An approach to the study of time, time-frequency and time-scale transformations for seismic migration problems

Juan Guillermo Paniagua C.
M.Sc. in Engineering
Ph.D. student in Mathematical Engineering
GRIMMAT - Research group in mathematical modeling

Advisor: Olga Lucía Quintero M.

Content

Antecedents

Research project ECOPETROL-COLCIENCIAS

Seismic pre-stack migration in depth by extrapolating wave fields using high performance computing for massive data in complex areas.

General objective

Develop and implement specialized algorithms for processing massive seismic data to obtain images with excellent focusing of energy, definition of structures and preservation of the attributes of the seismic data, to ensure more reliable interpretation processes in order to reduce exploration risk.

Antecedents

Research project ECOPETROL-COLCIENCIAS

Seismic pre-stack migration in depth by extrapolating wave fields using high performance computing for massive data in complex areas.

Specific objective

Develop algorithms of seismic migration using wave field extrapolation in the direction of time (RTM-Reverse Time Migration), evaluating the preservation of amplitudes and frequencies as well as the conditions of stability, numerical dispersion and computational cost.

Antecedents

Research project ITM-EAFIT

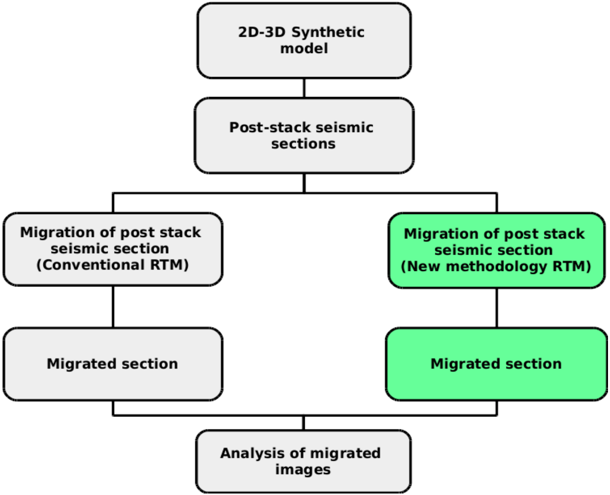
Study of Mathematical Modeling techniques and Functional Analysis in 2D-3D Reverse Time Migration. .

General objective

To develop and implement algorithms for the analysis and processing of massive seismic data of complex areas using the techniques of integral linear transformations and wavelet transformation system, looking for to approximate the system defined by the subsoil; in order to improve the results of imaging by seismic migration for use in oil exploration.

Methodology

First step



Methodology

Second step

Applying the new methodology for massive seismic data (2D, 3D) and computational improvement.

Third step

Applying the new methodology (First step) to pre-stack seismic data (2D, 3D).

Background

Wavelet analysis

Methods for the analysis in the frequency-time domain (scale). Analysis of non-stationary signals or strong changes in small intervals. They are used in:

- Geophysics ([9], [28])
- Astrophysics ([56])
- Biology ([48])
- Signal and image in Medicine ([7],[51])
- Compression fingerprints and images ([6])

Background

Wavelet analysis

- Satellite images ([16])
- Atmospheric analysis and turbulence ([31],[62], [26])
- Processing pressure transient signals ([28])
- Among others

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

A brief history

- Gabor transform,1946. [30].
- Gabor transform modified with dilated Windows, 1969. [22]
- Morlet wavelet basis, 1982. [49]
- Goupillaud, 1984, [36].
- Ortogonal wavelet transform and pyramid algorithm, 1988 – 1989.[15], [45], [46]
- Seismic data compression and satellite transmission, 1995.[44],[5], [19], [57]
- Emergence of new orthogonal wavelet transforms, 2005. [8], [42]

Background

Wavelets in Geology and Geophysics

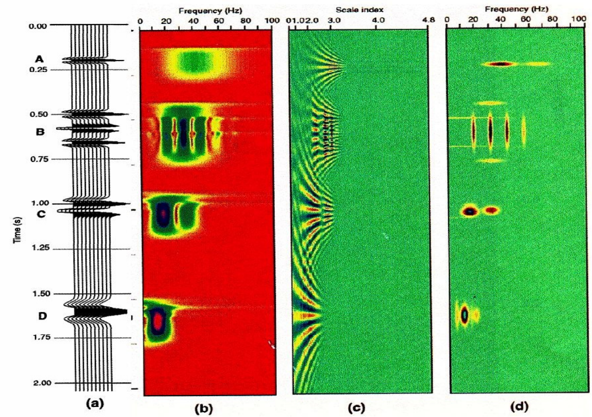
- Complex seismic trace analysis, 1979. [61]

