Geophysical Imaging with Localized Waves

ABSTRACTS

July 24 – 28, 2011, Sanya, China
Conference Sponsors
Preface

Localized waves refer to waves localized in propagation direction-space location or/and in time-frequency. Localized waves exist both in real world as beam wave, wave packet (pulsed beam), soliton, coherent state, or in wavefield decomposition schemes as certain elementary waves having some preferred physic-mathematical properties. With phase-space localized waves, local AVA (amplitude variation with angle), local inversion for rock/reservoir parameters can be performed and the close link between imaging and inversion can be established. In fact, many different forms of localized waves, such as Bessel beams, X-waves (X-shaped localized pulsed beam), frozen waves, acoustic bullets, have been proposed and demonstrated in different fields of applied physics. In geophysics, localized waves have been developed and applied in the recent decades as beamlets, curvelets, fast beams, various forms of wave packet, in addition to the traditional Gaussian beam. We feel that localized waves have great potential in applications to geophysical imaging and inversion, and an international symposium is warranted to exchange information on progress in related fields, such as mathematics, theoretical physics, signal processing, EM wave, acoustics, medical imaging and nondestructive evaluation in addition to seismic imaging. We have invited internationally renowned scientists to review the progress in the related fields. We also solicited the submission of contributing work in the form of oral or poster presentation. Applications in geophysical imaging and inversion are of particular interest. We believe that the symposium will promote the research in this area and bring significant impact to the future development in geophysical imaging/inversion using localized waves.

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**Marteen de Hoop** (Purdue University, USA)
**Bjorn Ursin** (Norwegian University of Science & Technology, Norway)
**Jinghuai Gao** (Xi'an Jiaotong University, China)
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Ground-roll separation by sparsity and morphological diversity promotion

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ABSTRACT

In land based seismic surveys, the seismic data are usually contaminated by low-frequency, high-amplitude ground roll noise, which overlay important reflector information in both the t-x and f-k domains and severely degrade the quality of the information obtained from the seismic record. Based on the morphological component analysis (MCA) technique, this paper proposes a method to separate out the ground roll signal while preserving reflector information, exploiting both the sparsity and the waveform diversity mechanism. The basic idea of this method is the use of two appropriate dictionaries, one for the representation of the reflector information and the other for the ground roll component. Both dictionaries are chosen such that they lead to sparse representation over one type of the signal content (reflector or ground roll). To further improve the wavefield separation quality, a modified-MCA (MMCA) algorithm is proposed. The validity of the proposed method is demonstrated by both the synthetic and real data.
Azimuth-preserved Local Angle Domain Prestack Time Migration in Isotropic, VTI and Azimuthally Anisotropic Media

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The industry has attached more importance to the azimuth-dependent seismic signals and is acquiring increasing numbers of azimuth-rich seismic data. In soft rock settings, the objective is usually to improve illumination and imaging of shadowed or structurally complex targets. In hard rock settings, the objective is to tackle azimuthal anisotropy in seismic imaging and to characterize the fractured reservoir and stress of the overburden.

Increasingly, people have taken more care to preserve and use azimuthal information through imaging to produce migrated azimuthal attributes for interpretation. Recent advances include sectored migration of the azimuth-limited data and common offset vector (COV) migration (e.g., Calvert et al., 2008). Because many 3D datasets suffer from low fold and poor azimuthal coverage, allsectoring methods may produce noisy prestack images due to limited fold within the sectors and often requires large sectors leading to poor statistics for analysis of anisotropic properties (Lynn, 2007). Therefore, azimuthal migration of full 3D data starts to draw more attention in the industry (Sicking et al., 2007). However, we found that all above attempts concern only source-receiver azimuth and offset on the surface. In fact, these parameters may be a poor representation of the direction of wavepath in the subsurface. Theoretically, migration in local angle domain can suppress offset- and shot-domain image artifacts in complex media, and provide high-resolution, angle-dependent migrated amplitude and moveout (e.g., Xu et al., 1998; Fomel,1999; Brandsberg-Dahl et al.,1999; Prucha,1999; Audebert, 2002; Bleistein and Gray, 2002; Xie and Wu, 2002; Wu and Chen, 2003; Sava and Fomel, 2003; Soubaras, 2003; Ursin, 2004; Fomel,2004; Biondi,2007; Koren,2008).

In this abstract, we proposed an implementation of subsurface angle domain Kirchhoff prestack time migration for extracting scattering-azimuth incident-angle domain common-image-gathers (CIGs) and illumination-azimuth illumination-dip domain CIGs in isotropic, VTI and azimuthal anisotropic media. The core of the algorithm is to calculate the phase slowness vectors of the incident and scattering rays and then evaluate the four angular attributes for subsurface angle-domain imaging. Synthetic data and real data examples show its advantages over the conventional sectored migration, and the value for AVA inversion and azimuthal analysis.

Acknowledgements: Thanks for supports by the National Natural Science Foundation of China (#41074083).
Seismic imaging and inverse scattering: A “curvelet” transform perspective

Maarten V. de Hoop

A key challenge in the imaging of (medium) coefficient discontinuities from surface seismic reflection data is subsurface illumination, given available data coverage on the one hand and complexity of the background model (of wavespeeds) on the other hand. The imaging is, here, described by the generalized Radon transform. To address the illumination challenge we develop a method for partial reconstruction of the mentioned coefficients. We make use of the curvelet transform, the associated matrix representation of the generalized Radon transform, which needs to be extended in the presence of caustics, and its structure, and phase-linearization. We pair an image target with partial waveform reflection data, and introduce a way to solve the matrix normal equations that connect their curvelet coefficients via diagonal approximation. We develop explicit separated expansions of the complex exponential in the oscillatory integral representations of the kernel the generalized Radon transform, viewed as a Fourier integral operator; we obtain a low separation rank using the dyadic parabolic decomposition of phase space. The second-order term in the expansion provides an accuracy $O(2^{-k/2})$ at frequency scale $2^k$. For each frequency scale, the separation rank depends on $k$ as $k / \log k$, but is otherwise independent of the problem size. We discuss an algorithm of complexity $O(N^{d/2} \log^2(N))$, or $DN^d \log(N)$ if $D$ is the number of significant boxes in the dyadic parabolic decomposition, valid in arbitrary dimension $d$. Moreover, we make use of prolate spheroidal wave functions in connection with the dyadic parabolic decomposition, while the propagation of singularities or canonical transformation is accounted for via an unequally spaced FFT (USFFT). Our algorithm also provides the basis of a computational procedure following the construction of weak solutions of Cauchy initial value problems for the wave equation if the (background) medium is $C^{2,1}$, in which, in addition, a Volterra equation needs to be solved. We briefly mention the integration of these developments with reverse-time continuation based inverse scattering.

Joint research with S. Holman, H. Smith, G. Uhlmann, R.D. van der Hilst and H. Wendt.
Quantitative assessment of the complexities of geological structures in terms of seismic migrators

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Abstract How a wave interacts with heterogeneous media has been pursued by many geophysicists. The complexity of subsurface heterogeneities is seismologically a relative concept to wavelengths of seismic waves. A growing perception is that velocity variations, propagation angles, and computational accuracies are closely related at a variety of scales.

In this abstract, a parameter termed as imaging efficiency is introduced by associating the geological heterogeneity spectra with the migrator’s angular spectra to understand the coherent interference between the medium’s heterogeneity and the migrator’s scaling characteristics. We express complex subsurface structures as the slowness- and angular-heterogeneity spectra to quantify velocity contrasts and dipping-angle distributions of complex geological structures. On the other hand, the scaling characteristics of a propagator are measured through dispersion analysis by its angular spectra plotted against refractive indexes and propagation angles, respectively. To quantify this orientation effect of an imaging operator to medium heterogeneity, we define a quantity $\eta$ termed as imaging efficiency:

$$\eta = \eta_n \ast \eta_\theta = \left( \int_0^1 f(n) p(n) dn \right) \ast \left( \int_0^1 g(\theta) q(\theta) d\theta \right), \quad \text{(1)}$$

Where $n$ is the refractive-index points, $\theta$ is the dipping-angle of a velocity field, $p(n)$ is the slab’s velocity heterogeneity spectrum, $q(\theta)$ is the slab’s angular heterogeneity spectrum, $f(n)$ and $g(\theta)$ are the Angular spectra migrators peak at the values of $n$ and $\theta$, $\eta_n$ and $\eta_\theta$ are the imaging efficiencies associated with velocity contrasts and dipping angles, respectively. The quantity termed as “complexity coefficient” could be defined as $\phi = 1 - \eta$ to measure the geological complexity in terms of propagators.

Fig. 1 Slab 1 and Slab 2 picked at different depths from the Marmousi velocity model (a), the Slowness-heterogeneity spectra for Slab 1 and Slab 2 (b), the Dipping-angle heterogeneity spectra for Slab 1 and Slab 2 (c)

To compute the imaging efficiencies and complexity coefficients for two slabs shown in Figure 1, we first use seismic data to compute the slowness and dipping-angle heterogeneity spectra for complex structures. Then, through interaction between the geological heterogeneity spectra and the migrator’s angular spectra, we obtain the imaging efficiency and complexity coefficient for complex structures, which quantitatively evaluate the geological complexity in terms of migrators. Table 1 demonstrates the imaging efficiencies and complexity coefficients by SSS, DP and FFD migrators for two slabs shown in Figure 1.

