Gopinath, J. E. Odegard, and C. S. Burrus, “On the correlation structure of multiplicity M scaling functions and wavelets,” In *Proceedings IEEE International Symposium on Circuits and Systems*, Vol. 2, pp. 959–962, San Diego, CA, May 1992.

[32] J. E. Odegard, R. A. Gopinath, and C. S. Burrus, “Optimal wavelets for signal decomposition and the existence of scale limited signals,” In *Proceedings IEEE International Conference on Acoustics, Speech and Signal Processing*, Vol. 4, pp. IV 597–600, San Francisco, CA, March 1992.

Technical Reports

[1] J. E. Odegard, G. H. Kaufmann, and A. Davila. “Speckle reduction in TV holography fringes using wavelets,” Technical report, Dept. of ECE, Rice University, Houston, TX, 1995. In Preparation.

[2] J. E. Odegard, M. Lang, H. Guo, R. A. Gopinath, , and C. S. Burrus, “Nonlinear wavelet processing for enhancement of images,” Tech. Report CML TR94-04, Rice University, Houston, TX, May 1994.

[3] J. E. Odegard, H. Guo, M. Lang, C. S. Burrus, R. O. Wells Jr., L. M. Novak, and M. Hiett. “Speckle reduction by wavelet thresholding combined with (spatial) polarimetric whitening of SAR for applications to ATD/R,” Tech. Report CML TR94-08, Rice University, Houston, TX, April 1994.

[4] J. E. Odegard, R. A. Gopinath, and C. S. Burrus, “Design of linear phase cosine modulated filter banks for subband image compression,” Tech. Report CML TR94-06, Rice University, Houston, TX, February 1994.

[5] J. E. Odegard. “The continuous wavelet transform for analysis of non-stationary signals,” Tech. Report CML TR91-21, Rice University, Houston, TX, 1991.

CURRICULUM VITAE

Name:	**Th. Philippe H. Steeghs**
Personal Data:	Born 11 May 1967, Heerlen, the Netherlands Dutch Citizen
Education:	Ph.D., Delft University of Technology, 9/1997 (Applied Science) Promotor: Jacob T. Fokkema Thesis: Local Power Spectra and Seismic Interpretation MS University of Utrecht, 9/1992, (Solid earth physics) Advisers: J. Brouwer and K. Helbig Thesis: Shallow seismic profiling in the Sorbas Basin (SE Spain)
Areas of Research:	exploration geophysics, quantitative seismic interpretation, imaging, seismic signal processing
Professional Appointments:	Research Associate, Rice University, 1997-present Research Assistant, Delft University, 1993-1997 Assistant Lecturer, Utrecht University, 1992 Teaching Assistant, Utrecht University, 1989-1992 Summer student, Shell U.K. Expro, 1990 Summer internship, NAM Assen, 1989

Professional Activities and Societies

Assistant editor of Geophysical Prospecting, 1994-1997
President, Delft Organisation of Geophysics Students, 1995
Party chief, seismic survey, the Netherlands, University of Utrecht, 1992
Party chief, seismic survey, Spain, Free University Amsterdam, 1992
Participant, 1st Unesco-Tredmar research cruise, R/V Gelendzhik, Black Sea, 1990
President, Students Association for Physics Students ‘$o\lambda\alpha$, 1989
Member, *SEG, EAGE, IEEE*

Publications

Steeghs, T.P.H., 1997, *Local Power Spectra and Seismic Interpretation*, Ph.D. Dissertation, Delft University of Technology, Delft, the Netherlands.

Tobback, T., Steeghs, T.P.H., Drijkoningen, G.G., and Fokkema, J.T., 1996, Decomposition of seismic Signals via Time-Frequency Representations, *Sixty-Sixth Annual International SEG Meeting Denver, Expanded Abstracts*, 1638-1641.

Steeghs, T.P.H. and Drijkoningen, G.G., 1996, Extraction of Attributes from 3D seismic Data, *EAGE 58th Meeting and Technical Exhibition, Amsterdam, the Netherlands, Extended Abstracts of Papers*, X032.

Steeghs, T.P.H. and Drijkoningen, G.G., 1996, Time-Frequency Analysis of Seismic Reflection Data, *Proceedings of the 1996 International Conference on Acoustics, Speech and Signal Processing, Atlanta*,

Steeghs, T.P.H. and Drijkoningen, G.G., 1995, Time-Frequency Analysis of seismic Sequences, *Sixty-Fifth Annual International SEG Meeting Houston*, *Expanded Abstracts*, 1528-1531.

Steeghs, T.P.H., Drijkoningen, G.G., Peet, W.E., and Fokkema, J.T., 1995, A new Method for the Extraction of seismic facies Attributes, *EAGE 57th Meeting and Technical Exhibition, Glasgow - Scotland, Extended Abstracts of Papers*, A029.

Steeghs, T.P.H. and Drijkoningen, G.G., 1994, Joint Time-Frequency Representation of seismic Data, *EAEG 56th Meeting and Technical Exhibition, Vienna - Austria, Extended Abstracts of Papers*, P163.

Steeghs, T.P.H., Stafleu, J. and Ten Veen, J., On-shore shallow seismic profiling in the Sorbas Basin (SE Spain), chapter 2 in: *Seismic models of geological outcrops,* Ph.D. Dissertation, Free University of Amsterdam, the Netherlands.

Presentations

Colloquium, Rice University, Local power spectra and seismic interpretation, July 1997
Research Day, Department of Applied Earth Sciences, Time-frequency analysis, September 1996
Colloquium, VU Amsterdam, Seismic attribute extraction, November 1995
Huygens Colloquium, Seismic attribute extraction, Centre for Technical Geoscience, May 1995
Dutch Geological Survey, Seismic attribute extraction, May 1995
Colloquium, VU, Seismic sequence analysis April 1994
Shell Research, Time-frequency analysis, April 1994
Dutch Geological Survey, Shallow seismic profiling, January 1993

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December 19, 1997

RESEARCH INTERESTS

Signal and image processing theory and applications, time-varying spectral analysis, time-frequency analysis, wavelets

EDUCATION

1992	University of Illinois–Urbana	Ph.D. in Electrical and Computer Engineering
1988	University of Wisconsin–Madison	M.Sc. in Electrical and Computer Engineering
1987	University of Manitoba (Canada)	B.Sc. in Electrical Engineering (with distinction)

POSITIONS

1996–present	Rice University	Associate Professor
1993–1996	Rice University	Assistant Professor
1992–1993	Ecole Normale Supérieure de Lyon (France)	Postdoctoral Research Fellow
1988–1992	University of Illinois–Urbana	Research Assistant
1987–1988	University of Wisconsin–Madison	Graduate Fellow
1987	National Research Council of Canada	Research Assistant
1986	Omron Tateishi Electronics (Kyoto, Japan)	R&D Engineer

RESEARCH SUPPORT

1997–2000	DARPA	*Wavelet-Based Automatic Target Recognition for Synthetic Aperture Radar* (co-PI)	$744,000
1996	NSF	*CISE Research Instrumentation: A Medium Scale, Tightly Coupled, Shared Memory Multiprocessor* (co-PI)	$85,000
1995–1998	ONR	*Operator-Based Approaches for Matching Signal Processing Tools to Data* (Young Investigator Award)	$283,000
1995–1997	NATO	*Information Theoretic Time-Frequency and Time-Scale Signal Analysis*	$7,500

1994–1999	NSF	*Signal Analysis and Processing in Matched Coordinate Systems* (National Young Investigator Award)	$335,000
1994–1996	Texas	*New Data Compression Technology based on Time-Varying Wavelets* (co-PI)	$245,000

Industrial sponsors: Nortel Technologies, MCI Communications, Northrop-Grumman, Mobil, Conoco, Shell Research Foundation

AWARDS and HONORS

1995 Office of Naval Research Young Investigator Award
1994 National Science Foundation National Young Investigator Award
1992 National Sciences and Engineering Research Council of Canada NATO Postdoctoral Fellowship
1987 Wisconsin Alumni Research Foundation Fellowship
Bacon Scholarship (U. Wisconsin)
Eta Kappa Nu Award for Second-Ranked Graduating Electrical Engineer (U. Manitoba)
IEEE Award for Best Undergraduate Thesis Defense (U. Manitoba)
1986 E. P. Fetherstonhaugh Scholarship (U. Manitoba)
1977 Top Project at the University of Winnipeg Science Symposium (Provincial Science Fair)

PROFESSIONAL ACTIVITIES

Chair: IEEE Signal Processing Society, Houston Chapter
Member: IEEE Signal Processing and Information Theory Societies, Eta Kappa Nu
Technical Program Committee for the *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, 1998
Panelist: NSF/ONR Workshop on Signal Processing for Manufacturing and Machine Monitoring, 1996
Reviewer: Various *IEEE Transactions*, *Journal of the Acoustical Society of America*, National Science Foundation

TEACHING

ELEC 431 Digital Signal Processing (developed)
ELEC 491/2 Undergraduate Research Projects (coordinator)
ELEC 532 Spectral Analysis (developed)
ELEC 539 Image Processing

Instructor: Dean's Teaching Workshop for New Faculty (1997)

Member: Signal Processing Education Consortium (supported by NSF)

Current students: Rolf Riedi (postdoc), Philippe Steeghs (postdoc), Hyeokho Choi (postdoc), Matthew Crouse, Roger Claypoole, Rohit Gaikwad

Previous students: Paulo Gonçalvès (INRIA, Paris, France), Robert Nowak (faculty at Michigan State University), Metin Bayram, Ediz Demirciler

UNIVERSITY SERVICE

1997	Dean's Committee on Departmental Structure
1996–present	Chair, ECE Graduate Committee
1996–present	University Committee on Admission and Student Financial Aid
1996–present	Texas Instruments Graduate Fellowship Committee
1994–present	KTRU Radio DJ
1994–present	Faculty Associate and Divisional Advisor, Hanszen College (Outstanding Associate 1995–1997)
1994–1996	ECE Graduate Committee
1994–1996	IEEE Student Branch Faculty Advisor
1994–1995	Faculty Mentor, Minority Student and "Posse" Programs
1993–1994	ECE Curriculum Committee

PERSONAL

Canadian citizen, USA permanent resident

JOURNAL PUBLICATIONS

M. S. Crouse and R. G. Baraniuk, "Simplified Wavelet-Domain Hidden Markov Models using Contexts," In preparation.

M. S. Crouse and R. G. Baraniuk, "Fast Synthesis of Long-Range Dependent Time Series," In preparation.

R. L. Claypoole, R. G. Baraniuk, and R. D. Nowak, "Adaptive Wavelet Transforms using Lifting," In preparation.

M. Bayram and R. G. Baraniuk, "Multiple Window Time-Varying Spectral Analysis," Submitted to *IEEE Transactions on Signal Processing*, 1997.