Reflection strenght — Instantaneous frequency — Apparent polarity

Background

Wavelets in Geology and Geophysics

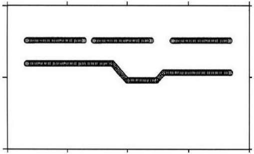
- STFT, CWT, MPD, 1995. [9]



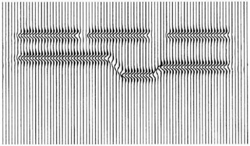
Background

Wavelets in Geology and Geophysics

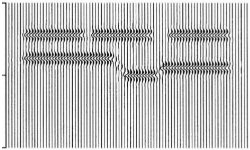
- Acoustic wavelet transform, 1998. [66]



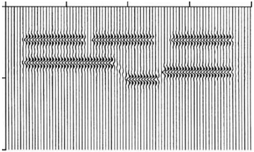
Synthetic model



Daubechies-4



Daubechies-8

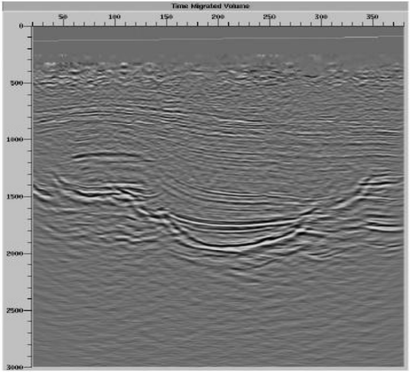


Daubechies-12

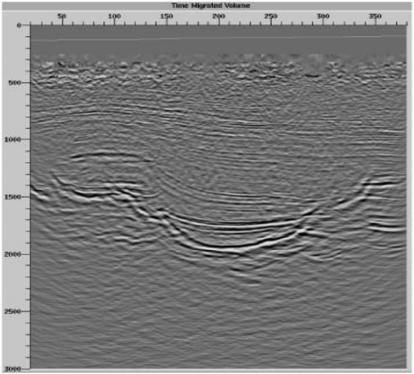
Background

Wavelets in Geology and Geophysics

- Fast Kirchhoff migration, 2002. [69]



Conventional prestack migration

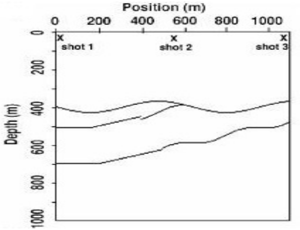


Wavelet prestack migration

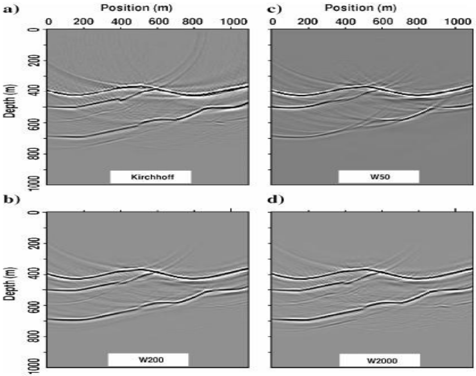
Background

Wavelets in Geology and Geophysics

- Prestack multiscale Kirchhoff migration, 2004.[67]



Reflectivity model

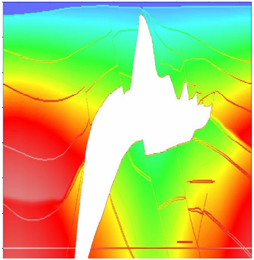


Migrated image

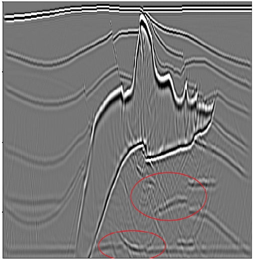
Background

Wavelets in Geology and Geophysics

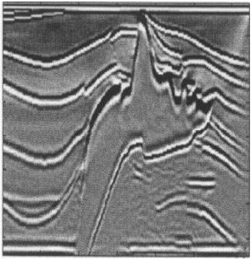
- Beamlet prestack depth migration, 2004. [12]



SEG-EAGE salt model



Split step migration

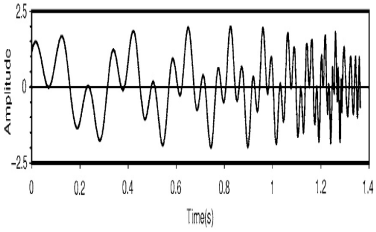


Beamlet prestack depth migration

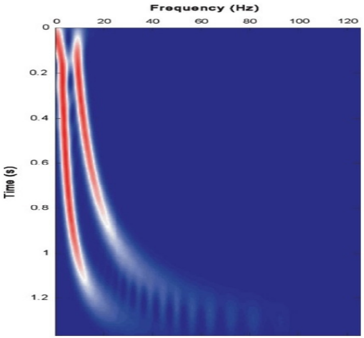
Background

Wavelets in Geology and Geophysics

- Time frequency continuous wavelet transform TFCWT, 2005. [55]