<table>
<thead>
<tr>
<th>Slab1</th>
<th>$\eta_n$</th>
<th>$\eta_\theta$</th>
<th>$\phi$</th>
<th>Slab2</th>
<th>$\eta_n$</th>
<th>$\eta_\theta$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSS</td>
<td>0.319</td>
<td>0.386</td>
<td>0.877</td>
<td>SSS</td>
<td>0.260</td>
<td>0.490</td>
<td>0.873</td>
</tr>
<tr>
<td>DP</td>
<td>0.598</td>
<td>0.764</td>
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<td>DP</td>
<td>0.584</td>
<td>0.778</td>
<td>0.546</td>
</tr>
<tr>
<td>FFD</td>
<td>0.633</td>
<td>0.769</td>
<td>0.513</td>
<td>FFD</td>
<td>0.610</td>
<td>0.780</td>
<td>0.524</td>
</tr>
</tbody>
</table>
Q factor estimation for seismic data with localized phase space method

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ABSTRACT

We develop a method for Q factor estimation in localized phase space. We derive an approximate equation combining the quality factor Q, the traveltime of a wave, and the variation of the instantaneous frequency (IF) at the envelope peaks of two successive seismic wavelets, along the wave propagating direction, based on the theory of one-way wave propagation in a 1D viscoelastic medium. We then propose a method (called the WEPIF method) to estimate Q by measuring the variations of the wavelet envelope peak IF (WEPIF) with the traveltime of seismic wavelet. For zero-offset VSP data and poststack seismic data, we describe how to implement the WEPIF method in detail. Applying the WEPIF to the prestack seismic data, we propose a method for Q estimation in the angle domain (called QEAD-method). In order to obtain reliable envelope and instantaneous frequency of seismic traces, we develop the theory and methods of features analysis in localized phase space. A test on synthetic VSP data shows that the WEPIF method is less sensitive to interference from the reflector than the logarithm spectral ratio and the centroid frequency shift methods. Applied to field VSP data, the WEPIF method gives a Q-curve with nearly the same distribution as the results from a known well. Applied to poststack seismic data, it produces a Q-profile that indicates an intense absorption zone corresponding to the excellent gas-bearing reservoir. This allows us to predict a potential high-productivity gas well. Drilling confirmed this prediction. The QEAD-method is applied to a great deal of prestack seismic data; the results demonstrate its validity. We compare the QEAD-method with a usual method, which uses the poststack seismic data; the results show that the Q-profiles produced by QEAD-method can characterize gas better than one by the usual method.
Vertical seismic profiling wavefield separation based on sparse representation

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ABSTRACT

An automatic vertical seismic profiling (VSP) wavefield separation method is presented according to the different apparent velocities of the different wavefields. Current methods typically assume that the waves propagate uniformly with an unvarying wavelet shape and amplitude. This assumption may break down in the presence of the wavelet variation and the leap of amplitude when passing through the interface of impedance. It can well preserve the wavefield characteristics such as the wavelet variations and the leap of amplitude, using the sum of a small number of rank-1 matrixes to approximate the wavefield of a single wave (e.g. up-going P-wave) after event alignment. Based on this point, for each single wave, we can construct a dictionary which can sparsely represent its wavefield but not sparsely represent the wavefields of other waves. Then we can use the block-coordinate relaxation method to separate different waves. We use synthetic data and real data to test our method. Our method can be used to the wavefield separation of VSP wavefield which contain tube-wave, and well preserve the wavefield characteristics. In addition, the proposed method can work automatically.

Key words: VSP, wavefield separation, sparse representation
Dreamlet transform and its application to seismic data compression

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In this abstract, we study the application of Dreamlet transform (Wu et al., 2008) into Seismic data compression and corresponding storage method based on zig-zag sequence and Run-length coding.

Our objective is to investigate the accuracy of wave propagation and imaging for direct application of compressed seismic data in the Dreamlet domain. The Dreamlet (Drumbeat-beamlet) transform is a time-space transform and it uses localized time-frequency space-wavenumber atoms as the basis. The localized atom is formed by the tensor product of a 1-D local harmonic transform along the time-axis (the drumbeat) and a 1-D or 2-D local harmonic transform along the spatial axes (the beamlet) depending on the dimensionality of the problem. Wu et al. (2011) has proved that Dreamlet is a type of physical wavelet introduced by Kaiser (1994) as localized wave solution on the light-cone. As a localized version of cosine/sine basis with a smooth window function, LCB/LEF can be used to form the Dreamlet atom. Due to the time-space localization property, Dreamlet shows great potential in efficient representation of the seismic data.

In this presentation, we first review the Dreamlet transform concept, and then present a new method combining the idea of Dreamlet transform, multi-scale decomposition to form a multi-scale Dreamlet transform. Unlike 2D adaptive local cosine transform, this multi-scale Dreamlet transform is more closely related to the physics of wavefield. We apply these decomposition methods to the post-stack/pre-stack SEG-EAEG salt model synthetic data set for analyzing the efficiencies of data representation and data compression. Dreamlet and multi-scale Dreamlet transform perform better than the Curvelet transform for compression ratio due to the efficient representation as well as orthogonality. Meanwhile, to keep the amplitude information of the compressed seismic data after applying decompressing, we use a zig-zag sequence combined with run-length coding to store the compressed coefficients in Dreamlet domain, which can preserve the value of compressed coefficients as exact as possible. After migration using the compressed post-stack data, the Dreamlet and multi-scale Dreamlet methods can still provide a high quality image of the structure even at high compression ratios. The migration results of using compressed pre-stack data show us the possibility of applying migration imaging in Dreamlet domain using highly compressed data.
Efficient Gaussian Packets representation and seismic imaging

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In this abstract we discuss an efficient way to apply Gaussian Packet method to data representation and seismic imaging. Similar to Gaussian Beam method, wavefield radiating from a seismic source as a set of Gaussian Packets can represent forward-modeling seismic data. Recorded wavefield at the surface can be expressed and downward continued by a set of Gaussian Packets as well. The evolution of Gaussian Packet is determined by parameter of central frequency, local time, local space and ray emergent angle, and the shape of Gaussian Packet is determined by its initial value. When ray emergent angle is small enough, the quadratic cross term between time and space can be ignored, and the Gaussian Packets can be reduced into tensor product of two Gabor function. Each Gaussian Packet is directly related to the ray emergent angle, and propagates along a central ray. Therefore, representation of seismic data using Gaussian Packets provides the local time slope and location information at certain central frequency, while summation of Gaussian Packets’ evolutions will reconstruct the corresponding propagated wavefield. These properties also make seismic imaging using Gaussian Packets easily be understood and implemented. Because the narrow band nature of explosion sources, the method can become efficient with proper initial parameter selection so that only Gaussian Packets with a few central frequencies are needed for representing propagated seismic wavefield. Numerical examples on impulse responses and an application to the 4 layer zero-offset data are shown to demonstrate the validity of the method.
Evolution of Gaussian Packets in inhomogeneous media

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In this abstract, we study the property and propagation of a single Gaussian Packet. A Gaussian Packet is a high-frequency asymptotic space-time particle-like solution of the wave equation, thus it is localized in both space and time. This kind of solution is also called quasiphotons, space-time Gaussian Beam, Gaussian Packet or coherent states. The evolution of a Gaussian Packet can be obtained through dynamic ray-tracing (DRT), which is similar to the calculation of Gaussian Beam. To define a Gaussian Packet, several parameters are needed, such as central frequency, ray emergent angle, local time and local space position, initial width along both time and space direction. We will study the dependence of Packet shape on these initial values. The evolutions of a Gaussian Packet in both smooth media and strong inhomogeneous media will also be studied to see the deviation of the DRT method from the exact solution in both smooth media and at sharp boundaries. Finite difference (FD) method is used to produce the accurate wave propagation results in strongly inhomogeneous media, such as the SEG/EAGE salt model. Figure 1 shows the comparison of DRT method and FD method in SEG/EAGE salt model. Through the comparison of DRT method and FD method, we find severe deviation of DRT method from FD method at large propagation time and near the salt boundaries.

Figure 1: comparison of Gaussian Packet method and FD method in SEG/EAGE salt model.
Seismic Applications of Beam Imaging Techniques

N. Ross Hill

Chevron Energy Technology Company

The complementary ray-path and wave-field aspects of beams have many applications for seismic imaging. One application is Gaussian beam depth migration. This technique overcomes the difficulties that standard Kirchhoff migration has with ray multipathing, while retaining many of the advantages of Kirchhoff migration, such as steep-dip fidelity, straightforward accommodation of detailed anisotropic velocities, computational efficiency, and the option to limit the computations to a targeted subvolume.

The separation of a recorded seismic wavefield into beam components that travel along raypaths can be useful during many additional processing and analysis steps that are necessary for forming an image of the subsurface. For example, the beam components can be analyzed to identify and process non-primary coherent events such as multiples. Also, the interpretive analysis of the beam components of seismic energy is useful during the estimation of seismic velocities.

Detailed computations of seismic energy propagation are justified only if there is a detailed description of the velocity field the energy is traveling through. Often these detailed velocity descriptions cannot be obtained by geophysical measurements alone and must be guided by geologic insights. Getting a good image depends on good geological assumptions and making the right geological assumptions often depends on the quality of the image. This suggests an iterative, interpretive procedure for developing the velocity model: provisional changes are made to the velocity model, and those changes are retained if they lead to a clearer, more geologically plausible image. The efficiency of beam imaging techniques provides the rapid image updates that are necessary for this interpretively guided revision of the velocity model.
Several image classification and model selection techniques are based on pointwise regularity techniques

By Stéphen Jaffard

We will first present the different notions of pointwise regularity that have been introduced up to now and discuss the relevance of each in signal and image processing.

When this regularity is either constant (e.g. the case of Fractional Brownian fields) or slowly varying, we show that classification can be based on a direct estimation of the pointwise regularity exponent. When the regularity index is extremely erratic, such estimators are no more stable, and the tools of multifractal analysis are required. In such cases, one rather estimates the fractional dimensions of the level sets of the pointwise regularity exponent.

We will expose the mathematical fundations of these techniques and show their relevance for various classes of signals and images.
Tectonic Features of Plate Juncture in Hokkaido, Japan Derived from Local Tomographic Inversion of P- and S-wave Travel Times

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Abstract: Local travel time tomography was applied to 68,531 P-wave travel times and 68,531 S-wave travel times observed at 238 seismic stations for 4,050 local earthquakes with depths 0-300 km in and around Hokkaido, Japan. RMS(root mean square) travel time residuals were found to be 0.538s and 0.826s for P and S-wave arrival times, respectively. As a result, the hypocenters shifted horizontally 0-9 km and vertically 0-10 km. RMS inversion errors after three iterations were found to be 0.473s and 0.734s for P and S-wave travel times, respectively.

P(Vp) and S-wave velocity (Vs) anomalies were clearly imaged from seismic Tomography in and around Hokkaido. Low velocity zones (LVZ) were found beneath the active volcanoes using low Vp and low Vs anomaly data. The heterogeneous distribution of Vp and Vs was found at the eastern margin beneath the Hokkaido corner at depths of 40-90 km. Data from the subducting Pacific slabs with distorted and tear-slabs from Vp and Vs anomalies support the surface collision hypothesis proposed by Moriya (1994) which states that the Kuril Arc (Okhotsk Plate or North American Plate) collides against the NE Japanese Arc (Amurian Plate or Eurasian Plate), along and beneath the Hidaka Mountain Range. At the same time the Pacific Plate subducts into these two plates, absorbing the convergence of tectonic forces along the intersection of the Hidaka Mountain Range (HMR) corner and the central tectonic axis (143° E) in Hokkaido. Consequently, these tectonic features make it evident that most large earthquakes occur outside Hokkaido due to the absorbing effect from the convergence of forces exerted at the intraplate juncture in Hokkaido.
Sensitivity Gaussian packets

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We study how the perturbations of a generally heterogeneous isotropic or anisotropic structure manifest themselves in the wavefield, and which perturbations can be detected within a limited aperture and a limited frequency band. We consider a smoothly varying heterogeneous generally anisotropic background medium, with an isotropic background medium as a special case. We consider generally anisotropic perturbations of the medium, with isotropic perturbations as a special case.