R. D. Nowak and R. G. Baraniuk, "Wavelet Domain Filtering for Photon Imaging Systems," Submitted to *IEEE Transactions on Image Processing*, 1997.

R. D. Nowak and R. G. Baraniuk, "Wavelet-Based Transformations for Nonlinear Signal Processing," Submitted to *IEEE Transactions on Signal Processing*, 1997.

M. Pasquier, P. Gonçalvès, and R. G. Baraniuk, "Hybrid Linear/Bilinear Time-Scale Analysis," Submitted to *IEEE Transactions on Signal Processing*, 1996.

K. A Farry, R. G. Baraniuk, and I. D. Walker, "Myoelectric Spectrum Estimation using Thomson's Multiple Window Method: Time-Frequency Analysis," Submitted to *IEEE Transactions on Biomedical Engineering*, 1995.

K. A Farry, R. G. Baraniuk, and I. D. Walker, "Myoelectric Spectrum Estimation using Thomson's Multiple Window Method: Single Signal Stationary Analysis," Submitted to *IEEE Transactions on Biomedical Engineering*, 1995.

R. G. Baraniuk, "Joint Distributions of Arbitrary Variables Made Easy," To appear in *Journal of Multidimensional Systems and Signal Processing* (Special issue on Time-Frequency Analysis), 1998.

R. D. Nowak and R. G. Baraniuk, "Optimal Weighted Highpass Filters using Multiscale Analysis," To appear in *IEEE Transactions on Image Processing*, 1998.

M. S. Crouse, R. D. Nowak, and R. G. Baraniuk, "Wavelet-based Statistical Signal Processing using Hidden Markov Models," To appear in *IEEE Transactions on Signal Processing* (Special issue on Theory and Applications of Filter Banks and Wavelet Transforms), 1998.

R. G. Baraniuk, "Beyond Time-Frequency Analysis: Energy Densities in One and Many Dimensions," To appear in *IEEE Transactions on Signal Processing*, 1998.

P. Gonçalvès and R. G. Baraniuk, "Pseudo Affine Wigner Distributions: Definition and Kernel Formulation," To appear in *IEEE Transactions on Signal Processing*, 1997.

R. G. Baraniuk and D. L. Jones, "Wigner-Based Formulation of the Chirplet Transform," *IEEE Transactions on Signal Processing*, Vol. 44, No. 12, pp. 3129–3135, December 1996.

K. A Farry, I. D. Walker, and R. G. Baraniuk, "Myoelectric Teleoperation of a Complex Robotic Hand," *IEEE Transactions on Robotics and Automation*, Vol. 12, No. 4, pp. 775–788, August 1996.

R. G. Baraniuk, "Signal-Dependent Time-Frequency Representations," Section 6.3.3 in *Introduction to Time-Frequency Analysis* by S. Qian and D. Chen. Prentice Hall, 1996.

P. Gonçalvès and R. G. Baraniuk, "A Pseudo-Bertrand Distribution for Time-Scale Analysis," *IEEE Signal Processing Letters*, Vol. 3, No. 3, pp. 82–84, March 1996.

R. G. Baraniuk, "Covariant Time-Frequency Representations Through Unitary Equivalence," *IEEE Signal Processing Letters*, Vol. 3, No. 3, pp. 79–81, March 1996.

R. G. Baraniuk, "Limitations of the Kernel Method for Joint Distributions of Arbitrary Variables," *IEEE Signal Processing Letters*, Vol. 3, No. 2, pp. 51–53, February 1996.

R. G. Baraniuk and D. L. Jones, "Unitary Equivalence: A New Twist on Signal Processing," *IEEE Transactions on Signal Processing*, Vol. 43, No. 10, pp. 2269–2282, October 1995.

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R. G. Baraniuk and L. Cohen, "On Joint Distributions for Arbitrary Variables," *IEEE Signal Processing Letters*, Vol. 2, No. 1, pp. 10–12, January 1995.

D. L. Jones and R. G. Baraniuk, "A Simple Scheme for Adapting Time-Frequency Representations," *IEEE Transactions on Signal Processing*, Vol. 42, No. 12, pp. 3530–3535, December 1994.

R. G. Baraniuk and D. L. Jones, "A Signal-Dependent Time-Frequency Representation: Fast Algorithm for Optimal Kernel Design," *IEEE Transactions on Signal Processing*, Vol. 42, No. 1, pp. 134–146, January 1994.

R. G. Baraniuk and D. L. Jones, "Shear Madness: New Orthonormal Bases and Frames Using Chirp Functions," *IEEE Transactions on Signal Processing*, Special Issue on Wavelets and Signal Processing, Vol. 41, No. 12, pp. 3543–3549, December 1993.

R. G. Baraniuk, "A Signal Transform Covariant to Scale Changes," *Electronics Letters*, Vol. 29 No. 19, pp. 1675–1677, September 17, 1993.

R. G. Baraniuk and D. L. Jones, "Signal-Dependent Time-Frequency Analysis Using a Radially Gaussian Kernel," *Signal Processing*, Vol. 32, No. 3, pp. 263–284, June 1993.

R. G. Baraniuk and D. L. Jones, "A Signal-Dependent Time-Frequency Representation: Optimal Kernel Design," *IEEE Transactions on Signal Processing*, Vol. 41, No. 4, pp. 1589–1602, April 1993.

D. L. Jones and R. G. Baraniuk, "Efficient Approximation of Continuous Wavelet Transforms," *IEE Electronics Letters*, Vol. 27, No. 9, pp. 748–750, April 25, 1991.

B. D. Van Veen and R. G. Baraniuk, "Matrix Based Computation of Floating Point Roundoff Noise," *IEEE Transactions on Acoustics, Speech and Signal Processing*, Vol. 37, No. 12, pp. 1995–1998, December 1989.

CONFERENCE PUBLICATIONS

D. M. Mittleman, R. G Baraniuk, and M. C. Nuss, "Applications of Terahertz Imaging," *International Topical Workshop on Contemporary Photonic Technologies*, Tokyo, Japan, January 1998.

R. L. Claypoole, G. Davis, W. Sweldens, and R. G. Baraniuk, "Nonlinear Wavelet Transforms for Image Coding," *31st Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1997.

M. S. Crouse and R. G. Baraniuk, "Contextual Hidden Markov Models for Wavelet-domain Signal Processing," *31st Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1997.

J. E. Odegard, R. G. Baraniuk, and K. Oehler, "Instantaneous Frequency Estimation using the Reassignment Method," *Society of Exploration Geophysicists 67th Annual Meeting*, Dallas, November 1997.

R. D. Nowak and R. G. Baraniuk, "Wavelet Transforms for Nonlinear Signal Processing," *IEEE Workshop on Nonlinear Signal and Image Processing*, Mackinac Island, MI, September 1997.

S. Ghael, A. M. Sayeed, and R. G. Baraniuk, "Improved Wavelet Denoising via Empirical Wiener Filtering," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VII*, San Diego, July 1997.

M. S. Crouse, R. D. Nowak, and R. G. Baraniuk, " Statistical Signal Processing Using Wavelet-Domain Hidden Markov Models," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VII*, San Diego, July 1997.

M. S. Crouse, R. D. Nowak, K. Mhirsi, and R. G. Baraniuk, "Detection and Classification using Wavelet-Domain Hidden Markov Models," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VII*, San Diego, July 1997.

R. D. Nowak and R. G. Baraniuk, "Wavelet Domain Filtering for Photon Imaging Systems," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VII*, San Diego, July 1997.

M. S. Crouse, R. D. Nowak, and R. G. Baraniuk, "Statistical Signal and Image Processing using Wavelet-Domain Hidden Markov Models," *29th Symposium on the Interface: Computing Science and Statistics*, Houston, TX, May 1997.

D. H. Johnson, P. Gonçalvès, and R. G. Baraniuk, "Improved Type-based Detection of Analog Signals," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP97*, Munich, Germany, April 1997.

R. D. Nowak and R. G. Baraniuk, "Wavelet-Based Nonlinear Signal Processing," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP97*, Munich, Germany, April 1997.

M. S. Crouse, R. D. Nowak, and R. G. Baraniuk, "Signal Estimation using Wavelet-Markov Models," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP97*, Munich, Germany, April 1997.

R. D. Nowak, D. J. Nowak, R. G. Baraniuk, and R. S. Hellman, "Wavelet Domain Filtering for Nuclear Medicine Imaging," *IEEE 1996 Medical Imaging Conference*, Anaheim, CA, November, 1996.

M. S. Crouse, R. D. Nowak, and R. G. Baraniuk, "Hidden Markov Models for Wavelet-based Signal Processing," *30th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1996.

R. G. Baraniuk, "Joint Distributions of Arbitrary Variables Made Easy," *Seventh IEEE Digital Signal Processing Workshop*, Loen, Norway, September 1996.

C. C. Carson and R. G. Baraniuk, "Window Design for Signal-Dependent Spectrogram using Optimal-Kernel Techniques," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VI*, Denver, CO, August, 1996.

M. Bayram and R. G. Baraniuk, "Multiple Window Time-Frequency and Time-Scale Analysis," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VI*, Denver, CO, August, 1996.