Chirp signal

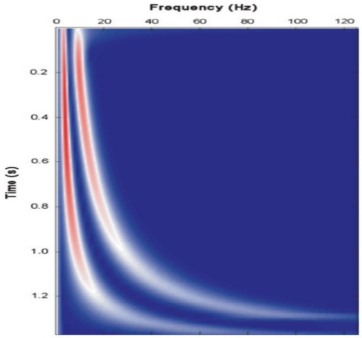


SFFT spectrum

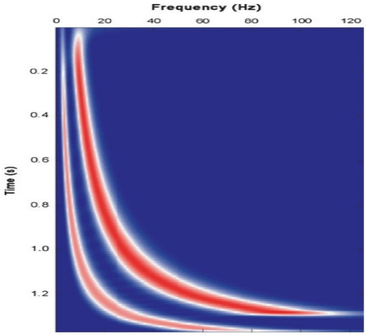
Background

Wavelets in Geology and Geophysics

- Time frequency continuous wavelet transform TFCWT. [55]



CWT spectrum

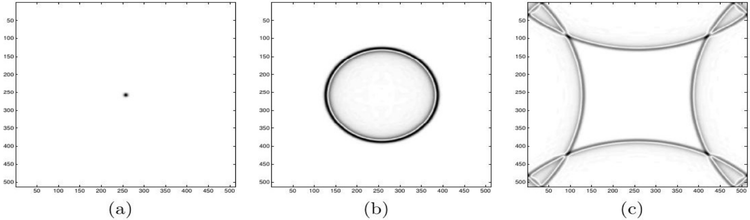


TFCWT spectrum

Background

Wavelets in Geology and Geophysics

- Fast discrete curvelet transform, 2006. [8]



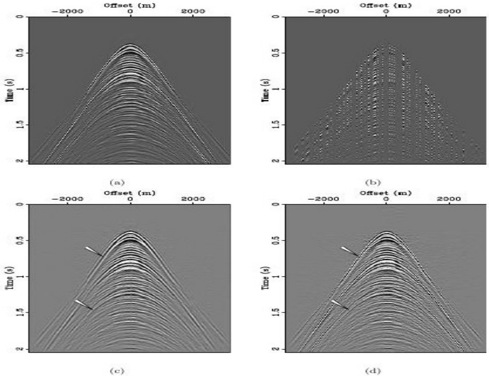
a) Delta function b) Approximate solution at $t = 0.25s$ c) Approximate solution at $t = 0.75s$

Image size	T_{Fwd}(s)	T_{Adj}(s)	T_{Inv}(s)	T_{Fwd}/T_{FFT}	ℓ^2 error
128×128	0.088832	0.091578	1.006522	24.6756	1.4430e-06
256×256	0.376838	0.390533	4.002353	19.0322	8.8154e-07
512×512	2.487052	2.579102	35.09599	18.2202	5.3195e-07
1024×1024	16.47702	16.87764	129.3631	28.9579	3.2390e-07
2048×2048	62.42980	65.09365	566.1732	24.1920	3.4305e-06

Background

Wavelets in Geology and Geophysics

- Fast discrete curvelet transform - reconstruct seismic data, 2007. [42]

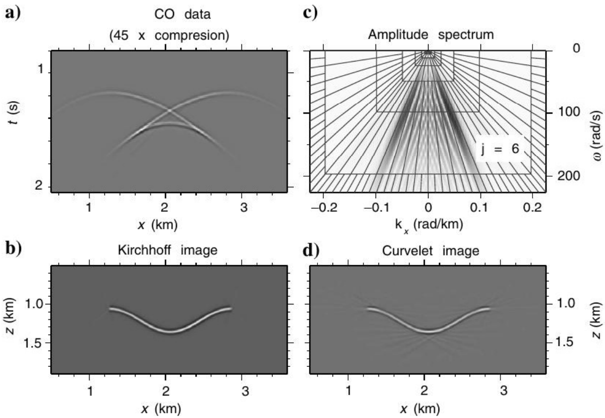


a) Fully sampled real data shot gather b) Ramdomly subsampled shot gather with 80% of the traces missing in the receiver and shot directions c) Curvelet-based recovery d) Curvelet-based recovery with focusing

Background

Wavelets in Geology and Geophysics

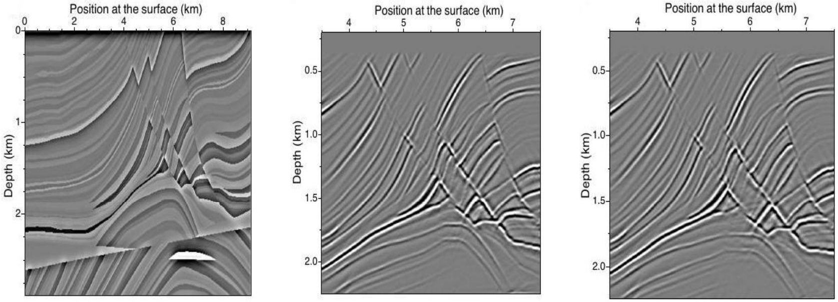
- Zero offset Kirchhoff migration with curvelets, 2007. [20]



