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Introduction

Volume 7, Number 2, 2000, of *Integrated Computer-Aided Engineering* was devoted to *Industrial Applications of the Wavelet Transforms*. This special issue on *Digital Wavelets* is dedicated to the pioneering researcher and scholar, Enders A. Robinson.

Enders Anthony Robinson, known as the father of digital geophysics, is the Maurice Ewing and J. Lamar Worzel Professor Emeritus of Geophysics at Columbia University in New York. He was born in Boston, Massachusetts on March 18, 1930 and received an S.B. degree in mathematics in 1950, S.M. degree in economics in 1952 and Ph.D. degree in geophysics in 1954, all from the Massachusetts Institute of Technology (MIT).

Robinson is a member of the National Academy of Engineering and the European Academy of Sciences. He is a recipient of the Reginald Fessenden Award of the Society of Exploration Geophysicists, the Conrad Schlumberger Award of the European Association of Geoscientists and Engineers, the Donald G. Fink Prize Award of the Institute of Electrical and Electronics Engineers, the Alexander von Humboldt Research Award for Senior Scientists, the Thayer Academy Alumni Achievement Award, and the Blaise Pascal Medal in Earth Sciences of the European Academy of Sciences. In 2001 Robinson received the Maurice Ewing Gold Medal from the Society of Exploration Geophysicists (SEG) with the citation: "*For a lifetime of remarkable achievements that began while he was in MIT graduate school, when he in essence invented the field of digital seismic data processing, and has continued to at least today when he is receiving the Best Paper in Geophysics award in addition to the Maurice Ewing Medal. The progress in our science over the last 50 years in large part has evolved from the work of Enders Robinson whose extraordinary scientific legacy we recognize today with SEG's highest honor*."

Robinson's work is summarized in the following citation by John Bissell in "*The Leading Edge*" (September 2001), published by the Society of Exploration Geophysicists. "*This year our highest honor, the Maurice Ewing Gold Medal, will be awarded to Enders Robinson who, 50 years ago as a graduate student at MIT, deconvolved 32 seismic traces by hand and initiated our industry's digital revolution. That, in and of itself, would have propelled Enders Robinson into the highest ranks of geophysicists, but it was only the start of a remarkable career. Robinson has produced a steady, almost nonstop, stream of significant papers and books over the past half-century. Astonishingly, he will also receive at our ceremony in San Antonio the award for Best Paper in GEOPHYSICS in 2000. This might be a "double" that is without precedent in the history of our Society and almost certainly a record for the greatest chronological distance between significant contributions to our science. Robinson's lifetime of achievements truly merit our highest honor, and I encourage all delegates to join me at the Presidential Session when we honor one of our profession's greatest benefactors*."

Tadeusz Ulrych, *University of British Columbia*
Hojjat Adeli, *The Ohio State University*

Introduction to Digital Wavelets and Historical Perspective

The word wavelet goes back to Christiaan Huygens in 1690 [13]. His search for better timepieces for the more accurate determination of longitude at sea led to the pendulum clock. Huygens ability to bring the disciplines of mathematics, mechanics and optics to bear on his interest in astronomy enabled him to design, construct and operate a telescope with which he discovered the fourth satellite of Saturn. Eminent as a physicist, as well as an astronomer, Huygens established the wave theory of light. Huygens principle, which appears in every elementary physics book, states: "*Every point on a primary wavefront serves as the source of secondary spherical wavelets. These secondary wavelets advance with a speed and frequency equal to that of the primary wave at each point in space. The primary wavefront at some later time is the envelope of these secondary wavelets*."

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For simplicity, consider the case of a homogeneous isotropic medium, so all the secondary spherical wavelets have the same radius. In such a case, the medium represents a linear space-invariant system. In engineering terms, the wavefront at the initial time is the input to the system, the wavelet is the impulse response of the system, and the wavefront at some later time is the output of the system. Thus Huygens principle, in fact, states that the wavefront at some later time (i.e. the output) is equal to the convolution of the wavefront at the initial time (i.e. the input) with the wavelet (i.e. the impulse response). In other words, Huygens principle is a spatial convolutional model in which the wavelet plays the key role. Despite the prominence of this principle, the Huygens wavelet always remained as a conceptual concept in the historical development of physics.