R. D. Nowak and R. G. Baraniuk, "Wavelet-based Decompositions for Nonlinear Signal Processing," *SPIE Conference on Wavelet Applications in Signal and Image Processing*, Denver, CO, August, 1996.

M. Pasquier, P. Gonçalvès, and R. G. Baraniuk, "Hybrid Linear/Bilinear Time-Scale Analysis," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Paris, France, June 1996.

M. Bayram and R. G. Baraniuk, "Multiple Window Time-Frequency Analysis," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Paris, France, June 1996.

L. F. Wisur-Olsen and R. G. Baraniuk, "Optimal Phase Kernels for Time-Frequency Analysis," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP96*, Atlanta, GA, May 1996.

P. Gonçalvès and R. G. Baraniuk, "Pseudo Affine Wigner Distributions," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP96*, Atlanta, GA, May 1996.

R. D. Nowak and R. G. Baraniuk, "Optimally Weighted Highpass Filters using Multiscale Analysis," *IEEE Southwest Symposium on Image Analysis and Interpretation*, San Antonio, TX, April 1996

M. Bayram and R. G. Baraniuk, "Multiple Window Time-Varying Spectral Analysis," *Proceedings of the 30th Annual Conference on Information Sciences and Systems — CISS 1996*, Princeton, NJ, March 1996.

J. E. Odegard, H. Guo, C. S. Burrus, and R. G. Baraniuk, "Joint Compression and Speckle Reduction of SAR Images using Embedded Zerotree Models," *Proceedings of the Ninth IMDSP Workshop on Image and Multidimensional Digital Signal Processing*, Belize City, Belize, March 1996.

R. G. Baraniuk, P. Flandrin, and O. Michel, "Measuring Time-Frequency Information and Complexity Using the Rényi Entropies," *IEEE International Symposium on Information Theory*, Whistler, BC, September 1995.

K. A. Farry, R. G. Baraniuk, and I. D. Walker, "Stationary Myoelectric Spectral Estimates from a Nonparametric, Low Bias, and Low Variance Estimator," *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS)*, Montreal, September 1995.

K. A. Farry, R. G. Baraniuk, and I. D. Walker, "Nonparametric, Low Bias, and Low Variance Time-Frequency Analysis of Myoelectric Signals," *International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS)*, Montreal, September 1995.

K. A. Farry, I. D. Walker, and R. G. Baraniuk, "Functional Separation of Myoelectric Signals using Thomson's Multiple Window Method," *Myoelectric Control '95 (MEC'95)*, Fredericton, NB, Canada, August 1995.

R. G. Baraniuk, "Marginals vs. Covariance in Joint Distribution Theory," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP95*, Detroit, MI, May 1995.

R. G. Baraniuk, "Nonlinear Wigner-Ville Spectrum Estimation using Wavelet Soft-Thresholding," *SPIE Technical Conference 2491 on Wavelet Applications for Dual-Use*, Orlando, FL, April 1995.

R. G. Baraniuk, "Warping Time-Frequency and Time-Scale Representations to Match Signals," *SPIE Technical Conference 2488 on Visual Information Processing IV*, Orlando, FL, April 1995.

R. G. Baraniuk, "Wavelet Soft-Thresholding Time-Frequency Representations," *IEEE International Conference on Image Processing — ICIP94*, Austin, TX, November 1994.

R. G. Baraniuk, "Warped Perspectives in Time-Frequency Analysis," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Philadelphia, PA, October 1994.

R. G. Baraniuk, "Wigner-Ville Spectrum Estimation via Wavelet Soft-Thresholding," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Philadelphia, PA, October 1994.

O. Michel, R. G. Baraniuk, and P. Flandrin "Time-Frequency Based Distance and Divergence Measures," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Philadelphia, PA, October 1994.

L. Cohen and R. G. Baraniuk, "On Joint Distributions of Arbitrary Variables," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Philadelphia, PA, October 1994.

R. G. Baraniuk, "Signal-Dependent Time-Frequency Representations," *Thematic Days on Time-Frequency, Wavelets, and Multiresolution: Theory, Models, and Applications*, Lyon, France, March 1994.

R. G. Baraniuk, "Beyond Time-Frequency Analysis: Energy Densities in One and Many Dimensions," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP94*, Adelaide, Australia, April 1994.

P. Flandrin, R. G. Baraniuk, and O. Michel, "Time-Frequency Complexity and Information," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP94*, Adelaide, Australia, April 1994.

R. G. Baraniuk, P. Flandrin, and O. Michel, "Information and Complexity on the Time-Frequency Plane," *14ème Colloque GRETSI*, Juan-Les-Pins, France, September 1993.

R. G. Baraniuk and D. L. Jones, "Unitary Equivalence: A New Twist on Signal Processing," *Proceedings of the International Symposium on the Mathematical Theory of Networks and Systems (MTNS)*, Regensburg, Germany, August 1993.

R. G. Baraniuk and D. L. Jones, "Warped Wavelet Bases: Unitary Equivalence and Signal Processing," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP93*, Minneapolis, MN, March 1993.

D. L. Jones and R. G. Baraniuk, "An Adaptive Optimal-Kernel Time-Frequency Representation," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP93*, Minneapolis, MN, March 1993.

D. L. Jones and R. G. Baraniuk, "A Simple Scheme for Adapting Time-Frequency Representations," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Victoria, BC, Canada, October 1992.

R. G. Baraniuk and D. L. Jones, "New Signal-Space Orthonormal Bases Via the Metaplectic Transform," *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Victoria, BC, Canada, October 1992.

D. L. Jones and R. G. Baraniuk, "An On-Line Signal-Dependent Time-Frequency Representation," *Fifth IEEE Digital Signal Processing Workshop*, Starved Rock, IL, September 1992.

R. G. Baraniuk and D. L. Jones, "New Dimensions in Wavelet Analysis," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP92*, San Francisco, CA, May 1992.

R. G. Baraniuk, D. L. Jones, T. Brotherton, and S. L. Marple, "Applications of Adaptive Time-Frequency Representations to Underwater Acoustic Signal Processing," *25th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, November 1991.

D. L. Jones and R. G. Baraniuk, "Efficient Computation of Densely Sampled Wavelet Transforms," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations II*, San Diego, CA, July 1991.

R. G. Baraniuk and D. L. Jones, "A Radially Gaussian, Signal-Dependent Time-Frequency Representation," *IEEE International Conference on Acoustics, Speech and Signal Processing — ICASSP91*, Toronto, Canada, May 1991.

D. L. Jones and R. G. Baraniuk, "Signal Dependent Time-Frequency Representations," *Fourth IEEE Digital Signal Processing Workshop*, New Paltz, NY, September 1990.

R. G. Baraniuk and D. L. Jones, "Optimal Kernels for Time-Frequency Analysis," *SPIE Technical Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations I*, San Diego, CA, July 1990.

INVITED PRESENTATIONS

"Wavelet-based Statistical Signal and Image Models," International Wavelets Conference: Wavelets and Multiscale Methods, Tangers, Morocco, April 17, 1998.

"Signal Analysis and Modeling using Time-Frequency Representations and Wavelets," INRIA Rocquencourt, France, October 2, 1997.

"An Introduction to Time-Frequency Analysis with Applications," Statistics Colloquium, Rice University, September 8, 1997.

"Time-Frequency Analysis Applications in Geophysics," Shell Research, Houston, March 26, 1997.

"An Introduction to Time-Frequency Analysis," Haliburton Geophysics, Houston, December 10, 1996.

"Time-Frequency Analysis: Theory and Application," Department of Electrical Engineering, Michigan State University, October 25, 1996.

"Time-Frequency Analysis for Geophysics," Department of Mining and Petroleum Engineering, Technical University of Delft, Netherlands, August 29, 1996.

"New Trends in Time-Frequency Analysis," University of Colorado at Boulder, Department of Electrical Engineering, August 9, 1996.

"Time-Frequency Signal Analysis," Plenary at *Dynamics Days '96*, Lyon, France, July 12, 1996.

"Energy Densities Beyond Time-Frequency: Overview and Synthesis," Invited tutorial at *IEEE-SP International Symposium on Time-Frequency and Time-Scale Analysis*, Paris, France, June 17, 1996.

"Wavelet-based Machinery Diagnostics," Euclid Laboratories, Rockwell Automation, Cleveland, OH, June 4, 1996.

"Time-Frequency Analysis and Wavelets," Texas Instruments, Houston, May 28, 1996.

"Seismic Attributes in Time-Frequency," Mobil Exploration and Producing Technical Center, Dallas, TX, April 22, 1996.

"Time-Frequency Analysis in Biomedical Engineering," University of Houston, Department of Biomedical Engineering, March 29, 1996.

"Interplay between Marginals and Covariance in Joint Distribution Theory," Office of Naval Research Time-Frequency/Time-Scale Analysis Workshop, Princeton, NJ, March 19, 1996.

"Wavelet-based Seismic Features," Exxon Production Research Company, Houston, February 26, 1996.

"Wavelets in Medicine and Biology," 14th Annual Houston Conference on Biomedical Engineering Research, February 8, 1996.

"Digital Signal Processing is Changing Your Life," Major Gifts Committee Luncheon on Computational Engineering, Rice University, January 24, 1996.

"Signal and Image Processing using Time-Frequency Representations," Schlumberger Wireline and Testing, Sugar Land, TX, August 3, 1995.

"New Directions for Time-Frequency Analysis," Mobil-Exxon-Conoco-Arco Wavelets Consortium, Exxon Production Research, Houston, July 10, 1995.

"New Time-Frequency Representations for Time-Varying Spectral Analysis," Western Geophysical, Houston, July 6, 1995.

"Adaptive Time-Frequency Representations," Acoustics and Radar Technology Laboratory, SRI International, Menlo Park, CA, March 10, 1995.