Background

Wavelets in Geology and Geophysics

- Seismic demigration/migration with curvelets, 2008. [10]



Current works

- Study of seismic migration methods.
- Generation and Migration of 2D synthetic seismic data using seismic unix.
- Forward modeling of 2D acoustic wave equation using finite differences method (second order in time and second order in space).
- Forward modeling of 2D acoustic wave equation using the pseudospectral method (second order in time, second, fourth and sixth order in space).

Current works

- Study of seismic migration methods.
- Generation and Migration of 2D synthetic seismic data using seismic unix.
- Forward modeling of 2D acoustic wave equation using finite differences method (second order in time and second order in space).
- Forward modeling of 2D acoustic wave equation using the pseudospectral method (second order in time, second, fourth and sixth order in space).

Current works

- Study of seismic migration methods.
- Generation and Migration of 2D synthetic seismic data using seismic unix.
- Forward modeling of 2D acoustic wave equation using finite differences method (second order in time and second order in space).
- Forward modeling of 2D acoustic wave equation using the pseudospectral method (second order in time, second, fourth and sixth order in space).

Current works

- Study of seismic migration methods.
- Generation and Migration of 2D synthetic seismic data using seismic unix.
- Forward modeling of 2D acoustic wave equation using finite differences method (second order in time and second order in space).
- Forward modeling of 2D acoustic wave equation using the pseudospectral method (second order in time, second, fourth and sixth order in space).

Current works

- C language implementation for Phase shift migration.
- The Haar system.
- Discrete approximation of a function using the Haar system.

Current works

- C language implementation for Phase shift migration.
- The Haar system.
- Discrete approximation of a function using the Haar system.

Current works

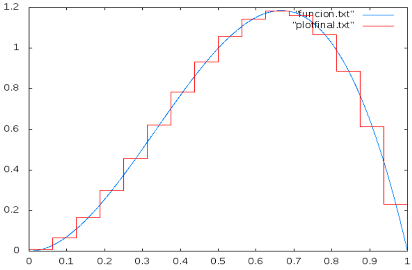
- C language implementation for Phase shift migration.
- The Haar system.
- Discrete approximation of a function using the Haar system.

Current works

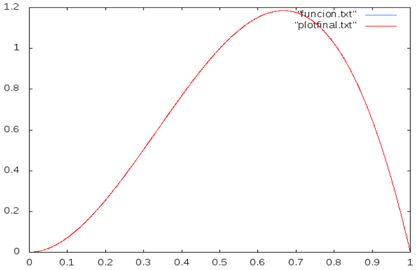
Haar system

$$f(x) = \sum_{k=0}^{2^J-1} a_{J,k} p_{J,k}(x) + \sum_{j=J}^{\infty} \sum_{k=0}^{2^j-1} b_{j,k} h_{j,k}(x) \qquad (1)$$

where $a_{J,k} = \langle f, p_{J,k} \rangle$, $b_{j,k} = \langle f, h_{j,k} \rangle$



$f(x) = 8x(1-x); J = 0, j = 3$



$f(x) = 8x(1-x); J = 0, j = 15$

Current works

- C language implementation for Phase shift migration.
- The Haar system.
- Discrete approximation of a function using the Haar system.
- Discrete Haar Transform.

Discrete Haar transform

Approximation and detail matrix

Given $L \in N$ even, define the $(L/2) \times L$ matrices H_L and G_L by

$$H_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 & 0 & & \dots & & 0 \\ 0 & 0 & 1 & 1 & 0 & \dots & 0 \\ & & & \ddots & & & \\ 0 & & & \dots & 0 & 1 & 1 \end{pmatrix} \tag{2}$$

Discrete Haar transform

Approximation and detail matrix

$$G_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 & 0 & & \dots & & 0 \\ 0 & 0 & 1 & -1 & 0 & \dots & 0 \\ & & & \ddots & & & \\ 0 & & & \dots & 0 & 1 & -1 \end{pmatrix} \tag{3}$$

The matrix H_L is referred as the approximation matrix, the matrix G_L as the detail matrix.