We decompose infinitesimally small perturbations \( \delta c_{ijkl}(x) \) and \( \delta \rho(x) \) of elastic moduli \( c_{ijkl}(x) \) and density \( \rho(x) \) into Gabor functions \( g^\alpha(x) \) indexed by \( \alpha \):

\[
\delta c_{ijkl}(x) = \sum_\alpha c^\alpha_{ijkl} g^\alpha(x), \quad \delta \rho(x) = \sum_\alpha \rho^\alpha g^\alpha(x), \quad g^\alpha(x) = \exp[i \mathbf{k}^\alpha \times (x - x^\alpha) - \frac{1}{2} (x - x^\alpha)^T \mathbf{K}^\alpha (x - x^\alpha)].
\]

Gabor functions \( g^\alpha(x) \) are centred at various spatial positions \( x^\alpha \) and have various structural wavenumber vectors \( \mathbf{k}^\alpha \). The wavefield scattered by the perturbations is then composed of waves \( u^\beta_i(x,t) \) scattered by individual Gabor functions:

\[
\delta u_i(x,t) = \sum_\alpha u^\beta_i(x,t).
\]

We approximate waves \( u^\beta_i(x,t) \) scattered by individual Gabor functions analytically.

We assume that a short-duration broad-band wavefield with a smooth frequency spectrum, incident at the Gabor function, can be expressed in terms of the amplitude and travel time. We approximate each wave \( u^\beta_i(x,t) \) scattered by one Gabor function by the first-order Born approximation with the paraxial ray approximation. These approximations enable us to calculate wave \( u^\beta_i(x,t) \), scattered by Gabor function \( g^\alpha(x) \), analytically (Klimes, 2007).

Considering the above approximations, wave \( u^\beta_i(x,t) \) scattered by one Gabor function is composed of a few (i.e., 0 to 5 as a rule) Gaussian packets. Each of these “sensitivity” Gaussian packets has a specific frequency and propagates from point \( x^\alpha \) in a specific direction. We denote by \( P_i \) and \( E_i \) the slowness vector and the unit polarization vector of the incident wave, and by \( P^\alpha \) and \( E^\alpha \) the slowness vector and the unit polarization vector of the sensitivity Gaussian packet. Each of the sensitivity Gaussian packets scattered by Gabor function \( g^\alpha(x) \) is sensitive to just a single linear combination \( \sum_\beta c^\beta_{ijkl} E_\beta P_j E_k P_i - \rho^\alpha \sum_i E_i E_i \) of perturbation coefficients \( c^\beta_{ijkl} \) and \( \rho^\alpha \) corresponding to the Gabor function. This information about the Gabor function is lost if the sensitivity Gaussian packet does not fall into the aperture covered by the receivers and into the legible frequency band (Klimes, 2010a). The situation improves with the increasing number of differently positioned sources. If we have many sources, the sensitivity Gaussian packets propagating from a Gabor function may be lost during the measurement corresponding to one source, but recorded during the measurement corresponding to another, differently positioned source. However, the problem is not only to record the Gaussian packets from a Gabor function, but to record them in as many different measurement configurations as to resolve perturbation coefficients \( c^\beta_{ijkl} \) and \( \rho^\alpha \).

The sensitivity Gaussian packets can enable to replace seismic migrations by true linearized inversion of reflection seismic data. For the algorithm of the linearized inversion of the complete set of seismograms recorded for all shots refer to Klimes (2008).

We can analogously study the sensitivity of electromagnetic waves, propagating in a heterogeneous bianisotropic medium, to small perturbations of the medium (Klimes, 2010b).

References


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A low-dispersion reverse-time migration method based on nearly-analytic discrete operators

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In recent years, reverse time migration (RTM) has been successfully applied for production in seismic processing, especially for imaging in areas where large velocity contrasts and/or steep dips pose a challenge. Using the two-way acoustic/scalar wave equation, it reconstructs the source wavefield forward in time and the receiver wavefield backward in time. Then an imaging condition is applied to extract reflectivity information out of the reconstructed wavefields. The heart of RTM is a forward method for modeling the two-way wavefield by solving the full wave equation. Numerical results indicate that the Optimal Nearly Analytic Discrete Method (ONADM) developed by Yang et al in 2006, can effectively suppress numerical dispersions caused by the discretization of wave equations, when models have strong velocity contrasts between adjacent layers or too few samples per wavelength are used. This means the ONADM enables wave propagation in heterogeneous media to be simulated in large-scale models much more effectively, using coarse computation grids. In this study, we employ the ONADM to solve the full acoustic-wave equation for wavefield propagation in reverse-time migration. As a result, we get a low-dispersion reverse-time migration method that can use large extrapolation step size.

We investigate the validity of the RTM based on the ONADM through choosing the Marmousi model and comparing with the fourth-order Lax-Wendroff correction (LWC) method. The velocity of the model varies from 1.5km/sec to 5.5km/sec and the number of grid points is 350 × 122. Figure 1(a) and 1(c) respectively show the reverse time migration results of the Marmousi model computed using the ONADM and LWC, of which the extrapolation step sizes are both 20 m. Then we enlarge the temporal and spatial increments twice of the Figure 1(a) and 1(c) and the number of grid points decreases to 175 × 61. The corresponding results computed using the ONADM and LWC are shown in Figure 1(b) and 1(d) and the extrapolation step sizes are both 40 m. The four images demonstrate that ONADM has a better performance than LWC method, using both the fine and the coarse grid, especially, in the red circle regions in Figure 1(b) and 1(d). What’s more, Figure 1(a) and 1(b) indicate that the main structure of the model can be well imaged, even using a coarse grid. All the migration results show that the RTM algorithm suggested in our present study can increase the computational efficiency and save the computer memory while maintaining image quality. On the other hand, these satisfactory results imply that the RTM employing the nearly-analytic discrete operator has a promising perspective.

![Figure 1. The reverse time migration results using the ONADM for the Marmousi model (Δx = Δz = 20 m) (a), (Δx = Δz = 40 m) (b); using the LWC (Δx = Δz = 20 m) (c), (Δx = Δz = 40 m) (d)](image-url)


Seismic Noise Suppression based on Contourlet Transform

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ABSTRACT

We proposed a threshold shrinkage method in contourlet transform domain and explore its application in seismic noise suppression. The contourlet transform is a new multiscale geometrical analysis tool for two dimensional signals, which can overcome the deficiency of two dimensional separable wavelets in capturing directional information. The transform not only offers a high degree of directionality and anisotropy, but also achieves nearly critical sampling. After considering that the classical shrinkage threshold doesn’t take account of the clustering property of coefficients, a new local adaptive shrinkage threshold is proposed in multiscale domain. The shrinkage threshold takes full advantage of the neighboring information of the contourlet coefficients, and hence it can effectively preserve the singularities of the desirable signal and obtain better denoising result. The synthetic and real data examples demonstrate the validity of this method in seismic noise suppression processing.
Zero-Positive Splitting For Exponential Map Of Variable Coefficient Differential Operator And Its Application In Seismic Imaging

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Zero-positive splitting is a splitting that the exponential of zeroth order derivatives is on the left, and the exponential of higher derivative on the right. This splitting can cause subsequent calculation of various depths to decouple, obtained coefficients take up less storage, and benefit to parallel calculation, particularly suitable to multi-stage internal storage on GPU parallel calculation.

Zero-positive splitting for exponential mapping for the differential operators, in which all of coefficient are lateral variable, are often encountered in order to obtain integral operator for depth extrapolation. This is different from the case of differential operators in time migration, in which not all coefficients are lateral variable, its zero-order differential coefficient is lateral unchanged. Under the time migration, its exponential map of differential operators can take advantage of zero-positive splitting method directly.

However, direct Zero-positive splitting are not suitable to all of coefficient are lateral variable, series obtained from Zero-positive splitting are not convergence, and the calculation accuracy is not high. Here a new method for Zero-positive splitting is proposed, which can get a faster convergence series. This method is divided into 4 steps. A first step, the integration of depth extrapolation and Perturbation of depth extrapolation are represented Zero-positive splitting. Second step, multiply Perturbation of depth extrapolation to the integration of depth extrapolation. The null-order derivative in integration depth extrapolation is on the left of higher-order derivative in Perturbation of depth extrapolation. Adjunctions formula is used to exchange the order of the higher-order derivative and the null-order derivative. The main part and perturbation form are obtained which can be Zero-positive splitted by direct method. The series gotten from the Zero-positive splitted can be convergence fast, the forth step is merging the zeroth order derivatives term.

The advantages of this approach in depth migration is that input is the velocity, the total amount of I/O smaller; polynomial coefficient is the target which take up less storage; recursive appears only in the second step recursive operation, parallel operation in favor of follow-up.

The full use of the exponential map of the zero-order and 1 order derivative are the feature of the method. Olver called the exponential map of the zero-order and 1 order derivative as vector field translation, which also be called geometry migration. This do not used in integral feature in the time migration operator, which without lens term characteristics. The result is coefficient of phase polynomial in depth domain which can be used to calculate the polynomial of travel time. Preliminary numerical study of the method are given, confirms the validity of the method.
Seismic scattering attenuation and its potential applications in seismic imaging and waveform inversion

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ABSTRACT

The interested geological bodies in seismology and seismic exploration are commonly related to strongly-scattered small-scale seismic heterogeneity. High heterogeneity in microscopic scale may also have a significant influence on macroscopic seismic response because of the multiple scattering of wave within the heterogeneity (microscopy physics). For example, the low frequency seismic swarms from volcanic and non-volcanic seismic tremors and the low frequency seismic anomalies from hydrocarbon reservoirs in micro-seismic monitoring. However, the physical procedures of seismic scattering attenuation are still not effectively incorporated into to seismic imaging and full waveform inversion.