"Signal-Dependent Time-Varying Spectral Analysis," Imaging and Detection Program, Lawrence Livermore National Laboratory, Livermore, CA, March 8, 1995.

"Group Theory, Coordinates, and Time-Frequency Analysis," Department of Electrical and Computer Engineering, University of Michigan, June 24, 1994.

"Répresentations Temps-Frequence Adaptatives," Thematic Days on Time-Frequency, Multiresolution, and Wavelets, INSA Lyon, France, March 10, 1994.

"Time-Frequency Analysis in the Frozen North," IEEE Communications Chapter Seminar Series, University of Manitoba, Canada, December 21, 1993.

"Unitary Equivalence: A New Twist on Signal Processing," Western Atlas International, Houston, November 22, 1993.

"Twisting Signal Processing," Texas Systems Day, University of Texas at Arlington, November 20, 1993.

"Unitary Equivalence: A New Twist on Signal Processing," Joint IEEE Circuits and Systems and Signal Processing Societies Colloquium, Houston Chapter, November 16, 1993.

"Warped Time-Frequency and Time-Scale Representations," Department of Communications, Technical University of Vienna, March 8, 1993.

“Adaptivity, Metaplecity, and Warping in Time-Frequency Analysis,” Workshop on Wavelets, Department of Mathematics, University of Vienna, March 6, 1993.

“Répresentations Temps-Frequence Dépendantes du Signal,” CNRS Groupe de Recherche GdR 134, Telecom Paris, France, January 19, 1993.

“The Karplus-Strong Sound Synthesis Algorithm,” CERL Sound Group Intensive Workshop on Sound Computation, University of Illinois, July 15–24, 1992.

“Getting Lost in Time-Frequency,” Department of Electrical and Computer Engineering, University of Wisconsin-Madison, June 29, 1992.

“New Techniques for Time-Frequency Analysis,” Department of Biomedical Engineering, The Johns Hopkins University, May 12, 1992.

“Signal-Dependent Time-Frequency Analysis or Else,” Department of Electrical and Computer Engineering, The Ohio State University, March 27, 1992.

“Sound Synthesis and Time-Varying Signal Analysis,” CERL Sound Group Intensive Workshop on Sound Computation, University of Illinois, May 22–31, 1991.

CURRICULUM VITAE

Name:	**Charles Sidney Burrus**
Address:	2336 University Blvd., Houston, TX 77005-2647
Telephone:	(713) 529-3125, home; 527-4020, office; (713) 524-5237, FAX; e-mail: csb@rice.edu
Birthplace	Abilene, Texas, October 9, 1934; ss# 465-54-5122
Family:	Married to Mary Lee Powell, 1958; two adult children
Education:	B.A., 1957; B.S. in E.E., 1958; M.S., 1960, Rice University Ph.D., 1965, Stanford University
Honors:	George R. Brown Teaching Awards 1969, 1974, 1975, 1976, 1980 and 1989 IEEE ASSP Society *Senior Paper Award*, 1974 Alexander von Humboldt Foundation Senior Award 1975 Senior Fulbright Fellow 1979 IEEE Fellow 1981 Humboldt Foundation Reinvitation Award 1982 Visiting Fellow at Trinity College, Cambridge, Summer 1984 IEEE ASSP Society *Technical Achievement Award* for research in DSP, 1985 IEEE ASSP Society *Distinguished Lecturer*, 1990-91 IEEE CAS Society *Distinguished Lecturer*, 1991-92 IEEE Signal Processing Society *Society Award*, 1995 Appointed the Maxfield and Oshman Professor of Engineering at Rice, 1995 Meritorious Service Award, Assoc. of Rice Alumni, 1997.
Memberships:	IEEE, ASEE, Tau Beta Pi, Sigma Xi, Scientia, Houston Philosophical Society
Editorships:	Associate Editor: Circuits, Systems, and Signal Processing, 1984 – Consulting Editor: Springer-Verlag Publishers, 1986 – 96.
Registration:	Registered Professional Engineer in Texas, #26351, April 1967
Positions:	
1960-62	U.S. Navy Nuclear Power School, Instructor
1964, 65	Stanford University, Lecturer in Elec. Engineering (Summers)
1965-70	Rice University, Assistant Professor of Electrical Engineering
1970-74	Rice University, Associate Professor of Electrical Engineering
1974-present	Rice University, Professor of Electrical Engineering
1972-78	Master, Lovett College, Rice University
1984-92	Chairman, Electrical and Computer Engineering Dept., Rice University
1992-present	Director of the Computer and Information Technology Institute, Rice Univeristy
1966-73	Baylor College of Medicine, Visiting Professor
1975-76, 79-80	University of Erlangen-Nürnberg, Germany, Guest Professor
1982, 90, 97	University of Erlangen-Nürnberg, Germany (Summers)
1989-90	MIT, Visiting Professor of Electrical Engineering
Consultant to:	TI, NSF, Aware Inc., MathWorks Inc., M.D. Anderson Research

Recent Grants:	NSF:	ENG 78-09033 for Digital Filtering, 3/78 – 2/81
	NSF:	ENG 78-11507 for Equipment in Signal Analysis, 8/78 – 80
	NSF:	ECS 81-00453 for Structures in Signal Processing, 2/81 – 11/83
	NSF:	ECS 83-14006 for Algorithms and Signals in DSP, 12/83 – 5/87
	NSF:	ECS 84-05435 for a Research Computer Facility, 1984–85
	AFOSR:	DARPA URI, Computational Mathematics Lab. 1990 – 2000
	NSF:	ECS-9018681 for Integration of Computing into the Engr. Classroom, 1990 – 93
	Nortel:	Grant for Research in Digital Filter Design, 1992–98
	TI:	Grant for Research on Wavelet Based DSP, 1993–94
	NASA:	Grant for Wavelet Based Signal Processing Research, 1994–95
	Texas:	ATP-Research grant, “Data Compression based on Wavelets”, 1994–96
	NSF:	MIP-9316588 “Digital Filter Design”, 1994–97.
	NSF:	Grant, “Multiprocessor Cluster Computing”, 1995-2000.
	Texas:	ATP-Research grant, “Wavelet based Image Processing”, 1996–98.

Courses Taught:
Engineering 241/Electrical Circuits
Engineering/Sociology 360/World Dynamics
Electrical Engineering 342/Electronics
Electrical Engineering 401/Linear System Theory
Electrical Engineering 507/Nonlinear Analysis
Electrical Engineering 502/Network Synthesis
Electrical Engineering 531/Digital Signal Processing
Electrical Engineering 696/Seminar in Digital Filtering
EECS 6.341/Discrete -Time Signal Processing (MIT)
Mentor in the Rice Fellows Program

Masters, PhD, and Post Doctoral Fellows Supervised

1. R. R. Read, “A Method of Computing the Fast Fourier Transform,” M.S. Thesis, June 1968.
2. R. S. McKnight, “A Numerical Procedure for Distributed RC Network Synthesis,” M.S. Thesis, June 1969.
3. T. L. Chang, “Approximate Solutions of Nonlinear Systems using a Time Varying Linear Systems,”M.S. Thesis, June 1969.
4. M. L. Fontenot, “Analytic Approximation of Galerkin’s Procedure for Computing Forced Oscillations of Nonlinear Systems,”Ph.D. Thesis, June 1970.
5. F. S. Souto, “A Mixed Flat and Equal Ripple Criterion for Filter Design,” Ph.D. Thesis, June 1970.
6. T. L. Chang, “Nonlinear Oscillations in Quantized Linear Discrete-Time Systems,” Ph.D., 1971.
7. R. R. Read, “Geometry of Partial Sums,” Ph.D. Thesis, May 1971.
8. R. C. Agarwal, “On Realization of Digital Filters,” Ph.D. Thesis,December 1973.
9. R. A. Meyer, “Analysis and Design of Periodically Time-Varying Digital Filters,” Ph.D. Thesis, April 1974.
10. Jatinder Gulati, “Time Domain Design of Recursive Digital Filters with Prespecified Poles,”M.S. 1974.
11. Shuni Chu, “Application of Distributed Arithmetic to Digital Signal Processing,” M.S. Thesis, July 1979.
12. C. M. Loeffler, “Finite Register Effects in Block Digital Filters,” M.S. Thesis, May 1979.
13. Shuni Chu, “On Efficient Digital Filtering,” Ph.D. Thesis, May, 1981.

14. C. M. Loeffler, “Analysis and Design of Periodically Time-Varying Digital Filters,” Ph.D. Thesis, 1982.
15. H. W. Johnson, “The Design of DFT Algorithms,” Ph.D. Thesis, April 1982.
16. M. T. Heideman, “Fast Algorithms for the DFT and Convolution with Constrained Inputs and Restricted Outputs,” Ph.D. Thesis, May 1986.
17. H. V. Sorensen, “FFT Algorithms for Constrained Data,” Ph.D. Thesis, May 1988.
18. R. A. Gopinath, “Analysis of Scale – Time Perturbed Signals Using Wavelets,” M.S. Thesis, May 1990.
19. A. W. Soewito, “Least Squared Error Methods in FIR Digital Filter Design,” Ph.D. Thesis, Dec. 1990.
20. José A. Barreto, “L_p-Approximation by the Iteratively Reweighted Least Squares Method and the Design of Digital FIR Filters in One Dimension”, M.S. Thesis, August 1992.
21. R. A. Gopinath, “Wavelets and Filter Banks – New Results and Applications”, Ph.D. Thesis, August 1992.
22. Haitao Guo, “Theory and Applications of the Shift-Invariant, Time-Varying and Undecimated Wavelet Transform”, MS Thesis, April 1995.
23. Dong Wei, “Image Data Compression Using Wavelet Decomposition”, MS Thesis, April 1995.
24. Jan Erik Odegard, “Moments, Smoothness and Optimization of Wavelet Systems”, Ph.D. Thesis, February 1996.
25. Ivan W. Selesnik, “New Techniques for Digital Filter Design”, Ph.D. Thesis, March 1996.
26. Haitao Guo, “Wavelet for Ajpproximate Fourier Transform and Data Compression”, Ph.D. Thesis, April 1997.
27. James Lewis, M.S. research in progress.
28. Markus Lang, Post doctoral fellow from University of Erlangen, 1993–95.
29. Jürgen Götze, Post doctoral fellow from the Technical University of Munich, 1995–96.
30. Ivan W. Selesnik, Post doctoral fellow from Rice Univerisity, 1996–97.
31. Hou Jin Chen, Visiting Scholar from Northern Jiaotong Universioty, Beijing, China, 1997–98
32. Nuria Gonzalez Prelcic, Visiting Scholar from Universidad de Vigo, Vigo, Spain, 1997–98.