Wavelet matrix

Define $L \times L$ matrix W_L by

$$W_L = \begin{pmatrix} H_L \\ G_L \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 & 0 & & \dots & & 0 \\ 0 & 0 & 1 & 1 & 0 & \dots & 0 \\ & & & \ddots & & & \\ 0 & & & \dots & 0 & 1 & 1 \\ 1 & -1 & 0 & & \dots & & 0 \\ 0 & 0 & 1 & -1 & 0 & \dots & 0 \\ & & & \ddots & & & \\ 0 & & & \dots & 0 & 1 & -1 \end{pmatrix} \quad (4)$$

1D Discrete Haar transform

If we consider a initial sequence of data, a_0, to be a vector of length $L = 2^N$, $N \in \mathbf{N}$

$$a_0 = (a_0(0), a_0(1), \ldots, a_0(2^N - 1))$$

The discrete Haar transform (DHT) of a_0 is given by

$$\begin{pmatrix} c_j \\ d_j \end{pmatrix} = W_L a_0 = \begin{pmatrix} H_L \\ G_L \end{pmatrix} a_0 = \begin{pmatrix} c_0 \\ c_1 \\ \vdots \\ c_{\frac{L}{2}-1} \\ d_0 \\ d_1 \\ \vdots \\ d_{\frac{L}{2}-1} \end{pmatrix}$$

1D Discrete Haar transform

c_j is called the averages block.

$$c_j = H_L a_0 = \begin{pmatrix} c_0 \\ c_1 \\ \vdots \\ c_{\frac{L}{2}-1} \end{pmatrix}$$

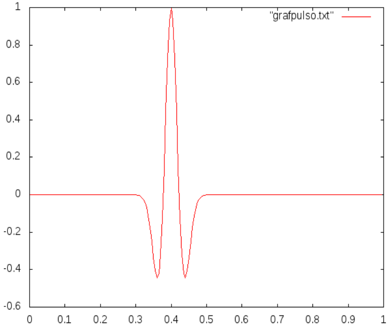
d_j is called the details block.

$$d_j = G_L a_0 = \begin{pmatrix} d_0 \\ d_1 \\ \vdots \\ d_{\frac{L}{2}-1} \end{pmatrix}$$

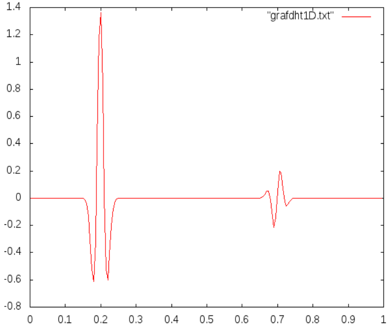
DHT Ricker Pulse

$$f(t) = (1 - 2\pi fc^2(t-0.4)^2)e^{-\pi^2 fc^2 (t-0.4)^2} \quad (5)$$

with $fc = 5\ hz$ y $0 \leq t < 1$



Original Ricker pulse



DHT Ricker pulse

2D Discrete Haar transform

2D Discrete Haar transform

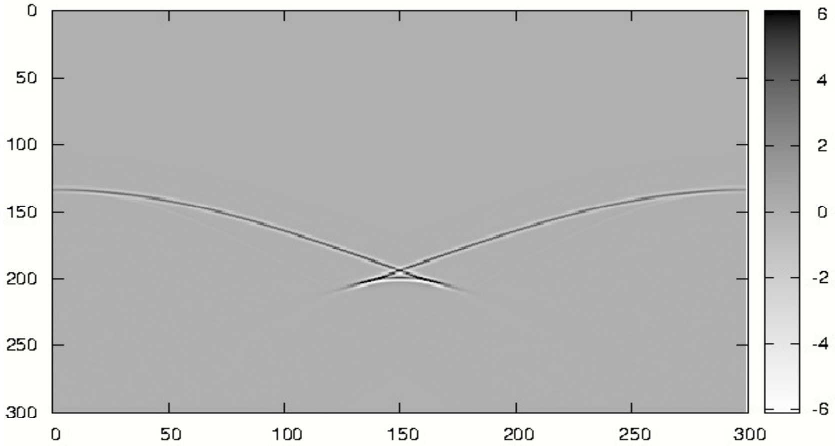
Suppose that A is an $M \times N$ matrix where M, N are even positive integers. The two-dimensional discrete Haar wavelet transformation of M x N matrix A is defined as

$$B = W_M \; A \; W_N^{'} \tag{6}$$

where W_M, W_N are defined by (4)