The multiple scattering of seismic wave in strongly-scattered small-scale heterogeneity may cause low frequency scattering resonance in transient regime and high frequency natural resonance in steady state regime. The frequency of low frequency scattering resonance is much lower than that of the natural resonance of the system. Thus low frequency scattering resonance may provide much higher resolution than that according to the standard principle of diffraction theory. The two kinds of resonances from the same medium heterogeneity have different physical mechanisms and provide a tremendous resonance for identifying and monitoring small-scale seismic heterogeneity. Based on seismic scattering attenuation characterizations and time reversal invariance principle in linear wave propagation, develop seismic waveform inversion and imaging methods for identifying and monitoring small-scale seismic heterogeneity.
Multiple removal with local plane waves

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As long as successful migration / inversion with multiples remains a challenge (especially migration / inversion without a proper initial velocity model), efficient suppression of free-surface multiples remains the key success factor in offshore exploration. For marine data from areas with hard and/or irregular sea-floor, water-layer multiples and peg-legs are often the most troublesome part of the free-surface multiples. For such data the so-called wave-equation (WE) approaches (introduced by Berryhill and Kim, 1986 and by Wiggins, 1988) are powerful alternatives to the popular SRME method (Berkhout and Verschuur, 1997). Each iteration of SRME gives the sum of multiples of different orders, while the amplitude correction for predicted multiples of different orders should be different. The difference in the required correction for interfering multiples of different orders creates problems for adaptive subtraction, and this inconsistency between prediction and subtraction is a fundamental drawback of iterative SRME even for a 1D Earth. Recently van Groenestijn and Verschuur (2009) introduced an approach for Estimation of Primaries by Sparse Inversion (EPSI) with the goal to avoid adaptive subtraction problems with SRME. In 2D case, efficiency of EPSI in comparison with best alternatives (optimal WE approach or a combination of WE approach and SRME) remains to be proven. In 3D, the use of EPSI remains a computational challenge.

The basic idea of WE approach is very simple: if we forward extrapolate the input data down to the sea floor and up to the free surface, then a primary event is transformed into a multiple event; first-order multiple is transformed into a second-order multiple, etc. After such forward extrapolation, the predicted multiples can be adaptively subtracted from the input data. In Lokshtanov (1999) it is shown that suppression of all water-layer multiples and peg-legs requires three prediction terms - prediction from the source-side, prediction from the receiver-side and prediction from the source-side after prediction from the receiver-side (a second-order term in the deconvolution). Independently of hardness of the water bottom and water-bottom depth all water-layer multiples and peg-legs of all orders are suppressed simultaneously by adaptive subtraction of these three terms in one or a few time windows. In our approach the main two steps - WE prediction and adaptive subtraction - are consistent, since each prediction term contains multiples, which require the same amplitude correction.

The great advantage of SRME is that it does not require any structural information and its potential ability to predict a larger class of multiples than just water-layer multiples and peg-legs. At the same time when data themselves are used as a prediction operator, then obviously noise in data and poor sampling significantly degrade the prediction quality. This is specially the case for 3D prediction with current quasi-3D marine acquisition. SRME requires the same dense sampling between sources as between receivers. Therefore it is hardly possible to talk about ‘true’ 3D SRME when the source interval in the crossline direction (swath distance) is several hundred metres. Of course, one can try to reconstruct the input data (Levin, 2002; Hokstad, 2004; Pica et al., 2005; Kurin et al., 2006 and 2010; Lokshtanov et al., 2007; Dragoset et al., 2008) or to use inversion during prediction (van Dedem and Verschuur, 2001). For data from areas with strong lateral variations the prediction quality of these approaches are far from ideal, especially for multiple diffractions at large offsets. The requirements for data sampling for 3D WE approaches are less severe than for 3D SRME. Indeed, with current marine acquisition (dense sampling between receivers for each shot) we can accurately perform 3D data extrapolation through the water-layer from the receiver-side, and this leads to accurate prediction of all ‘pure’ water-layer multiples (with multiple diffractions included) and of all receiver-side peg-legs. The 3D WE extrapolation from the source-side requires additional assumptions or better sampling between shots in the crossline direction. Therefore, ‘true’ 3D prediction of source-side peg-legs cannot be performed with current marine acquisition. It is important to underline that, in contrast to 3D SRME, the 3D WE approach has problems with ‘true’ 3D prediction not for all multiples, but only for some of them. Finally, as in WE migration, we use very different extrapolation operators for data from different areas: fully 2D/3D extrapolation for a generally arbitrary 2D/3D Earth (Lokshtanov, 2003 and 2006), or much faster approaches based on the assumption of ‘locally’ 1D sea-floor with arbitrary 2D/3D structure below it (Lokshtanov, 2000 and 2005). Note that the latter is the case for the majority of data from the North Sea. Our fast approach for a simple sea floor works with Radon transformed CMP gathers, while general but slower approach with Radon transformed CS gathers. In both approaches the prediction and adaptive subtraction of multiples are performed in the same domain, therefore no additional sorting or additional transformations are required. Adaptive filters account for angle dependency of the local generalized reflection coefficients from the sea floor. Numerous synthetic and real data examples prove the efficiency of the approach.
On the use of sparse wavelet expansions for seismic tomography: Methods and algorithms

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ABSTRACT

In signal and image processing, wavelets refer to a family of multiscale basis functions that offer a compromise between localization in space and localization in scale. Wavelets are suitable to build geophysically reasonable models: they can represent models that are mostly smooth (but with some localized sharp features allowed) using only few nonzero coefficients. In this talk I will explain how this sparsity of wavelet coefficients can be used as a priori knowledge in inverse problems of seismic tomography, and discuss which penalization strategies are appropriate for promoting such sparsity. I will also discuss which numerical algorithms can be used to find these sparse models.
Beamlet migration is a wave equation based migration method, which uses wavelet propagation and local perturbation theory. Compared with global methods, i.e., Generalized screen propagator (GSP), Fourier finite difference propagator (FFD), beamlet propagator use local reference velocity, which more accurate. FFD propagator uses split-step implementation for the wide angle correction, which bring in some numerical anisotropic errors. As a result, Beamlet method can provide us high-quality migration images. Here we present the 3D beamlet migration results for both isotropic medium and anisotropic medium (VTI medium). Another advantage of beamlet propagator is that the directional information is built in during the wave propagator, which can be easily used for angle domain analysis. With this, it can be also used for directional illumination analysis, which is a powerful tool to study the influence of acquisition aperture and overlaying structure to the quality of a migration image. Further, we can apply the illumination compensation to correct the acquisition aperture effect in local angle domain.

Figure 1 Prestack Migration image of LCB propagator for 45-shot SEG model
Seismic depth migration is to get an image of subsurface reflectors from seismic reflections and diffractions. However, the image amplitude is unreliable, which is influenced by many factors (e.g. propagator errors, acquisition aperture effects, etc.). As most of the subsurface structures are angle dependent or dip dependent, the image amplitude correction for those dipping structures have to be formulated in angle domain. In recent years, 3D datasets are more and more acquired and processed in the industry. The 3D true reflection imaging becomes very crucial for seismic interpretation. Here we present the 3D true beamlet migration with acquisition aperture correction in local angle domain. 3D beamlet migration propagators are based on local perturbation theory and wavelet decomposition, which can handle large velocity contrast medium and provide us migration image with very good image quality. The traditional local plane wave decomposition is computational demanding in the 3D case. In order to overcome the problems of computation and storage costs in the 3D case, we use an efficient local wavenumber-domain decomposition method based on the local exponential frame (LEF) wavefield decomposition. With this fast decomposition method, we can get the partial image and the amplitude correction factor in the three-dimensional local angle domain. This method is designed for a target oriented implementation. The expensive local angle domain decomposition and storage need only to be performed in some target areas we are interested. We test this method on the 45-shot 3D SEG salt model, and the results shows significant improvement on the image quality, for both structures in the shallow area and those in the subsalt area. The amplitude correction in local dip-angle domain for the acquisition effect can not only balance the image amplitudes, enhance the structural continuity, reduce the shadow zone effect in the subsalt area, but also can diminish the migration artifacts and increase the apparent resolution.

Figure 1 Acquisition aperture correction for 3D SEG model: (a) original image; (b) corrected image.
Operator Localization with Generalized Windowed Transforms

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Windowed transforms have been used for many years to provide time/frequency or space/wavenumber decompositions for constructing localized wave operators. Construction of an invertible windowed transform that allows for manipulation of localized plane waves has proven to be a difficult task. In this talk, we describe a Generalized Windowed Transform (GWT) framework that collects ideas and algorithms from a variety of sources (i.e. windowed Fourier transforms, filter banks, Gaussian beams, beamlets, wavelet transforms, curvelets, etc.) for constructing localized plane wave decompositions. The GWT framework exploits familiar concepts from signal processing in the Fourier domain along with computational efficiencies of the Fast Fourier transform to construct invertible local plane wave decompositions with low redundancy and reasonable computational efficiency. The windowing framework is based on filter bank theory for wavelet transforms in the frequency domain, with extensions that replace sub-band aliasing in window overlap zones with blending, and a computational structure based on the Fast Fourier transform. The classical normalization and aliasing constraints of the wavelet transform are satisfied by the GWT with redundancy factors less than 2. Multidimensional transforms are constructed in a fashion analogous to Fourier transforms, using repeated application of the 1D GWT along each axis of a higher dimensional object. Constructions analogous to the curvelet transform can be implemented with the GWT in multiple dimensions with reasonable computational complexity. We show a number of applications of the GWT to relevant problems in wavefield processing and imaging, including dip filtering, 3D re-migration of seismic data, and comparisons of sparsity between the GWT and the curvelet transform.
New approach to joint geophysical imaging of electromagnetic and seismic wave fields

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Summary

A significant obstacle in developing a robust joint imaging technology exploiting seismic and electromagnetic (EM) wave fields is the resolution at which these different geophysical measurements sense the subsurface. Imaging of seismic reflection data is an order of magnitude finer in resolution and scale compared to images produced with EM data. A consistent joint image of the subsurface geophysical attributes (velocity, electrical conductivity) requires/demands the different geophysical data types be similar in their resolution of the subsurface. The superior resolution of seismic data results from the fact that the energy propagates as a wave, while propagation of EM energy is diffusive and attenuates with distance. On the other hand, the complexity of the seismic wave field can be a significant problem due to high reflectivity of the subsurface and the generation of multiple scattering events. While seismic wave fields have been very useful in mapping the subsurface for energy resources, too much scattering and too many reflections can lead to difficulties in imaging and interpreting seismic data. To overcome these obstacles a new formulation for joint imaging of seismic and EM wave fields, where each data type is matched in resolution, is introduced. In order to accomplish this, seismic data are first transformed into the Laplace-Fourier Domain, which changes the modeling of the seismic wave field from wave propagation to diffusion. Though high frequency information (reflectivity) is lost with this transformation, several benefits follow: (1) seismic and EM data can be easily matched in resolution, governed by the same physics of diffusion, (2) standard least squares inversion works well with diffusive type problems including both transformed seismic and EM, (3) joint imaging of seismic and EM data may produce better starting velocity models critical for successful reverse time migration or full waveform imaging of seismic data (non transformed) and (4) possibilities to image across multiple scale lengths, incorporating different types of geophysical data and attributes in the process.