Research Grants:

NSF Grant GK 807 for Research in Nonlinear Systems, 1966-1968, $18,700.

NSF Grant GK 23697, Digital Signal Representation and Filtering” (with T.W. Parks), 9/01/70 – 9/01/72, $86,300; renewed through 9/01/75, $92,900.

A.P. Sloan Foundation Grant, “The Use of Macro-Simulators of Global Interactions in Motivation and Training of Engineering Students,” (Sub-allotment) Sep. 1972 – Sep. 1975.

NSF Grant ENG 75-22862, “Digital Signal Representation and Filtering” (with T.W. Parks), March 1976 – Aug. 1978, $88,200.

DOD Grant DASG 60-77-C-0091 and 60-78-C-0082, for Ballistic Missile Defense Advanced Technology Center, “Efficient Techniques for Signal Processing,” May 1977 – May 1979, (with T.W. Parks and P. Kazakos), $85,000.

NSF Grants ENG 78-09033 and ECS 81-00453, “Digital Signal Representation and Filtering”, and ”Efficient Structures for DSP”, (with T.W. Parks), 8/1/78 – 11/30/83, $264,520.

NSF Grant ENG 78-11507, Equipment grant for research in Signal Analysis and Image Processing, Aug. 1978 – Jan. 1980, (with R.J.P. deFigueiredo and others), $62,200.

NSF CER Grant MCS-81-21884, "R^n : An Experimental Local Computer Network to Support Numerical Computation" (contributing investigator), 6/82 – 6/87; $2,336,700.

NASA Grant NGT 44-006-804, student support for "Research on Digital Signal Processing," 4/83 – 4/86, $34,300.

NSF Grant ECS 83-14006, "Algorithms and Signal Representation for Digital Signal Processing" (with T.W. Parks), 12/15/83 – 5/31/87; $284,366.

NSF Grant ECS 84-05435, "Computer and Graphics Facility for Research in System Theory" (with five others), 1984 - 5, $64,800.

Texas Instruments, Inc., REDDI contract, "Development of FFT Algorithms for the TMS 320," 1/88 – 11/88, $26,963. Aware, Inc., REDDI contract ECE 114, "The Investigation of Wavelets and their Application to Signal Processing," 6/89 – 6/90, $29,400.

NSF Grant ECS-9018681, "Integration of Computational Resources into the Engineering Classrooms", 7/1990 – 8/93, $49,977.

DARPA URI, "Computational Mathematics Laboratory for Multiscale Analysis", (with R. O. Wells), 1990 – 93, $600,000; renewed for 1993 – 96, $500,000.

Nortel (BNR), Inc., "Design of Digital Filters", Research grant, 1992–98; $210,000.

Texas Instruments, Inc., "Wavelet Based Signal Processing", Research grant, 9/1993–94; $20,000.

NASA grant, "Wavelet Based DSP", (Wells PI), 1994–95, $60,000.

ATP grant from the Texas Higher Education Coordinating Board, "New Data Compression Techniques based on Time-Varying and Data-Dependent Wavelets", (with R. Baraniuk), 1994–96, $244,600.

NSF grant MIP-9316588, "Iterative Reweighted Least Squares Design of Digital Filters", 1994–97, $251,000.

NSF grant, "Multiprocessor Cluster Computing", 1995-2000, with Zwaenepoel (PI), Kennedy, Symes, and Vardi, $1,153,000.

ATP grant from the Texas Higher Education Coordinating Board, "Compression, Recognition and Classification Algorithms for Digital Images", 1996–98, $150,000, (with Wells, Starkschall, and Cabrera).

NSF CISE Research Instrumentation grant CDA-96-17383, "Design and Evaluation of Architecture, Programming Environments, and Applications for Shared-Memory Systems", $83,000, (S. Adve, et al).

AFOSR grant F4962097-1-053 for "Wavelet Compression and Modeling for ATR Problems", $744,000 for three years. (Wells PI, with Baraniuk) 1997–2000.

Northrop Grummand subcontract from AFOSR – DARPA for work on SAR and sonar using wavelets. $75,000 over three years. (with Wells and Baraniuk) 1997 – 2000.

NSF grant suppliment for undergraduate student research, $10,000, 1997.

Consortium in Geophysical Signal Processing, funded by Mobel, Arco, Conoco, and Halliburton, (with Baraniuk and CML), $25,000 per year per company.

SBI grant from NIH, "Wavelet-Based Automated Chromosome Identification", (with PSI, Inc and Ken Castleman), $95,000, Sept. 1997.

Services to University and Community:

Master of Lovett College, 1972-78
Acting Master of Will Rice College, Spring 1971
Associate of Will Rice College, 1966 - 72
Associate of Lovett College, 1980 - 89
Faculty Sponsor of Student Senate 1971-72
Faculty Sponsor of Student Radio Station KTRU, 1973-1988

Elected member of Faculty Council, 1971-74
Elected member of Rice Alumni Executive Board, 1970-73, 1983-86
Elected member of Rice Engineering Alumni Board, 1970-76
Elected member of University Council, 1977-81
Elected speaker of the Faculty Council, 1978-79
Elected member of the University Presidential Search Committee, 1984-85

University Committees:

Committee of College Masters, 1971-78
Undergraduate Teaching Committee, 1967-72, 1976-79, 1990-94
University Welfare Committee, 1968-71
Undergraduate Affairs Committee, 1968-72
Committee on Undergraduate Curriculum, 1973-1974
Committee on Student Affairs, 1976-77
Danforth Fellowship Selection Committee, 1978; Rhodes and Marshall, 1983-84
Computer Science Program Committee, 1981-1984
Computer Committee, 1982-83
Coordinator of the C.D. Broad Exchange program between Rice and Trinity College at Cambridge University, 1983–85
Engineering Computer Facility Committee, 1985–87
Committee on Public Lectures, 1986–89, 93–
Ad Hoc Committee on Curriculum Reform, 1986–87
Member of Assoc. Provost and VP for Computing Search Committee, 1986–87, 1991–92
Member of Task Force on Substance Abuse, 1987–88
Member of Planning Board on Computing, 1987-
Chair of University Educational Computing Planning Committee, 1987-89
Member of Owl-Net Steering Committee, 1987 – 89
Member of Search Committee for the Chair of Computer Science, 1989
Member of CITI Steering Committee, 1988–
Member of Alumni Publication Editorial Board, 1991–94
University Self-Study Steering Committee, 1983–84, 1993–95
Member of Search Committee for Director of the Baker Institute on Public Policy, 1993–94
Member of Search Committee for the Dean of Humanities, 1994–95
Member of Search Committee for University Librarian, 1995–96
Member of Library Planning Committee, 1995–
Member of Search Committee for Freidkin Chair in the Jones School, 1995–96
Member of Ad Hoc University Curriculum Committee, 1996–98

Professional

Elected to IEEE Signal Processing Society's Ad-Com., 1991-93.

Member of the Technical Committee on Signal Processing of the IEEE Circuits and Systems Society, 1974 - 83 (Chair 1976-1979).

Member of Program Committee for the IEEE International Symposium on Circuits and Systems, Munich, 1976; Phoenix, 1977; Houston, 1980. Session chair: Chicago, 1981; Espoo, 1988.

Session chair ICASSP: San Diego, CA, 1984, Tampa, FL, 1985, Tokyo, Japan, 1986, Dallas, TX, 1987, New York, NY, 1988, Glasgow, 1989, Albuquerque, 1990; Toronto, 1991.

Session Chair and Organizer: IEEE ASSP Society *1988 Digital Signal Processing Workshop,* Stanford Sierra Lodge, Tahoe, CA, September 16, 1988.

Member of the Technical Program Committee for the Asilomar Conference on Systems, Signals, and Computers, Pacific Grove, CA, November 1987; November 1988.

IEEE representative for university accreditation of engineering programs, ABET, 1980-85, 1986-91.

Member of NSF Panel to evaluate Research Initiation Grant proposals, 1979, 1992.

Member of NSF panel meeting on "Communications Systems and Signal Processing," January 21-22, 1986.

Member of the NSF Advisory Committee for Electrical, Communications, and Systems Engineering Division, 1986-92; Tri–annual Oversight Committee, May 1987, 1990.

Member of NSF panel to evaluate Presidential Young Investigator Award proposals, 1987.

Member of National Research Council graduate fellowship evaluation panel, Feb. 1988, 1989, 1990.

Member of ONR Electronics Division Board of Visitors, 1992–93

Service, Short Courses, etc.

Texas Society of Professional Engineers teaching award, 1968.

J. S. Fulton Service Award from Will Rice College, 1971.

Member of the Technical Advisory Committee of the Model City Program for Houston, 1969-70.

Member of Board of Directors, Citizens for Good Schools, 1974-76.

Science Fair Judge, Houston, TX, 1982-83.

Presented Short Course on "Digital Signal Processing" through the Office of Continuing Studies, May 1972, May 1973, April 1975, and January 1977.

Taught advanced short course on "Efficient Algorithms for Convolution and the DFT," Ford Aerospace, Palo Alto, CA, July 13-17, 1981; IBM - Federal Systems Div., Manassas, VA, June 1983.

Taught short course on Matlab at MathWorks, Inc., Natick, MA, Aug. 9, 1991.