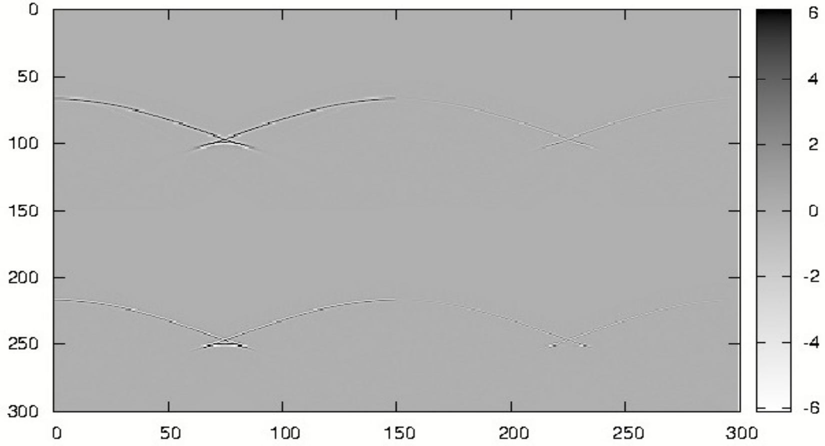
Sinclina model

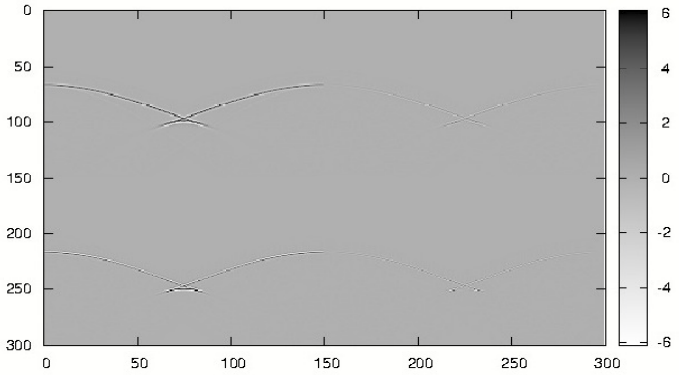
Zero offset seismic section



DHT Sinclina model

DHT Zero offset seismic section





$H_L A H_L'$ $H_L A G_L'$

$G_L A H_L'$ $G_L A G_L'$

Work perspectives

Is it possible to calculate the Laplacian (2D, 3D) using a different method that does not use a finite differences scheme or pseudoespectral?

Work perspectives

Is it possible to improve the dispersion in wave propagation using a different method to calculate the Laplacian (2D, 3D), for example, a wavelet transform or another transform?

Work perspectives

Is it feasible to find other 2D, 3D orthogonal transformation that can be used in another method of migration, such as reverse time migration, allowing improve the images obtained through the analysis of the signals recorded on the surface?

Work perspectives

Search for a methodology to find the subsurface velocity field (2D, 3D) through the analysis of the signals recorded on the surface.

References I

- Baysal, E., Kosloff, D. D., and Sherwood, J. W. C., 1983, Reverse time migration: Geophysics, 48,1514 -1524.
- Bednar, J. B., 2005, A brief history of seismic migration: Geophysics, 70,3MJ-20MJ.
- Berkhout, A. J., 1984, Seismic migration: Imaging of acoustic energy by wavefield extrapolation. B:Practical aspects, Elsevier Science Publ.
- Bleinstein, N., 1987, On the imaging of reflectors in the earth:Geophysics, 52, 931 - 942.
- Bosman, C., and Reiter, E., 1993, Seismic data compression using wavelet transforms: 63th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts, 1261 - 1264.

References II

- Bradley, J., Brislawn, C., and Hopper, T., 1993, The FBI wavelet/scalar quantization standard for gray-scale fingerprint image compression: Tech. Report LA-UR-93-1659: Los Alamos Mat'l LAb, Los alamos, N.M.
- Burt, P. J., 1989, Mulriresolution techniques for image representation, analysis and smart transmission: Proc. SPIE Conf. on visual communication and image processing, 2 - 15.
- Candes, E., Demanet, L., Donoho, D., Ying, L., 2006, Fast discrete curvelet transforms: SIAM Multiscale Model. Simul., 5, 3, 861 - 899.

References III

- Chakraborty, A., and Okaya, D., 1995, Frequency-time decomposition of seismica data using wavelet-based methods: Geophysics, Soc. of Expl. Geophys., 60, 1906 - 1916.
- Chauris, H., Nguyen, T., 2008, Seismic demigration/migration in the curvelet domain: Geophysics, 73, 2, $S35$ - $S46$.
- Chen, W., Novak, M. D., Black, T. A., and Lee, X., 1997, Coherent eddies and temperature structure functions for three contrasting surfaces. Part 1: ramp model with finite microfront time: Boundary Layer Meteorology, 84, 99 - 123.
- Chen, L., Wu, R., Wang, W., 2004, Common angle image gathers obtained from Gabor- Daubechies beamlet prestack depth migration: Chinese Journal of Geophysics, 47, 5, 987 - 997.

References IV

- Claerbout, J. F., 1971, Toward a unified theory of reflector mapping: Geophysics, 30, 467 - 481.
- Claerbout, J. F., and Doherty, S. M., 1972, Downward continuation of moveout corrected seismograms: Geophysics, 37, 741 - 768.
- Daubechies, I., 1988, Orthonormal bases of compactly supported wavelets: Communications in pure an applied mathematics, 41, 909 - 1005.
- Demirel, H., and Anbarjafari, G., 2010, SAtellite image resolution enhancement using complex wavelet transform: IEE Geoscience and remote sensing letters, 7, 123 - 126.