Important numerical details of 3D seismic wave field simulation in the Laplace-Fourier domain for both acoustic and elastic cases will also be discussed.
Solutions of the wave equation as decompositions of localized solutions

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Localized solutions of the wave equation with constant speed in several spatial variables are represented as exact superpositions of elementary localized solutions. Such decompositions are constructed by using continuous wavelet analysis in a similar way as the well-known plane wave decompositions are constructed by using the Fourier analysis.

Basic facts of the methods of continuous wavelet analysis are provided. Decompositions of solutions in elementary ones comprised the following steps: the choice of a mother solution, the construction of a family of elementary solutions by applying some transformations to the mother solution, the calculation of the wavelet transform. The wavelet transform determines a contribution of every elementary solution to the wave field under consideration.

Requirements for a choice of mother solutions are discussed. An exact packet-like solution given by a simple explicit formula is suggested as an example of the mother solution. This solution is exponentially localized in the vicinity of a point moving with light speed along a straight line. This solution depends on free parameters; its properties for different parameters are discussed.

Two ways of constructing the family of elementary solutions are overviewed. In the first case, the elementary solutions are built by means of shifts, global scaling and spatial rotations applied to the mother solution. Such elementary solutions are suitable for the decomposition of a solution of the initial value problem. The coefficients in the decomposition are expressed in terms of the wavelet transform of the initial data. Another way of building elementary solutions is to apply to the mother solution transformations of the Poincaré group: shifts, global scaling, and Lorentz transformations (hyperbolic rotations). Decompositions obtained in such a way are suitable for the boundary value problem in a half-plane (or half-space). Time-dependent data given on the boundary line (or plane) propagate as a superposition of elementary solutions traveling away from the boundary. The contribution of each elementary solution depends on the value of the corresponding Poincaré wavelet transform of boundary data.

Examples of numerical calculations are presented.

Literature
Gaussian Beam Summation Method, mathematical grounds and application

M.M. Popov

What we call today Gaussian beams was invented by specialists in theory of open optical resonators for gas lasers in the late 1960’s. They describe real physical phenomenon, namely, propagation of monochromatic and coherent beam of light generated by a gas laser working in quasi-stationary regime.

Mathematical theory of optical resonators in most general formulation—multi-mirror resonators immersed in inhomogeneous medium—has been developed in Petersburg Mathematical School in wave propagation and diffraction at that time. This theory is based on the so-called parabolic equation of the diffraction theory which is actually non-stationary Schrödinger type equation where arc length of the central ray substitutes the time. In the presentation we give short sketch of appropriate quantum mechanics technique for construction of the Gaussian beams.

The Gaussian beams possess remarkable and mathematically attractive properties: they are concentrated in the vicinity of the central ray and do not have singularities on this ray and its vicinity. Therefore they have been developed for many equations including, naturally, acoustic and elastodynamic equations and used for constructions of different asymptotic solutions in wave propagation problems. This method we call the Gaussian Beam Summation Method.

Now Gaussian beams— we use only so-called main mode of a resonator, or ground quantum state of a quantum oscillator and not the higher order Gaussian beams—loose their physical sense and are being considered solely as a mathematical tool. In order to compute a wave field at an observation point by GBSM we have to proceed as follows: to construct a fan of central rays which covers some vicinity of the observation point; to construct a Gaussian beam propagating along each central ray with appropriate initial data and finally to sum contribution of beams to the observation point. In the presentation we demonstrate the results of GBSM application to a number of wave propagation problems.

Recently we have started to work on migration problems in geophysics with GBSM. Our approach can be visually explained as follows. Assume that we have reflected wave on the seismogram. For a smoothed version of the velocity model we propagate this wave backward in depth together with the direct wave field generated by the explosion and fix it in such a position in migration domain where both fields are coherent, i.e. coincide in phase. This procedure allows restoring reflecting interfaces in subsurface.

It turns out that internal degrees of freedom of GBSM enables us to estimate the reflection coefficients on the interfaces and to naturally implement true amplitude approach. In the presentation we present migration results for a number of benchmark models. We demonstrate also some results of application of GBSM for reconstruction of the subsurface velocity model (tomography).

In conclusion we briefly discuss main difference between Hill’s method and our approach to the depth migration.
Gaussian beams for high frequency waves: some recent developments

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ABSTRACT

I will summarize some recent theoretical and algorithmic developments in Gaussian beams for high frequency waves. Specifically, I will focus on the following aspects: (1) beam width grows exponentially in generic situations, which will result in deteriorating beam accuracy due to the Taylor expansion; (2) beam reinitialization will allow us to control the growth of beam width; (3) I will demonstrate how to reinitialize beam propagation by using fast Gaussian wavepacket transforms; (4) I will demonstrate how to design multiscale Gaussian beams for wave equations by using fast multiscale Gaussian wavepacket transforms; (5) I will also demonstrate how to design an Eulerian Gaussian beam framework by solving PDEs.
Wide-azimuth angle gathers for anisotropic wave-equation migration

Paul Sava and Tariq. Alkhalifah

Extended common-image-point gathers (CIP) constructed by wide-azimuth TI wave-equation migration contain all the necessary information for angle decomposition as a function of the reflection and azimuth angles at selected locations in the subsurface. The aperture and azimuth angles are derived from the extended images using analytic relations between the space- and time-lag extensions using information which is already available at the time of migration, i.e. the anisotropic model parameters. CIPs are cheap to compute because they can be distributed in the image at irregular locations aligned with the geologic structure. If information about the reflector dip is available at the CIP locations, then only two components of the space-lag vectors are required, thus reducing computational cost and increasing the affordability of the method. The transformation from extended images to angle gathers amounts to a linear Radon transform which depends on the local medium parameters. This transformation allows us to separate all illumination directions for a given experiment, or between different experiments. We do not need to decompose the reconstructed wavefields or to choose the most energetic directions for decomposition. Applications of the method include illumination studies in areas of complex geology where ray-based methods are not stable, and assuming that the subsurface illumination is sufficiently dense, the study of amplitude variation with aperture and azimuth angles.
Localized Waves and "Frozen Waves": An introduction
(with a brief mention of evanescent waves)

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After presenting a bird's-eye view of some remarkable experiments with evanescent waves (and/or tunneling photons), we go on to consider the new "Localized Solutions" (LW) to the wave equations. For instance, soliton-like pulses—which travel without deforming—can be constructed for arbitrary frequencies and bandwidths, and with higher and higher localization properties. Such results can be extended, e.g., to dispersive and even lossy media; or can be used for focussing the LWs in order to get high intensity peaks, with potential applications even in medicine. Our solutions may actually find application in any fields in which an essential role is played by a wave-equation (like seismology and geophysics, besides electromagnetism, acoustics, gravitation, elementary particle physics, etc.). The LWs may be endowed with any group-velocity, from zero to infinity: The superluminal LWs having been called X-shaped waves.

We briefly investigate also the (not less interesting) case of the subluminal Localized Waves. In particular, we mention the peculiar topic of zero-speed waves: Namely, of the localized fields with a static envelope, called "Frozen Waves" by us. Such Frozen Waves promise to have even more applications. The speaker's homepage is www.unibg.it/recami .

A minimal bibliography:

A scheme of automatic velocity update by the local angular image and the angular Hessian

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Velocity plays a key role in the seismic migration. Even for the Full Waveform Inversion (FWI), a better initial velocity model can avoid the local minimum near wrong parameters. There are several techniques to get initial velocity models. One scheme is to do the tomography based on the travel-time information. The misfit function is formulated in the data domain, just like the FWI. The restriction produced by the high-frequency approximation can be partly solved by the finite-frequency tomography. Another way to get the initial velocity is the Migration Velocity Analysis (MVA) which is implemented in the imaging domain. Traditional MVA methods are widely used into the industry in the seismic data processing. But there are two main disadvantages for the traditional method: one is that the forward propagation is based on the Normal Move-Out (NMO) which assumes the velocity model is laterally invariant and is not always true. Another one is that it needs the picking by hand. Therefore several automatic velocity analysis methods have been proposed to solve these problems. Basically, all these schemes make use of the redundancy during the migration imaging, which is produced by different imaging conditions.

In this presentation, we present a method for automatic velocity analysis of seismic data using the local angle domain common image gathers (LAD-CIGs). With the local angle domain propagator, like the Local-Cosine-Basis (LCB) operator, we can get the angular components of the Green’s function. The LAD-CIGs is obtained naturally. For a true velocity model, the LAD-CIGs dependent on the scattering angle should be flatten gathers. Otherwise, the gathers are curved. Based on this, we can formulate a misfit function in the local angle domain. After some derivations, including the Adjoint-State idea based on the local Born approximation, we can get the gradient of the misfit function with respect to the velocity model. By the local optimization methods like Conjugate Gradient (CG), the iteration for the velocity updates can be carried out automatically. And also, the gradient can be dependent on the local scattering angle. The iteration may be accelerated by the angular Hessian proposed by our previous works.
Tomographic inversion and model building based on beam migration

John Sherwood, Junru Jiao*, Hans Tieman, Kevin Sherwood, Chaoguang Zhou, Sonny Lin and Sverre Brandsberg-Dahl
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In the last decade, beam prestack depth migration (Sherwood et al. 2008 and Rieber, 1936) has evolved into an effective way to prepare data for model building. It consists of decomposition of preprocessed data into wavelets, migration to map the wavelets to the depth domain, and reconstruction. Thus, beam prestack depth migration defines a point to point mapping between the un-migrated and the migrated center of each seismic wavelet (Sherwood et al. 2008). The point-to-point mapping makes beam migration a powerful tool for velocity model building, especially for tomographic inversion. We first review beam migration’s application in routine model building combined with conventional tomography. Then we propose a new tomographic inversion to directly utilize many more wavelet attributes. Finally, we show a field example.