Taught short course on Wavelets and Wavelet Transforms for Western Geophysical, Inc. Houston, Tx, May 25, 1995; for Halliburton Energy Services, Houston, Tx, Jan. 7, 1997.

Reviewed Journal Publications

[1] C. S. Burrus, "Versatile FM Transducer," *Electronics*, November 13, 1959, vol. 32, no. 46, p. 79; also in *Design Manual for Transistor Circuits*, edited by J. M. Carrol, McGraw-Hill, 1961, p. 207.

[2] C. R. Wischmeyer and C. S. Burrus, "The Varactor Upper-Sideband Up-Converter," *Microwave Journal*, vol. 7, no. 6, June 1964, pp. 87-92.

[3] C. S. Burrus and T. W. Parks, "Time Domain Design of Recursive Digital Filters," *IEEE Trans. on Audio and Electroacoustics*, vol. AU-18, no. 2, June 1970, pp. 137-141.

[4] C. S. Burrus, T. W. Parks, and T. B. Watt, "A Digital Parameter-Identification Technique Applied to Biological Signals," *IEEE Trans. on Bio-Medical Engineering*, vol. BME-18, no. 1, January 1971, pp. 35-37.

[5] C. S. Burrus, "Block Implementation of Digital Filters," *IEEE Trans. on Circuit Theory*, vol. CT-18, no. 6, November 1971, pp. 697-701.

[6] R. R. Read and C. S. Burrus, "Use of the Geometry of Partial Sums in Digital Filter Analysis," *IEEE Trans. on Audio and Electroacoustics*, vol. AU-20, no. 3, August 1972, pp. 213-218.

[7] C. S. Burrus, "Block Realization of Digital Filters," *IEEE Trans. on Audio and Electroacoustics*, vol. AU-20, no. 4, October 1972, pp. 230-235.

[8] M. L. Fontenot and C. S. Burrus, "An Analytical Method for Approximating High Order Galerkin Solutions," *The Journal of Mathematical Analysis and Applications*, vol. 42, no. 1, April 1973, pp. 158-173.

[9] R. C. Agarwal and C. S. Burrus, "Fast One-Dimensional Digital Convolution by Multi-Dimensional Techniques," *IEEE Trans. on Acoustics, Speech, and Signal Processing*, vol. ASSP-22, no. 1, February 1974, pp. 1-10.

[10] R. C. Agarwal and C. S. Burrus, "Fast Convolution using Fermat Number Transforms with Applications to Digital Filters," *IEEE Trans. on Acoustics, Speech, and Signal Processing*, vol. ASSP-22, no. 2, April 1974, pp. 87-97.

[11] C. S. Burrus, "A Review of *Discrete Time Systems* by Cadzow," IEEE Trans. on Acoustics, Speech and Signal Processing, vol. ASSP-23, no. 1, February 1975, p. 5. Also in *Proc. IEEE*, vol, 63, no. 8, August 1975, p. 1262.

[12] R. A. Meyer and C. S. Burrus, "A Unified Analysis of Multirate and Periodically Time Varying Digital Filters," *IEEE Trans. on Circuits and Systems*, vol. CAS-22, no. 3, March 1975, pp. 162-168.

[13] R. C. Agarwal and C. S. Burrus, "Number Theoretic Transforms to Implement Fast Digital Convolution," *Proc. of IEEE*, vol. 63, no. 4, April 1975, pp. 550-560.

[14] C. S. Burrus, R. R. Read, and T. W. Parks, "Parameter Identification of Signals Composed of Delayed Exponentials," *IEEE Trans. on Bio-Medical Engineering*, vol. BME-22, no. 3, May 1975, pp. 246-248.

[15] R. C. Agarwal and C. S. Burrus, "New Recursive Digital Filter Structures Having Very Low Sensitivity and Round-Off Noise," *IEEE Trans. on Circuits and Systems*, vol. CAS-22, no. 12, December 1975, pp. 921-927.

[16] T. B. Watt and C. S. Burrus, "Arterial Pressure Contour Analysis for Estimating Human Vascular Properties," *Journal of Applied Physiology*, vol. 40, no. 2, February 1976, pp. 171-176.

[17] R. A. Meyer and C. S. Burrus, "Design and Implementation of Multirate Digital Filters," *IEEE Trans. on Acoustics, Speech and Signal Processing*, vol. ASSP-24, no. 1, February 1976, pp. 53-58.

[18] S. K. Mitra and C. S. Burrus, "A Simple Efficient Method for the Analysis of Structures of Digital and Analog Systems," *Archiv für Elektronik und Übertragungstechnik (AEÜ)*, vol. 31, no. 1, Jan. 1977, pp. 33-36.

[19] C. S. Burrus, "Index Mapping for Multidimensional Formulation of the DFT and Convolution," *IEEE Trans. on Acoustics, Speech and Signal Processing*, vol. ASSP-25, no. 3, June 1977, pp. 239-242.

[20] J. K. Monts, M. S. Lynn, and C. S. Burrus, "Interdisciplinary Instruction of the Dynamic Simulation of Social Systems," *Teaching Sociology*, vol. 4, no. 4, July 1977, pp. 315-333.

[21] C. S. Burrus, "Digital Filter Structures Described by Distributed Arithmetic," *IEEE Trans. on Circuits and Systems*, vol. CAS-24, no. 12, Dec. 1977, pp. 674-680.

[22] C. S. Burrus and P. W. Eschenbacher, "An In-Place, In-Order Prime Factor FFT Algorithm," *IEEE Trans. on Acoustics, Speech, and Signal Processing*, vol. ASSP-29, no. 4, Aug. 1981, pp. 806-817.

[23] S. Chu and C. S. Burrus, "A Prime Factor FFT Algorithm using Distributed Arithmetic," *IEEE Trans. on Acoustics, Speech and Signal Processing*, vol. ASSP-30, no. 2, April 1982, pp. 217-227.

[24] C. S. Burrus, "Computation of the Discrete Fourier Transform," *Trends and Perspectives in Signal Processing*, vol. 2, no. 2, Apr. 1982, pp. 1-4.

[25] C. S. Burrus, "Comments on 'Selection Criterion for Efficient Implementation of FFT Algorithms'," *IEEE Trans. on ASSP*, vol. ASSP-31, no. 1, Feb. 1983, p. 106.

[26] I. Pitas and C. S. Burrus, "Time and Error Analysis of Digital Convolution by Rectangular Transforms," *Signal Processing*, vol. 5, no. 2, March 1983, pp. 153-162.

[27] H. W. Johnson and C. S. Burrus, "The Design of Optimal DFT Algorithms using Dynamic Programming," *IEEE Trans. on ASSP*, vol. ASSP-31, no. 2, April 1983, pp. 378-387.

[28] S. Chu and C. S. Burrus, "Optimum FIR and IIR Multistage Multirate Filter Design," *Circuits, Systems and Signal Processing*, vol. 2, no. 3, July 1983, pp. 361-386.

[29] S. Chu and C. S. Burrus, "A Recursive Realization of FIR Filters, Part I: The Filter Structures," *Circuits, Systems and Signal Processing*, vol. 3, no. 1, Feb. 1984, pp. 3-20.

[30] S. Chu and C. S. Burrus, "A Recursive Realization of FIR Filters, Part II: Design and Application," *Circuits, Systems and Signal Processing*, vol. 3, no. 1, Feb. 1984, pp. 21-57.

[31] M. T. Heideman, D. H. Johnson, and C. S. Burrus, "Gauss and the History of the FFT," *IEEE ASSP Magazine*, vol. 1, no. 4, Oct. 1984, pp. 14-21.

[32] C. M. Loeffler and C. S. Burrus, "Optimal Design of Periodically Time Varying and Multirate Digital Filters," *IEEE Trans. on ASSP*, vol. ASSP-32, no. 5, Oct. 1984, pp. 991-998.

[33] S. Chu and C. S. Burrus, "Multirate Filter Designs using Comb Filters," *IEEE Trans. on Circuits and Systems*, vol. CAS-31, no. 11, Nov. 1984, pp. 913-924.

[34] S. Chu and C. S. Burrus, "Roundoff Noise in Multirate Digital Filters," *Circuits, Systems and Signal Processing*, vol. 3, no. 4, Nov. 1984, pp. 419-434.

[35] H. W. Johnson and C. S. Burrus, "On the Structure of Efficient DFT Algorithms," *IEEE Transactions on ASSP*, vol. ASSP-33, no. 1, Feb. 1985, pp. 248-254.

[36] H. V. Sorensen, D. L. Jones, C. S. Burrus and M. T. Heideman, "On Computing the Discrete Hartley Transform," *IEEE Transactions on ASSP*, vol. ASSP-33, no. 5, Oct. 1985, pp. 1231-1238.

[37] M. T. Heideman, D. H. Johnson, and C. S. Burrus, "Gauss and the History of the FFT," *Archive for History of Exact Sciences*, vol. 34, no. 3, 1985, pp. 265-277.

[38] M. T. Heideman and C. S. Burrus, “On the Number of Multiplications Necessary to Compute a length-2^n DFT,” *IEEE Transactions on ASSP*, vol. ASSP-34, no. 1, Feb. 1986, pp. 91-95.

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[111] C. S. Burrus "Wavelet Based Signal Processing: Where are We and Where are We Going?", Plenary Talk, *Proceedings of the International Conference on Digital Signal Processing, DSP-97*, Santorini, Greece, July 1997, vol. I, pp. 3–5.