References V

Dessing, F. J., and Wapenaar, C. P. A., 1994, Wavefield extrapolation using the wavelet transform: 64th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts, 1355 - 1358.

Dessing, F. J., and Wapenaar, C. P. A., 1995, Efficient migration with the one-way operators in the wavelet transform domain: 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts, 1240 - 1243.

Donoho, D. L., Ergas, R. A., and Villasenor, J. D., 1995, High-performance seismic trace compression: 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts, 160 - 163.

Douma, H., De Hoop, M., 2007, Leading-order seismic imaging using curvelets: Geophysics, 72, 6, $S231$ - $S248$.

References VI

- Dubrulle, A. A., 1983, Numerical methods for the migration of constant-offset sections in homogeneous and horizontally-layered media: Geophysics, 48, 1195 - 1203.
- Dziewonski, A., Bloch, S., ans Landisman, M., 1969, A technique for the analysis of transient seismic signals: Bull. Seis. Soc. Am., 59, 1, 427 - 444.
- Ekren, B. O., and Ursin, B., 1999, True-amplitude frequency-wavenumber constant-offset migration: Geophysics, 64, 915 - 924.
- Etgen, J., 1986, High-order finite-difference reverse time migration with the 2-way non-reflecting wave equation: Stanford Exploration Project, 48, 133 146.

References VII

- Etgen, J., 1998, V(z) F-K prestack migration of common-offset common-azimut data volumes, part 1: theory: 68*th* Annual Internat. Mtg. Soc. Expl. Geophys., Expanded abstracts, 1835 - 1838
- Farge, M., 1992, Wavelet transforms and their applications to turbulence: Annu. Rev. Fluid. Mech., 24, 395 - 457.
- Fehler, M., 2008 Seismic migration imaging. In D.Havelock, S. Kuwano and M. Volnder (Eds.), Handbook of signal processing in acoustics (pp. 1585 - 1592). New york, NY: Spriner New York.
- Foufoula-Georgiou, E., and Kumar, P., (Eds.), 1995, Wavelets in Geophysics. Academic Press.

References VIII

- Foufoula-Georgiou, E., and Kumar, P., (Eds.), 1997, Wavelet analysis for Geophysical applications: Reviews of Geophysics, 35, 385 - 412.
- Gabor, D., 1946, Theory of communication:Journal of the Institute of Electrical Engineers, 93, 429 - 457
- Gamage, N., and Blumen, W., 1993, Comparative analysis of low-level cold fronts: Wavelet, Fourier, and empirical orthogonal function decompositions: Mon. Wea. Rev., 121, 2867 - 2878.
- Garotta, R., 1999, Shear waves from acquisition to interpretation.Tulsa, Ok, USA: Society of exploration Geophysicist.

References IX

- Gazdaz, J, 1984, Migration of seismica data: Proc IEEE, 72, 1302-1315.
- Gazdag, J, 1978, Wave equation migration with the phase-shift method: Geophysics, 43, 1342 - 1351.
- Gazdag, J and Sguazzero, P, 1984, Migration od seismica data by phase shift plus interpolation: Geophysics, 49, 124 - 131.
- Goupillaud, P., Grossmann, P., Morlet, J., 1984, Cycle-octave and related transmforms in seismic signal analysis: Geoexploration, 23, 85 - 102.
- Griffiths, D. H., King, R.,F., 1988. Applied geophysics for geologists and engineers: The elements of geophysical prospecting. Oxford, U.K: Pergamon press.

References X

Grechka, V., Zhang, L., Rector, J. W., 2004, Shear waves in acoustic anisotropic media: Geophysics, 69, 2, 576 - 582.

Grinsted, A., Moore, J. C., Jevrejeva, S., 2004, Application of the cross wavelet transform and wavelet coherence to geophysical time series: Nonlinear Processes in Geophysics, 11, 561 - 566.

Hagedoorn, J. G., 1954, A process of seismic reflection interpretation: Geophysics Prospecting, 2, 85 - 127.

Herrera, Y and Cooper, N, 2010, Manual para la adquisición y procesamiento de sísmica terrestre y su aplicación en Colombia: Publicaciones Universidad Nacional, Facultad de Ciencias, Departamento de Geociencias.

References XI

- Herrmann, F. J., Wang, D., Hennenfent, G., Moghaddam, P. P., 2007, Curvelet-based seismic data processing: a multiscale and nonlinear approach: Geophysics, 73, 1, *A*1 - *A*5.
- Li, H,G, 1997, Application of wavelet transforms to seismic data processing and inversion: PhD thesis in Geosciences and Ocean sciences.
- Luo, Y., and Schuster, G. T., 1992, Wave packet transform and data compression: 62nd Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts.
- Mallat,S., 1989, A Theory for multiresolution signal decomposition: The wavelet representation, IEEE Trans. Pattern Anal. Machine Intell., 11, 7, 674 - 693.