In addition to reducing the cost of migration, beam migration has been used to prepare preconditioned gathers (Jiao et al. 2009) for postmigration tomography according to various wavelet attributes. According to ray parameter and tolerance of travel time, both surface and interbed multiples can be easily attenuated. By ray-path discrimination, a targeted area can be imaged without interference from other zones. For example, removing wavelets with transition through a salt-sediment interface results in a clean image of subsalt which makes subsalt model building much easier than conventional image.

A unique attribute of wavelet is three dimensional residual normal moveout (3DRNMO) (Sherwood et al. 2008). Using the spatial residual, the reflector orientation, the velocity model and other attributes of the wavelet, a time residual $\Delta t$ is calculated. This residual has been used for residual migration to improve imaging quality. Here, we propose a new method that directly uses the time residuals for tomographic inversion and velocity model update. After migration, the time residual $\Delta_{3DRNMO}$ is expressed as

$$\Delta_{3DRNMO} = f(x, y, t, h, \theta) \cdot \frac{dt}{dx} \frac{dt}{dy} \frac{dt}{dh} \frac{d^2}{d\theta d\phi} \frac{d^2}{d\phi d\psi} \frac{d^2}{d\psi d\theta}.$$  

The time residual $\Delta_{3DRNMO}$ for a wavelet is caused by the errors in slowness ($\Delta s$) and thickness ($\Delta z$) from every cell that the wavelet travels through. This residual time can be directly used to update models expressed in matrix form as:

$$[A, A^T] \begin{bmatrix} \Delta s \\ \Delta z \end{bmatrix} = \Delta t_{3DRNMO}.$$  

The proposed method uses all attributes. Furthermore, we not only utilize reflected waves but also diffracted waves and turning waves since both un-migrated and migrated information are considered. The synthetic example validates the proposed method. The field data test demonstrates that the model derived from the tomography flattens events in the gathers and yields stacked image with better focusing and clarity (Figure 1).

Acknowledgements
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References

FIG.1. Comparison of the starting model (left) and the updated model (right) overlaid by their corresponding stacks.
The integral expression and numerical calculation of the acoustic multiple scattering about cracks

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The research on the scattering about cracks is important but difficult. On the basis of classical formulas proposed by Eshelby(1957), people try to put forward many kinds of approximate methods in the calculation of the elastic constants of the non-uniform media. These methods mainly include the HKT theory which proposed and advanced by Hudson, Kuster and Toksoz and the Biot-jet theory.

Here, we proposed a new integral solution of the acoustic multiple scattering about cracks. This solution is expressed by the exponential function, separable approximation and fractional operators, and it contains two important features of the scattering about cracks: one is the spherical harmonic mode couple, the other is the multiple scattering, which can be showed in the Ellipse Reflection Coefficient that can be read as:

\[ R(k_x, k_y, \theta, n - m) = \frac{k_x - k_y - \frac{b \sin \theta}{(n + b \cos \theta)} (n - m)}{k_x + k_y + \frac{b \sin \theta}{(n + b \cos \theta)} (n - m)} \]

Where \( R \) is an evolitional form of the Sphere Reflection Coefficient, \( n-m \) is the Mode Coupling Coefficient, and the factor \( \frac{b \sin \theta}{(n + b \cos \theta)} \) is depending on the shape of the crack. If \( b=0 \), \( R \) is the spherical reflection coefficient.

We all know that the value of \( \kappa a \) is important in the determination of the scattering. When \( \kappa a << 1 \), the scattering will be very weak and the Born scattering and the Hudson’s formulas is valid for this to a large extent. But when the wavelength is comparable or smaller than the scale \( a \), there is no useful method to describe the scattering of cracks. The integral expression that was proposed in this research is suitable to any value of \( \kappa a \). Meantime, several characteristics of scattering matrix of cracks has been given with regard to the range of \( \kappa a \) from 0.5 to 5.

Compared to the past research by others, the integral expression does well in reflecting the scattering properties about the cracks. Specifically, it shows two important characteristics of the scattering: firstly, it reflects the spherical harmonic mode coupling which is different from the sphere scattering. Second, it gives an expression about the multiple scattering which is distinct from static field. In other words, the traditional methods ignore the multiple scattering and the mode coupling, and the result is that the velocity anomaly becomes smaller while the absorption anomaly become larger.
Wave Propagation Modeling by a Wavelet-Optimized Adaptive Finite-Difference Method

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The staggered-grid finite-difference (FD) methods are applied extensively for wave propagation in complex region, due to its high computational accuracy. However, the methods need serious computation overburden for long wave propagation, since the grid size is calculated in terms of the shortest wave-length to avoid numerical dispersion. Thus, the entire model should be divided into small grids even when the layer of low velocity occupies only a small part. Many adaptive FD methods are proposed to avoid spatial oversampling when applied to multi-scale media. Advanced wavelet transform can naturally decompose the signal at different scales, thus adaptively characterizing its components at different resolutions.

In this abstract, we present a wavelet-optimized adaptive staggered-grid FD method for wave propagation. A Boxcar/Wavelet (B/W) transform is employed, which each coefficient is obtained by a finite linear combination of boxcar coefficients at a single scale. B/W transform has two advantages over pyramid type wavelet, like Haar transform. One is that their coefficients decay much faster than Haar coefficients when the underlying object is piecewise smooth. The other one is that partial reconstructions involve superpositions of smooth functions and so avoid jaggies. The wavelet scale parameter is related directly to the level of meshes. We can reconstruct the solution with good accuracy using finite terms of wavelet expansion under some threshold sets for refinement/coarsening in a low- or high-degree of regularity. The adaptive meshes, in response to the heterogeneities of media and the resolution scales of wave fields, lead not only to a great saving of computation time and memory but also to an enabling method for solving problems with high accuracy in some local complex zones. Numerical examples demonstrate that the proposed wavelet-optimized adaptive FD scheme is efficient and accurate for wave propagation simulation.

![Multiscale decomposition of a signal by B/W transform](image-url)
Flux-normalized wavefield decomposition and migration of seismic data

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ABSTRACT

Separation of wavefields into directional components can be accomplished by an eigenvalue decomposition of the accompanying system matrix. In conventional pressure-normalized wavefield decomposition, the resulting one-way wave equations contain an interaction term which depends on the reflectivity function. By directional wavefield decomposition using flux-normalized eigenvalue decomposition these interaction terms are absent. By also applying a correction term for transmission loss, the result is an improved estimate of reflectivity. The flux-normalized migration scheme is also applied to a normalized wave-equation angle transform to estimate the reflection coefficient as function of slowness. Synthetic and field data examples show the effectiveness of the new methods.
Full waveform inversion based on GPU

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ABSTRACT

Computational cost and storage requirement are the main obstacles that inhibit the research and practical application of full waveform inversion (FWI). We develop a fast parallel scheme to speed up FWI on graphics processing unit (GPU), which is a parallel computing device, via CUDA (an acronym for Compute Unified Device Architecture), developed by NVIDIA and used as the programming environment. In this parallel scheme, to avoid frequent and low-bandwidth data transfer between host memory and device memory, the entire computing task, including propagator and backpropagator, are coded as a sequence of kernel functions that can be called from the compute host for each iterative inversion. The saving boundary wavefield technology is used when propagating source wavefield to solve the storage requirement, so that we do not have to save all the source wavefield data. To test our algorithm, we implement the FWI using conjugate gradient algorithm on a Personal Computer (PC) to reconstruct the Marmousi velocity model using synthetic data generated by the finite-difference time domain code. This numerical test indicates that the GPU-based FWI typically is more than 81 times faster than the CPU-based.
Differential evolution algorithm with local fitness function for high-dimensional waveform inversion

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Seismic waveform inversion is a major topic of interest in whole earth geophysics and exploration geophysics due to the need for developing accurate earth models and for gaining a better understanding of subsurface structures. The gradient-based waveform inversion algorithms are popular and have got some successful applications, but they are limited by the nonlinearity of the inverse problem and need a good guess for initial model. Global optimization methods don’t need to compute the gradient and can work well without good guess of an initial model. As powerful computers, especially the large parallel computer systems, became available, global optimization methods are attracting more and more attentions from geophysicists, e.g., Sen and Stoffa use simulated annealing (SA), Sambridge uses neighborhood algorithm, and Varela et al. use very fast simulated annealing (VFSA) to estimate earth model from fitting of seismic waveforms.

In this paper, we propose an improved Differential Evolution (DE) for the high-dimensional waveform inversion. In conventional evolutionary algorithms, the individual is treated as a whole and all its variables are evaluated using a uniform fitness function. This evaluation criterion is not effective for the high-dimensional individual. So, for high-dimensional waveform inversion, we incorporate the decomposition strategy of Cooperative Coevolution into DE to decompose the individual into some subcomponents. Then another novel feature of our algorithm is that we introduce a local fitness function for each subcomponent, and a new mutation operator is designed to guide the mutation direction of each subcomponent with the corresponding local fitness value. Co-evolution among different subcomponents is realized in the selection operation with the global fitness function. In addition, the concept of selection probability from Simulated Annealing is combined into DE. Many experiments are carried out to evaluate the performance of this new proposed algorithm. The results clearly show that for high-dimensional waveform inversion, our algorithm is effective and performs better than some other methods. Finally, the new method is successfully applied to real seismic data.
Sedimentary Cycle Analysis with Localized Phase Space Method

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ABSTRACT

We propose a localized phase space based method to characterize the sedimentary cycle. This is accomplished through wavelet analysis, which is a powerful and popular tool for the analysis of nonstationary signals. We introduce a new class of analytic wavelets, the Generalized Morse Wavelets (GMWs), into sedimentary cycle analysis, which have some desirable properties and provide an alternative to the Morlet Wavelets. When properly integrated with seismic and geological knowledge, the localized phase space method can act as an important tool in the reservoir appraisal process. Sedimentary cycle is a series of related processes and conditions appearing repeatedly in the same sequence in a sedimentary deposit. The energy distribution of seismic data in time-frequency domain, which can be obtained by wavelet analysis, supplies the effective information for sedimentary cycle analysis. The sedimentary cycle curve can be extracted from the wavelet power spectrum of the seismic records. Given a seismic profile, in order to display the sedimentary cycle more precisely, the suitable parameters of the GMWs must be determined according to the logging data, such as the Gamma logging curve. Integrate the geological background with well logs, the results of sedimentary cycle analysis can match the known drilling results and predict the possible areal distribution of oil. The efficiency of our method is demonstrated by both synthetic and real data.
Abrupt feature extraction via the combination of sparse representations