It was the advent of the digital computer that led to the introduction of the operational concept of digital wavelet. In 1952 Robinson programmed the digital signal processing methods of digital filtering and deconvolution for the MIT Whirlwind vacuum-tube digital computer. The computer was physically so large that it filled a whole building at MIT, and yet by today's standards its processing capacity was miniscule. In 1953 and 1954 Robinson used the Whirlwind computer to process seismic data provided by oil companies to convince them of the efficacy of the methods.

In his 1954 Ph.D. thesis at MIT, Robinson [30] introduced the seismic convolutional model. In exploration seismology, a source of energy is initiated on the surface and the resulting seismic waves travel down through the earth and are reflected from various interfaces and boundaries in the subsurface layers. The returning waves come back to the surface where they are recorded as a seismic trace. The basic problem is that there is a host of other signals coming in, such as multiple reflections, reverberations, diffractions, surface waves, refracted waves, all of which hide the desired primary reflections. The problem is how to unscramble this maze.

For example, in seismic exploration at sea the water layer acts as an imperfect lens that masks the reflections from depth. In other words, the water layer, reverberating like a drumhead, hides the signals coming from the geologic interfaces. A major problem in the 1950s was that oil companies could not successfully explore in the ocean because the water reverberations hid the reflected signals. The reverberation, which is a slowly damped oscillation, represents the wavelet. The convolutional model for this case states the recorded seismic trace is the convolution of the reverberation wavelet with the reflected signal coming from depth. Having the convolutional model of the trace, the next step is to deconvolve the trace. In other words, unscramble the trace to get back the components. The deconvolution operator is the inverse of the seismic wavelet. Deconvolution removes the wavelet, thereby making the recorded trace reverberation-free.

The success of deconvolution led to a digital revolution in geophysics in the 1960s. From that time onward the digital wavelet has been at the center of seismic research. The exciting thing was that extensive difficult land areas as well as water-covered areas as the Gulf of Mexico, the North Sea, and the Persian Gulf, were opened up to seismic exploration. Great oil and natural gas discoveries were made. Also Robinson [31] broadened the use of the wavelet to other areas of communication and control. Today deconvolution is used in many aspects of digital signal processing. Deconvolution can increase the amplitude and time resolution of signals and correct amplitude and phase shift characteristics. Deconvolution restores proper bandwidths and frequency resolution. For example, corrected by deconvolution the Hubble space telescope's blurred vision has produced the sharpest images ever obtained from space.

Innovative applications of wavelets can now be found in a variety of disciplines such as image processing and video coding [10,16,25], signal processing of encephalographic (EEG) signals obtained from patients with neurological disorders such as epilepsy [5], active and hybrid control [3], intelligent transportation systems [1,2,4,13,19–21,32,33], traffic flow forecasting [18], earthquake engineering [34,38,39], bridge engineering [22], smart structures [23], electromagnetic induction system design for corrosion detection [37], and digital communications modulation [6]. Many textbooks have been published on wavelets during the past dozen years [7–9,12,17,26,28,29,35,36].

Geophysicists have been concerned with the digital wavelet for many years and have produced remarkable results. In the early 1980s the story switches to Jean P. Morlet, a French geophysicist, who applied his wavelet knowledge to Gabor's transform [11]. Gabor covered the time-frequency plane with uniform cells, and associated each cell with an invariant envelope with a carrier of variable frequency. In contrast Morlet [27] perceived that it was the wavelet shape that must be invariant to give uniform resolution in the entire plane. To do this, Morlet adapted the sampling rate to the frequency, thereby creating a changing time scale producing a stretching of the wavelet. Morlet called his technique the cycle-octave transform. While a student at the Ecole Polytechnique, Morlet had a classmate named Roger Balian, who was a theoretical physicist. In 1982 Balian introduced Morlet to Alexandre F. Grossman, a professor of mathematical physics at Marseilles. Morlet visited Grossman in Marseilles, and Grossman developed the rigorous basis of the cycle-octave transform. Grossman and Morlet used the expression "wavelets of constant shape" in their 1984 paper [14]. The name wavelet transform caught on, and the cycle-octave transform became universally known as the wavelet transform.

A name is a way of encompassing a concept, and the word wavelet is powerful. In conclusion, the wavelet concept has a lineage, which can be traced from the wavelet of Huygens, to the digital wavelet used in geophysics and other areas of signal processing, and then to the wavelet transform. This special issue encompasses various usage of the wavelet concept.

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