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CURRICULUM VITAE

Name:	Raymond O. Wells, Jr.
Personal Data:	Born 12 June 1940, Dallas, Texas U.S. Citizen Married, 2 children
Education:	Ph.D. New York University, 1965 MS New York University, 1964 BA Rice University, 1962
Areas of Research:	Several Complex Variables, Algebraic Geometry Mathematical Physics, Mathematics Education, Applied Mathematics
Professional Appointments:	Professor, Rice University, 1974–present Visiting Professor, University of Bremen, 1995-96 Ulam Visiting Professor, University of Colorado, 1983–84 Member, Institute for Advanced Study, 1979–80 Visiting Professor, University of Göttingen, 1974–75 Associate Professor, Rice University, 1969–74 Member, Institute for Advanced Study, 1970–71 Assistant Professor, Rice University, 1965–69 Visiting Assistant Professor, Brandeis University, 1967–68

Presentations

Invited Address, Amer. Math. Soc.-Mex. Math. Soc. Joint Meeting, Oaxaca, Mexico, December 1997
Colloquium, Rice University School Mathematics Project, June 1997
Colloquium, University of Houston, April 1997
Colloquium, University of Texas at Dallas, April 1997
Lecture Series (3 Lectures) Swiss Federal Institute of Technology, February, 1997
Presentation, DARPA Program Review, Washington, June 1996
Colloquium, Rice University School Mathematics Project, June 1996
Colloquium, Swiss Federal Institute of Technology, May 1996
Presentation, Houston Advanced Research Center, April 1996
Colloquium, University of Hamburg, April, 1996
Colloquium, University of Freiburg, Freiburg, February 1996
Colloquium, Max Planck Institute for Mathematics, December 1995
Invited Lecture, German Computer Science Society, Bremen, September 1995
Colloquium, University of Bremen, May 1995
Special Lecture Series, University of Bremen, November 1994
Invited Lecturer, IEEE Section Meeting, NASA Johnson Space Center, August 1994
Special Lecture Series, University of Bremen, May 1994
NASA Dual Use Technology Conference, Invited Lecturer, February 1994
Invited Lecturer, SPIE Meeting, April 1994
Eisenhower Program Lecture, Texas Higher Education Coordinating Board, Feb 1994
Invited Lecturer, Lanczos Centenary Conference, N. Carolina State Univ, December 1993
Invited Lecturer, ARPA ATR Conference, Lincoln Laboratories, Lincoln, Massachusetts, November 1993
Invited Lecturer, International Conference on Wavelets, Taormina, Italy, October 1993
Invited Lecturer, SIAM Minisymposium, April 1993
Invited Lecturer, NATO Intl. Conf. on Mathematical Physics, San Antonio, January 1993
Invited Lecturer, SPIE International Conference, Boston, November 1992

Invited Lecturer, International Congress on Mathematics Education, Quebec City, August 1992
Invited Lecturer, IEEE Signal Processing Chapter, Houston, December 1991
Invited Lecturer, Society of Exploration Geophysicists, Houston, November 1991
Annual Mathematics-Physics Lecture, Syracuse University, April 1990
Invited Lecturer, Special Session of Amer. Assn. Adv. Science, February 1990
Invited Lecturer, Special Session of Amer. Math. Soc. Meeting, January 1990
Invited Lecturer, Mathematicians and Education Workshop, Minneapolis, July 1989
Invited Lecturer, International Conference *Physics and Geometry*, Lake Tahoe, 1989
Invited Lecturer, University of California Summer School on Nonlinear Science, University of California Davis, June 1989
Invited Lecturer, International Symposium on Differential-Geometric Methods in Theoretical Physics, Montreal, July 1988
Invited Lecturer, International Symposium on Relativity, Spinors and Twistors, Durham, England, July 1988
Invited Lecturer, International Congress on Mathematics Education, Budapest, August 1988
Invited Address, Rice Alumni Institute, October 1987
Invited Lecturer, Nankai Institute of Mathematics, China, Oct.–Nov. 1986
Invited Lecturer, University of Madrid, July 1986
Invited Lecturer, International Conference on Non–linear Differential Equations and Solitons, University of Montreal, August 1985
Invited Lecturer, Western States Mathematical Physics Meeting, Cal. Inst. Tech., April 1985
Invited Lecturer, Math. Research Inst., Bulgarian Acad. of Sciences, Sofia, Bulgaria, October 1984
Invited Lecturer, Int. Conf. on Algebra & Analysis, Steklov Institute, Moscow, USSR, Sep 1984
Hour Address, Mathematical Association of America, Colorado Springs, April 1984
Invited Lecturer, Int. Conf. on Diff.-Geom. Meth. Th. Physics, Clausthal, W. Germany, Aug 1983
Invited Lecturer, Summ. Sch. on Diff.- Geom. Meth. in Th. Physics, Varna, Bulgaria, Sep. 1982
Hour Address, Pacific Northwest Geometry Symposium, May 1982
Hour Address, Western States Mathematical Physics Meeting, May 1982
Hour Address, Mathematical Association of America, Pittsburgh, August, 1981
Invited Lecturer, Summ. Sch. Non–Linear Part. Diff. Operators and Quant. Procedures, Tech. University Clausthal, W. Germany, July 1981
Four Week Lecture Series, University Mannheim, June 1981
Invited Lecturer, Symposium on Nonlinear Problems in Science, Rice University, March 1981
Three Week Lecture Series, University of Montreal, August 1980
Symposium on the Mathematical Heritage of Henri Poincaré, Bloomington, IN, March 1980
Two Week Lecture, Stefan Banach International Mathematical Center, Warsaw, February 1979
Conference on Complex Manifold Tech. Theoretical Physics, University of Kansas, July 1978
Pacific Northwest Geometry Seminar, University of Utah, February 1978
Invited Lecturer, Rice Alumni Institute, February 1977
Special Session Invited Lecture, Amer. Math. Soc. Meeting, San Antonio, 1976
Hour Address, Amer. Math. Soc. Meeting, Chicago, 1975
Amer. Math. Soc. Summer Institute, Williamstown, MA, 1975
Amer. Math. Soc. Summer Institute, Stanford, 1973
Conference on Complex Analysis, Park City, UT, 1969
Complex Analysis Conference, Oberwolfach, Germany, 1965

Honors:

Fellow, American Association for the Advancement of Science, 1986
National Academy of Sciences Exchange Visitor: Bulgaria, 1984
Guggenheim Fellow, 1974
Cosmos Club of Washington, 1978-present
Alexander von Humboldt Senior U. S. Scientist Award, 1974

Fulbright Award, 1968

Professional Activities:

Member, AMS-MAA Committee on Teaching Assistants and Part-Time Instructors, 1992-Present
Member, Editorial Board, Sallyport, 1991-present
Member, Editorial Board, Expositions in Mathematics, de Gruyter & Co., Berlin, 1988-present
Member, Steering Group, AAAS Section in Mathematics, 1989-1994
Member, Oversight Committee, Resources for Mathematics Reform Project, Educational Development Corp., Newton, MA, 1989-1992
Member, Advisory Committee, Mathematicians and Education Reform Network, 1988-1992
Member, Committee on Mathematics Enhancement for Teachers, Math Assoc. Amer., 1988-1992
Consultant and Fellow, Aware, Inc., Cambridge, MA, 1987-present
Member, Committee on Assessment, Council of Chief State School Officials, 1987–88
Chairman, Steering Committee, American Mathematics Project, Berkeley, 1987–1992
Delegate, International Math. Union General Assembly, Berkeley, 1986
Member, Nominating Committee, Amer. Math. Society, 1985–86
Member, U. S. Commission on Mathematical Instruction, 1985–1989
Member, Mathematical Sciences Advisory Board of College Board, 1985–88
Managing Editor, Mathematical Surveys and Monographs, Amer. Math. Society, 1985–88
Chairman, MAA–NCTM Teacher Support Network Project Steering Committee, 1984–1987
Member, U. S. National Committee on Mathematics, 1984–87
Member, Organizing Committee, Summer Research Conference on Integral Geometry, Bowdoin College, Maine, August 1984
Member, Organizing Committee, Research Conference: Asymptotic Behavior of Mass and Space–time, Oregon State University, October 1983
Managing Editor, Contemporary Mathematics, Amer. Math. Society, 1983–87
Editor, Mathematical Surveys and Monographs, Amer. Math. Society, 1983–85; Managing Editor, 1985–1987
Member, Educational Testing Service, Committee on Achievement Tests, 1982–present; Chairman 1984–88
Member, Amer. Math. Society Committee on Summer Research Conferences, 1979–present; Chairman 1981–86
Member, Review Panel, NSF Program in Classical Analysis, October 1978
Member, Council of the Amer. Math. Society, 1979–88
Editor, Transactions and Memoirs of the Amer. Math. Society, 1979–82; Managing Editor, 1983–85
Member, Steele Prize Committee, Amer. Math. Society, 1978–82
Member, Amer. Math. Society Committee to select hour speakers for Western Sectional Meetings, 1976–78; Chairman 1977–78
Member, Organizing Committee, Bicentennial History of Mathematics Conf. Series, 1974–77
Member, Organizing Committee of the Amer. Math. Committee Summer Institute on Several Complex Variables, Williamstown, MA, 1975
Elected member, Amer. Math. Society Nominating Committee, 1975–77; Chairman 1976–77
Member, Regional Conference Board of Mathematical Sciences, 1974–77
Co–organizer, Conference on Complex Analysis, Rice University, 1972
Classifier, Mathematics articles in complex analysis for Amer. Math. Society, 1967–74
Co–organizer, Conference on Complex Analysis, Rice University, 1969
Co–organizer, Conference on Complex Analysis, Rice University, 1967

Post-Doctoral Students Supervised:

Kathrin Berkner, 1997
Xiaodong Zhou, 1990-1995

Andreas Rieder, Feodor von Lynen Fellow, 1992-1993

Graduate Students Supervised:

Yuan Wang, 1998
Jun Tian, 1996
Oscar Garcia-Prada, MA, 1988
Carl Haske, Ph.D., 1986
Victoria Yasinovskaya, Ph.D., 1983
Robert Pool, Ph.D., 1981
Eric Swartz, MA, 1981
David Johnson, Ph.D., 1978
Oscar Melendez, MA, 1977
James Drouilhet, Ph.D., 1974
J. Becker, Ph.D., 1971
R. Carmignani, Ph.D., 1970
Michael Windham, Ph.D., 1970
L. R. Hunt, Ph.D., 1970
Joseph E. Krueger, MA, 1966

University Activities:

Chairman, Education Department, 1994-present
Chairman, Education Council, 1994-present
Rice University Press, Editorial Board, 1991-1993
Director, Computational Mathematics Laboratory, 1989-present
Education Council, 1987-1991
Director, Rice University School Mathematics Project, 1987–present
Baker College Associate, 1985–1991
Chairman, G. C. Evans Committee, 1985–86
Rice University Press, Editorial Board, 1985–88
Member, SCIENTIA (An Institute for the History of Science and Culture), 1980–present; Director, 1982–88
Chairman, Graduate Committee, Math. Dept., Fall 1975; 1982–83; 1986–present
Chairman, Curriculum Committee, Math. Dept., 1980–82
Rice University Studies Review Board, 1980–85
Jones College Associate, 1968–80
Chairman, Department of Mathematics, 1976–79
Chairman, Appointments Committee, Math. Dept., Jan.–March 1974
Member, University Library Committee, 1977–77; Chairman 1975–77
Rice University Self Study Committee, Jan. 1973–May 1974; Chairman, Library and Computer Subcommittee

Honorary and Professional Societies:

American Association for the Advancement of Science
American Mathematical Society
Association of Members of the Institute for Advanced Study
Houston Philosophical Society
Mathematical Association of America
National Council of Teachers of Mathematics
Phi Beta Kappa
Society for Industrial and Applied Mathematics

Civic Activities:

Stages Repertory Theater, Board of Directors, 1988-present, Secretary 1988-89, President, 1989-91.