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ABSTRACT

The complexity of channels in 3D seismic data always makes detailed interpretation challenging. Similarly, definition of sand bars and beaches is also complicated as they are only partially visible when seismic amplitude is examined. To improve the imaging of these features, current interpretation workflows use advanced color and opacity based co-rendering techniques to merge multiple attributes information. Other than to enhance these sedimentary features in 3D views with combinations of different attributes, this paper proposes to separate their reflection waveforms directly from 3D imaging data by exploiting the waveform diversity mechanism. Our separation model is set up upon the assumption that seismic data are composed of coherent events and abrupt features (correspond to sedimentary features). According to their appearance in vertical sections, we model these two kinds of seismic features as linear structures and punctate structures respectively. Two appropriate waveform dictionaries are chosen, one of which is used for the representation of the coherent events and the other for the sedimentary features. The separation process is promoted by the sparsity of both waveform components in their corresponding representing dictionaries. The capacity of the proposed method is illustrated using modeling data and real 3D seismic data with complex depositional systems.
On Seismic discontinuities detection in 3D wavelet domain

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ABSTRACT

The consistent and reliable detection of discontinuity in 3D seismic data provides interpreters with very powerful means to quickly visualize and map complex geological structures. The computational cost of these methods, such as 3rd generation coherence algorithm and local structure entropy, will increase as the width of analyzing window become larger. 1D continuous wavelet transform (CWT) can not properly characterize the correlated information between neighboring traces. Taking the Morlet as the mother wavelet, Boucherea applies 2D CWT to detect the faults in a seismogram. It is noticed that the 2D CWT usually fails to some weak discontinuities due to the influence of amplitude. Just as 1D CWT has some shortage to analyze the 2D data, 2D CWT has some shortages for 3D seismic data which was frequently used in industry. 3D CWT has good properties such as multiscale and orientation selectivity. In this work, we propose a multiscale method which can detect seismic discontinuities via 3D CWT. There are three steps in our method. First we used Hilbert transform to obtain instantaneous phase (IP) cubes to reduce the affection of amplitude. Then we do 3D CWT to IP cube and obtain the coefficients in 3D wavelet domain. Finally we define the discontinuities measured in 3D wavelet domain. The synthetic data example shows our method’s depicting ability of large fault and tiny discontinuities. Then we apply our method to 3D field data, the results show our method can detect seismic discontinuities more subtly compared with commonly used methods.
Orthogonal dreamlet shot-profile prestack depth migration

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Dreamlet (Drumbeat-beamlet) migration is seeking to develop theory and algorithm for both the decomposition of seismic wavefield and one-way wave propagation operator by the complete time-space localized atoms, that is, dreamlet atoms (Wu et al., 2008). Dreamlets can be considered as time-space localized directional wavepackets and are generated by the tensor product of time and space localized bases, such as the local cosine/sine bases and/or the local exponential frames. The complete time-space localized atoms have the feature of sparsely representing the seismic data and wavefield. The dreamlet propagator has the ability to migrate the data directly in the sparsely transformed domain (the compressed domain). Intuitively, time-space localized downward-continuation extrapolator will be sparser than that in the frequency domain. After a small depth stepping, the directional dreamlet atoms cannot propagate to arbitrary locations in the time-space seismogram panel, it must observe causality which is dictated by the wave equation. The value of the propagator matrix is concentrated on the bands which obey the traveltime-distance relation.

In this work, we apply the orthogonal local cosine bases on both the time and space localizations to construct the orthogonal dreamlets. In fact, research has been done to test the effects using two dimensional semi-adaptive local cosine/sine bases to 2D seismic data compression (Wang and Wu 1998, 2000), which is demonstrated to be an efficient method providing high compression ratio as well as preserving seismic data information. The orthogonal dreamlet decomposition can efficiently shuffle the wavefield between time-space and dreamlet domain and also posses other outstanding features. Since the time-space records obtained from the acquisition system are real functions and the local cosine transform doesn’t change the data type, the wavefield decomposition and propagation based on the multi-dimensional local cosine dreamlet will be kept in real number calculation through the process. The one-way dreamlet propagator always migrates the seismic data in one direction along the time axis and part of the seismic data used to image the shallower structures will flow out the time space panel.

We demonstrate the accuracy and imaging quality based on the 2D benchmark salt model and investigate the seismogram evolution by the dreamlet migration during depth stepping and also the variation of dreamlet coefficient amount.

![Single dreamlet and beamlet atoms propagation in constant velocity model](image)

(a) Vertical-propagating dreamlet; (b) Vertical-propagating beamlet; (c) Oblique-propagating dreamlet; (d) Oblique-propagating beamlet.
Dreamlet survey sinking migration

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Survey sinking migration downward continues the entire surface collected multi-shot data to the subsurface space simultaneously. The extrapolated wavefield data at each new depth level can be considered as a new data set that would have been acquired if a fictitious acquisition system is located at that level of subsurface. In order to save computer memory, survey sinking downward continuation scheme is commonly conducted in frequency domain, one frequency at a time, and consists of two steps: first, downward continue the receivers for a common point source gather; second, downward continue the sources for a common point receiver gather. The reflected amplitudes from subsurface reflectors would be visible at zero time and zero offset in the “survey sunk” wavefield (Sava and Hill, 2009). According to the concept of the survey sinking, the survey system beneath a reflector should no longer contain records from the imaged reflector. However, due to operations in the frequency domain for downward continuation, the signals will wrap around to the other end of the working time axis after reaching to the zero time moment. These anti-causal signals can contaminate the image of deeper structures.

Dreamlet (Drumbeat-Beamlet) migration is seeking to develop algorithm for wavefield decomposition and propagation with complete time-space localization. The space localization of the dreamlet propagator can handle the strong lateral velocity variations and drastically reduce the strength of local perturbations. The localization on time gives more flexibility on time-varying operations during downward continuation and imaging. The survey sinking migration by dreamlet propagator can automatically keep only the data for imaging the structures beneath the survey system and get rid of the data used to image upper structures. The valid length of the time records is shorter as the depth increases for the dreamlet survey sinking. For the wavefield decomposition, dreamlet transform is equal to the multi-dimensional localized transform, in a tensor product form along common source, common receiver and time axes. The downward continuation is now changed from point source and point receiver gathers to common beamlet source and common beamlet receiver gathers. The wavefield compression ratio for the survey sinking wavefield decomposition is higher than the shot-profile migration, which decomposes the source and receiver wavefield separately for each shot. In principle, these properties can be major factors to speed up the migration process while keeping good image quality.

2D SEG/EAGE poststack migration results
(a) Dreamlet migration; (b) Beamlet migration.
Decomposition, extrapolation and imaging of seismic data using beamlets and dreamlets

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In this presentation, I review the major concepts and progress on the development of beamlets and dreamlets (Drumbeat-beamlets), as well as their applications to seismic data decomposition, wave propagation, illumination, imaging and local inversion. Seismic data or wavefield are special data sets. They cannot fill the 4-D space-time in arbitrary ways. The time-space distributions must observe causality, an inherent property of the wave equation. Wave solutions can only exist on the “light cone”, which is a hyper-surface in the 4-D space or its dual space (the 4-D Fourier space). It is also known that the information on the light-cone can be recovered from the information on hyper-planes (cross-sections in the 4-D space). Seismic data acquired on the earth surface, or data available during downward extrapolation, survey-sinking, depth migration, etc., all involve data on an observation plane. Therefore, phase-space localization through wavelet transform can be applied to either the light cone or the hyper-planes. These two decompositions are linked by the causality or dispersion relations.

The distinctive and fundamental feature of wavelet transform (in a generalized sense) applied to wave phenomena is the multi-scale phase-space localization. In the context of wave propagation, the phase-space localization means the localizations in both the space and propagation direction (wavenumber), and also in both time and frequency. The phase-space localization gives the advantages in treating the strongly varying heterogeneities in wave propagation, and in obtaining the rich information about local parameters of wavefield.

Beamlet is referred to any elementary function of decomposing a wavefield by wavelet transform (in the generalized sense) along the spatial axes and represents a space-wavenumber localization atom in the frequency domain. The dispersion relation imposed by the wave equation relates the localization of wavenumber into the localization in direction. To have full time-space localization, “dreamlet” is introduced (Wu et al., 2008) as a tensor product of a time-frequency atom “drumbeat”, and the space-wavenumber atom “beamlet” in decomposing the wavefield on an observation plane. Drumbeat × beamlet = dreamlet. The phase-space localization is defined in a hyper-plane in the 4-D space (or 8-D phase-space). Therefore, dreamlet is a type of physical wavelet introduced by Kaiser (1994) as localized wave solution on the light-cone. It is also closed related to pulsed-beam and other wave-packet decompositions. The decomposition of seismic data or wavefield on observation planes (or extrapolation planes) using dreamlet is very efficient and the corresponding propagator matrices are quite sparse.

Beamlet and dreamlet propagations in heterogeneous media have been derived using local perturbation theory with a two-scale media decomposition. Local perturbation method can drastically reduce the local perturbation strength (with local reference media) for strongly heterogeneous media and has been applied to seismic propagation and imaging in complex media, including subsalt imaging. Due to the readily availability of the local angle (or wavenumber) domain information about the wavefield and the image field, different angle-gathers can be extracted easily from the local image matrix defined in beamlet migration. Widely used angle gathers extracted from the local image matrix are the local dip-angle gather and local reflection-angle gather. The former is used in illumination analysis and acquisition aperture correction; the latter is used in local AVA (amplitude variation with angle) and reflection analyses, and in angle-filtering for removing migration artifacts. Beamlet propagator can be also easily adapted to the calculation of energy-flux Green's function in the local angle domain, which is the core of efficient algorithm for directional illumination analysis (including acquisition-dip response: ADR). Based on directional illumination analysis, a theory of acquisition-aperture correction in the local angle domain has been developed, such that the local image amplitude can be corrected to approaching the value of local reflectivity (True-reflection imaging). Numerical examples have shown that acquisition-aperture correction can not only balance the image amplitude, improve the continuity of structures, but also reduce artifacts and noises, increase resolution, and improve the overall image quality. The local angle domain information provided by the beamlet decomposition can be also used in resolution analysis and local angle domain inversion, such as the generalized diffraction tomography. Dreamlet decomposition of seismic data has a high compression ratio, and the compression ratio maintains to a high level or increase further during migration/imaging. This feature opens the door for implementing migration in the compressed domain.
Super-wide angle beamlet propagator based on iterative wavefront reconstruction

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One way method in imaging has many advantages, such as fast computation speed and easy to store the wavefield. However, regular one way method has a severe shortcoming about angle limitation. To get more accurate imaging result in large angle case, Wu and Jia introduced the idea of super wide angle one way method by weighting both horizontal propagated wavefield and downward propagated wavefield in 2006. Jia and Wu implemented the idea based on GSP method by direct interpolation after the extrapolation. In the presentation, an improved method is presented based on local cosine basis one way method, and iteratively reconstruction of wavefront with two orthogonal wavefields. Numerical tests in homogeneous medium and 2D Salt model show that this method can image steep dips more than 90°, such as the overhung part of salt.