References XII

- Mallat, S., 1989, Multifrequency channel decomposition of images and wavelet models: IEEE Transactions on Acoustic, Speech and signal processing, 37, 12, 2091.
- McMechan, G, A, 1983, Migration by extrapolation of time - depend boundary values: Geophysics Prospecting, 31, 413 - 420.
- Meyers, S. D., Kelly, B. G., and O'brien, J. J., 1993, An introduction to wavelet analysis in oceanography and meteorology: With application to the dispersion of Yanai waves: Mon. Wea. Rev., 121, 2858 - 2866.
- Morlet, J., Arens, G., Fourgeau, E., and Giard, D., 1982, Wave propagation and sampling theory part I: Complex signal ans scattering in multilayered media: Geophysics, 47, 203 - 221.

References XIII

- Morlet, J., Arens, G., Fourgeau, E., and Giard, D., 1982, Wave propagation and sampling theory part II: Samplig theory and complex waves: Geophysics, 47, 222 - 236.
- Polikar, R., Greer, M. H., Udpa, L., and Keinert, F., 1997, Multiresolution wavelet analysis of ERPs for detection of Alzheimer's disease. Proceedings, 19*th* Intl. Conf. IEEE/EMBS, 1301 - 1304.
- Schneider, W., 1971, Developments inseismic data processing and analysis: 1968 - 1970: Geophysics, 36, 1043 - 1073.
- Schneider, W., 1978, Integral formulation for migration in two and three dimensions: Geophysics, 43, 49 - 76.

References XIV

- Schuster, G., T., 2007. Basic of seismic wave theory. Utah, US: University of Utah.
- Sinha, S., Routh, P. S., Anno, P. D., Castagna, J. P., 2005, Spectral decomposition of seismica data with continuous-wavelet transform: Geophysics, 70, 6, 19 - 25.
- Starck, J. L., Bobin, J., 2010, Astronomical data analysis and sparsity: from Wavelets to compressed sensing: Proceedings of the IEEE, 98, 6, 1021 - 1030.
- Stigant, J. P., Ergas, R. A., Donoho, P. L., Minchella, A. S., and Gilbert, P. Y., 1995, Field trial of seismic compression for real-time transmission: 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts, 960 - 962.

References XV

- Stoffa, P. L., Fokkema, J. T., De Luna Freire, R. M., and Kessinger, W. P., 1990, Split-step Fourier migration: Geophysics, 55, 410 - 421.
- Stolt, R, H, 1978, Migration by Fourier transform: Geophysics, 43,23-48.
- Szilagyi, J., Katul, G. G., Parlange, M. B., Albertson, J. D., and Cahill, A. T., 1996, The local effect of intermittency on the inertial subrange energy spectrum of the atmospheric surface layer: Boundary Layer Meteorology, 79, 35 - 50. (Ch 4)
- Taner, M. T., Koehler, F., Sheriff, R. E., 1979, Complex seismic trace analysis: Geophysics, 44, 6, 1041 - 1063.

References XVI

Weng, H., and Lau, K. M., 1994, Wavelets, period doubling, and tiem-frequency localization with application to organization of convection over the tropical western Pacific: J. Atmos. Sci., 51, 2523 - 2541.

Womack, J. E., and Cruz, J. R., 1994, Seismica data filtering using a Gabor representation: IEEE Trans. on Geosciences and remote sensing, 32, 2, 467 - 472.

Wornell, G., 1996, Emerging, applications of multirate signal processing and wavelets in digital communications, Proceedings of the IEEE, 84, 4, 586 - 603.

References XVII

- Wu, Y., and McMechan, G. A., 1995, Wavefield extrapolation in the wavelet domain with application to poststack migration: 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts, 1236 - 1239.
- Wu, R. S., Dong, X. L., Gao, J. H., 1998, Application of acoustic wavelet transform to seismic data processing: 68*th* Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded abstracts.
- Yu, Z., McMechan, G. A., Anno, P. D., Ferguson, J., 2004, Wavelet transform.based prestack multiscale Kirchhoff migration: Geophysics, 69, 1505 - 1512.

References XVIII

Zhang, Y., J. Sun, and S. Gray, 2007, Reverse-time migration: Amplitude and implementation issues: 77th Annual International Meeting, SEG, Expand-ed Abstracts, 2300 - 2304.

Zheludev, V. A., Ragoza, E., Kosloff, D. D., 2002, Fast Kirchhoff migration in the wavelet domain: Exploration Geophysics, 33, 23 - 27.