PUBLICATIONS

Books:

1. (with Resnikoff, H. L., editors) *Proceedings of the Conference on Complex Analysis, Rice University, 1967,*) Rice University Studies, **54**, No. 4, 1968.
2. (with Resnikoff, H. L., editors) *Proceedings of the Conference on Complex Analysis, Rice University, 1969,* Rice University Studies, **56**, No. 2, *Complex Analysis*, 1970.
3. (with Resnikoff, H. L., editors) Rice University Studies, **59**, Nos. 1, 2, *Proceedings of the Conference on Complex Analysis, Rice University, March 1972*, 1973.
4. (with Resnikoff, H. L.) *Mathematics in Civilization* (Preliminary edition 1971), Holt, Rinehart, and Winston, Inc., New York, 372 pp., 1973.
5. *Differential Analysis on Complex Manifolds,* Prentice Hall, Inc., Englewood Cliffs, NJ, 252 pp., 1973.
6. *Differential Analysis on Complex Manifolds,* (Russian translation by E.M. Chirka), MIR, Moscow, 283 pp., 1976.
7. *Several Complex Variables. (Proc. Sympos. Pure Math., Vol.XXX, Parts 1,2, Williams College, 1975),* Amer. Math. Soc., Providence, RI, 1977.
8. (with Stanton, R.J.) *History of Analysis*, Rice University Studies, **68**, Nos. 2, 3, ,1978.
9. *Differential Analysis on Complex Manifolds*, 2nd Edition, Springer–Verlag, Berlin–Heidelberg, New York, 1980.
10. *Complex Geometry and Mathematical Physics,* University of Montreal Press, Montreal, 1982.
11. (with Resnikoff, H.L.) *Mathematik in Wandel der Kulturen,* (German ed. of Math. in Civilization, including supplement), Vieweg Verlag, Braunschweig–Wiesbaden, 338 pp., 1983.
12. (editor of translation from Russian) Monastyrskii, M. I. *Riemann, Topology, and Physics,* Birkhauser Boston, Boston, 1985.
13. (with Chance, Jane, editors) *Mapping the Cosmos,* Rice University Press, Houston, Texas, 1985.
14. (with Resnikoff, H.L.) *Mathematics in Civilization,* (second edition), Dover Books, New York, 1985.
15. (with Bryant, R.L., Guillemin, V., and Helgason, S., editors) *Integral Geometry,* Amer. Math. Soc., Providence, RI, 1985.
16. (with Shnider, S.) *Supermanifolds, Super Twistor Spaces and Super Yang–Mills Fields*, University of Montreal Press, 1989.
17. (Editor) *The Mathematical Heritage of Hermann Weyl, Amer. Math. Soc.,* Providence, RI, 1989.
18. (with Ward, Richard) *Twistor Geometry and Field Theory,* Cambridge University Press, 1990.
19. (with Resnikoff, H. L.) *Wavelet Analysis*, Springer-Verlag (to appear), 1998.
20. (with Penrose, Roger) *A Changing View of Geometry*, W. H. Freeman (in preparation, to appear), 1998.

Articles:

1. (with Gutzwiller, M. C.) The electronic states around a dislocation, *J. Phys. Chem. Solids,* **27**, 349–352, 1966.
2. On the local holomorphic hull of a real submanifold in several complex variables, *Comm. Pure Appl. Math.,* **19**, 145–165, 1966.
3. Locally holomorphic sets, *J. Analyse Math.*, **17**, 337–345, 1966.
4. Holomorphic approximation on real–analytic submanifolds of a complex manifold, *Proc. Amer. Math. Soc.*, **17**, 1272–1275, 1966.
5. (with Nirenberg, R.) Holomorphic approximation on real submanifolds of a complex manifold, *Bull. Amer. Math. Soc.*, **73**, 378–381, 1967.
6. Holomorphic hulls and holomorphic convexity of differentiable submanifolds, *Trans. Amer. Math. Soc.*, **132**, 245–262, 1968.
7. Holomorphic hulls and holomorphic convexity, Rice University Studies, **54**, No. 4, 75–84, 1968.
8. (with Harvey, Reese) Compact holomorphically convex subsets of a Stein manifold, *Trans. Amer. Math. Soc.,* **136**, 509–516, 1969.

9. Compact real submanifolds with nondegenerate holomorphic tangent bundles, *Math. Ann.,* **179**, 123–129, 1969.
10. Real–analytic subvarieties and holomorphic approximation, *Math. Ann.*, **179**, 130–141, 1969.
11. (with Nirenberg, R.) Approximation theorems on differentiable submanifolds of a complex manifold, *Trans. Amer. Math. Soc.*, **43**, 15–36, 1969.
12. Concerning the envelope of holomorphy of a compact differentiable sub-manifold of a complex manifold, *Annali Scuola. Norm. di Pisa*, **23**, 347–361, 1969.
13. (with Bigolin, Bruno) Concerning the refined Chern classes of a holomorphic vector bundle, *Ati Accad. Naz. Lincei Rend.*, **46**, 379–384, 1969.
14. (with Hunt, L. R.) The envelope of holomorphy of a 2–sphere in C^2, Rice University Studies, **56**, No. 2, 51–62, 1970.
15. Parametrizing the compact submanifolds of a period matrix domain by a Stein manifold, Lecture Notes in Mathematics, **184**, *Symposium on Several Complex Variables, Park City, Utah, 1970,* Springer–Verlag, Berlin–Heidelberg–New York, 121–150, 1971.
16. (with Harvey, Reese) Holomorphic approximation on totally real submanifolds of a complex manifold, *Bull. Amer. Math. Soc.*, **77**, 824–828, 1971.
17. (with Harvey, Reese) Holomorphic approximation and hyperfunction theory on a C^1 totally real submanifold of a complex manifold, *Math. Ann.*, **197**, 287–318, 1972.
18. (with Harvey, Reese) Zero sets of nonnegative strictly plurisubharmonic functions, *Math. Ann.*, **201**, 165–170, 1973.
19. Automorphic cohomology on homogeneous complex manifolds, Rice University Studies, **59**, No. 2, 147–155, 1973.
20. Function theory on differentiable submanifolds, *Contributions to Analysis*, Academic Press, Inc., 407–441, 1974.
21. Moisezon spaces and the Kodaira embedding theorem, *Proceedings of the Tulane University Program on Value–Distribution Theory*, *Part A,* Marcel–Dekker Inc., 29–41, 1973.
22. Comparison of deRham and Dolbeault cohomology for proper surjective mappings, *Pac. J. Math.*, **53**, 281–300, 1974.
23. (with Hunt, L.R.) Holomorphic extension for nongeneric CR–submanifolds, *Proceedings of Symposia in Pure Mathematics*, **27**, Pt. 2, American Math. Soc., Providence, RI, 81–88, 1975.
24. (with Hunt, L.R.) Extensions of CR–functions, *Am. J. of Math.*, **98**, 805–820, 1976.
25. (with Polking, John) Hyperfunction boundary values and a generalized Bochner–Hartogs' Theorem, *Proceedings of Symposia in Pure Mathematics*, **30**, Pt. 1, Amer. Math. Soc., Providence, RI, 187–194, 1977.
26. (with Wolf, Joseph A.) Poincaré theta series and L^1 cohomology, *Proceedings of Symposia in Pure Mathematics*, **30**, Pt. 2, Amer. Math. Soc., Providence, RI, 55–68, 1977.
27. Deformations of strongly pseudoconvex domains in C^2, *Proceedings of Symposia in Pure Mathematics*, **30**, Pt. 2, Amer. Math. Soc., Providence, RI, 125–128, 1977.
28. The invariants of E. Cartan–Chern–Moser for a real hypersurface in C^n, *Analyse Complex et Geometrie Analytique (1973–75)*, (ed.: P. Dolbeault), Univ. of Paris VI, Paris, X–1–X.12, 1976.
29. (with Wolf, Joseph A.) Poincaré series and automorphic cohomology on flag domains, *Ann. of Math.*, **105**, 397–448, 1977.
30. (with Polking, John) Boundary values of Dolbeault cohomology classes and a generalized Bochner–Hartogs' Theorem, *Abhand. Math. Sem.*, Univ. Hamburg, **47**, 1–24. 1978.
31. (with Burns, Daniel, and Snider, Steven) Deformations of strongly pseudoconvex domains, *Invent. Math.*, **46**, 237–253, 1978.
32. Function theory on differentiable submanifolds, *Uspehki. Math. Nauk.* **33**, (Russian translation by G. Henkin), 152–193, 1978.
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