Local cosine bases was constructed by Coifman and Meyer (1991)\textsuperscript{(Coifman and Wickerhauser 1992; Pascal Auscher, Weiss et al. 1992)}. These localized cosine functions remain orthogonal and have small Heisenberg products. The basis element can be characterized simultaneously in space and wavenumber domain. Local perturbation field and background field can be obtained based local basis. Small-scale local perturbations are fluctuations around the local reference velocity. Localized propagators can be more accurate for strongly heterogeneous media than global ones.

For one-way wave propagation, large-angle waves with respect to the z-axis become small-angle waves to the x-axis, and vice versa. If we just use one direction for wave field reconstruction, large-angle waves with propagation angles exceeding 70°, inevitably carry some errors in phase and amplitude. Super-wide angle one-way method extends the capability of one-way propagators by combining and interpolating the two orthogonal propagated one-way wavefield, horizontal propagation wave field and downward propagation wave field. (Wu and Jia 2006). The scheme can improve accuracy for large-angle propagation.

In the implementation of interpolated super-wide angle one-way method, We first separately propagate down downgoing part $P_D$ and laterally horizontal part $P_H$ and save the two wavefields, then interpolate the two wavefields and obtain final wavefield $P$. In fact, each wavefield of two directions exist angle limitation.

In the new method, we make the two orthogonal wavefields interact during extrapolation. In detail, firstly, we propagate down $P_D(z_0)$ for the first step with depth interval $\Delta z$ and save the wavefield at depth $z_0 + \Delta z$, then propagate $P_H(z_0)$ laterally (left and right) for the first step with lateral interval $\Delta x$ and save the wavefield at horizontal location $x_0 \pm \Delta x$, after that we interpolate the two wavefields to construct the accurate wavefront. In Secondly, We separately propagate down and laterally for the second step, and get the wavefront at $z_0 + 2\Delta z$ and $x_0 \pm 2\Delta x$. Iteratively we can get the third, fourth, …, and finally the last wavefront. We can see from the flow that every wavefront gets reconstructed before next step’s propagation in two directions. Due to the increased phase and amplitude accuracy of the propagator, the image quality and resolution gets further improvement with the iterative wavefront reconstruction method. Because of the local nature of the beamlet propagator, the wavefront reconstruction can be very efficient. The total computational cost is 1.5-2 times of regular one-way method, which is acceptable for many applications.

In conclusion, Super-wide angle propagator based on iterative wavefront reconstruction combines two orthogonal propagated wavefields and reconstruct wavefront iteratively. The method overcome the angle limitation of regular one-way method and can deal with super wide angle (larger than 90 degree) wave and turning wave propagation.

Snapshot: (a) Regular LCB One-way Method  
(b) New Super-wide Angle One-way Method
Sensitivity kernels for finite-frequency signals: Applications in migration velocity updating and tomography

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ABSTRACT

Seismic reflection surveys conducted on the Earth’s surface generate seismic data which can be used in depth migration for imaging subsurface structures. Due to the lack of an accurate velocity model, the migration is usually calculated in an initial model and the resulting image is often incoherent. The distortion of the image carries important information regarding the errors in the migration velocity model. The migration velocity analysis links the incoherence in the image to errors in the model and uses this information to modify the initial model towards the optimal velocity model. This process simultaneously improves the quality of the image and the velocity model.

The most important part in migration velocity analysis is converting the observed residual moveout into velocity corrections and back-projecting them into the model space for velocity updating. Currently, this has been dominated by the ray-based techniques which assume an infinitely high-frequency. When a band-limited seismic wave propagates through a complex region, the rays often poorly approximate the actual wavepaths. The sensitivity of finite-frequency signals to the velocity model has been recently investigated by researchers working in earthquake seismology, ocean acoustics and applied seismology. Finite-frequency sensitivity kernels have been used for solving many tomography problems with great success. The major obstacle that prevents this method from being used in migration velocity analysis is that these finite-frequency sensitivity kernels are mostly used for transmitted waves propagating from a point source to a point receiver and the information is extracted from the data domain (e.g., traveltime delays or amplitude fluctuations in seismograms). In seismic migration/imaging, unlike dealing with the seismograms directly, the information regarding the velocity error must be extracted from the depth image instead of from the data.

Based on the scattering theory, we derive the broadband sensitivity kernel particularly for shot-record prestack depth migration. This sensitivity kernel relates the observed residual moveout in depth image to the velocity correction in the model. Based on the sensitivity kernel, a new tomography method is proposed for migration velocity analysis. The new approach is a wave-equation based method. It is formulated for the shot-record prestack depth migration and shot-index CIGs, thus expensive angle decomposition is not required. An efficient method based on one-way wave equation and multiple-forward scattering and single-back scattering approximation is used for calculating the sensitivity kernel. We also use synthetic data sets to test potential applications of this broadband sensitivity kernel in migration velocity analysis.
Angle Gather Extraction for Isotropic Elastic Reverse Time Migration

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Localized waves refer to waves localized in direction/space or time/frequency, etc. Comparing to conventional waves, the localized waves may provide additional insights into the interactions between waves and media. In seismic migration, the subsurface image is obtained by summing up waves coming from different directions. This process compresses the noise in the data but also loses the directional information carried in the waves. This research aims to extract angle related images at localized space locations. The resulted angle-domain common image gathers (ADCIGs) add an additional dimension to the seismic data and can be widely used in many data analysis processes, e.g., migration velocity analysis (MVA), amplitude versus angle (AVA) analysis, illumination analysis or aperture/dip correction of the image. The ADCIGs may also provide necessary information for petro-physical inversions.

We present a slowness-based method to compute ADCIGs from the wavefields reconstructed by elastic reverse time migration (RTM). Both the source and receiver wavefields are fully vectorized and mixed with P and S modes. We perform slowness analysis to decompose the source- and receiver-side wavefields into local beams. Figure 1a and 1b demonstrate that all energy peaks are located along two circles which satisfy P- and S-wave dispersion relations. Slowness vectors ending at the energy peaks give localized plane P- and S-waves. In this way, the elastic wavefields are decomposed into a superposition of local plane waves along different directions. Then, angle-domain imaging condition is applied to these plane wave components. These partial images form the local image matrix (LIM) which is a function of local incident and scattering angle pairs. By sorting the energy distributed in the LIM, we can extract the angle related information and calculate the ADCIGs. The process is illustrated in Figures 1c, 1d and 1e. Synthetic datasets from a five-layer elastic model and elastic Marmousi2 model are used to demonstrate this technique.

![Figure 1](image1.png)

Figure 1. (a) and (b) are source- and receiver-side slowness analysis. (c) is the coordinate system in local angle domain analysis. (d) and (e) are local image matrices (LIMs) for PP and PS reflections.
Multi-scale Nature of Tsunami Waves: A Lesson to be learned from the Great 2011 Tohoku Earthquake

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Tsunami waves are generated by many kinds of excitations. The most common and well-studied mechanism is that due to the displacement of the seafloor by elastic deformation from large earthquake dislocation sources. Since December 26, 2004, there have been several examples of the massive destruction caused by tsunami waves. The devastation caused by the recent Tohoku earthquake and the nuclear plant disaster at Fukushima are further testaments to the need to understand more about the nature of tsunami waves in order to improve our ability to mitigate future disasters of disasters caused by waves invading the coast. Modeling of tsunami waves is a difficult computational problem because of its multiscale nature in both time and space. For obtaining a realistic assessment of an event such as Tohoku or Sumatra earthquakes, one must bridge up to five orders of magnitude in each spatial and temporal scale. This obliges numerical modellers to resolve spatial scales of linear waves going across deep oceans, which is relatively trivial, to nonlinear waves coming ashore and jumping over seawalls with a spatial scale of on the order of ten meters. The time-scales also span a range of between 10**4 to 10**5 from a few seconds for the waves cresting over the seawalls to long-wavelength linear gravity waves going across the ocean. Traditionally this was done with distinct models for the different phases of the simulation, the ocean-going portion and the run-up stage, with a clear of separation of scales in mind. The adaptive hyperbolic software Geoclaw, recently developed by Randy Leveque and his group, enable the entire tsunami problem to be solved without this artificial separation of timescales. Geoclaw employs accurate second-order conservative finite-volume discretization based on Riemann solvers, which can model the inundation of coastal regions, often a few to ten kilometers, as in in the case of the city Sendai. The Riemann solver uses some form of "wetting and drying" algorithm that allows grid cells to change from zero depth (dry state) to positive depth (a wet or inundated state). Adaptive mesh refinement (AMR) is also included in Geoclaw because of the need to achieve the desired resolution in some regions without an excessive number of grid cells in the overall region. We must have a fine enough grid of the order of 10 to 100 meters, along the coastline and the inland region where the flooding takes place. At the same time the grid points out in the Pacific Ocean can be much sparer. Otherwise, the computational time would take far too long. This requirement is due to the multiscale nature of tsunami waves, which changes character, as it approaches the beach. We will discuss these points pertaining to the waves attacking the Fukushima power plant and to the waves which hit Crescent City in California.
The Green’s Function for Compressible Viscous Fluid Velocity Equation

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ABSTRACT

The equation for viscous fluid velocity motion describing seismic wave propagation in fluid-saturated rocks is decomposed into a pair of potential systems that characterize compressional motion and shear motion, respectively. The Green’s functions for three-dimensional (3D) compressional and shear motion equations in infinite homogeneous space are obtained using the distribution theory and Fourier transform, which are in the form of 3D inverse Fourier transform. Especially, an explicit expression of the Green’s function for 1D shear motion equation is given. Finally, the numerical results for 1D case with different fluids such as water, oil and gas are given, which suggest that inherent characteristics of fluid have great influence on the solutions. For compressional motion, gas-saturated rocks absorb the high-frequency part of seismic wave most obviously, followed by oil-saturated rocks, and then water-saturated rocks. And for shear motion equation, the inherent characteristics of fluid have great influence on the amplitude and shape of the Green’s function. All the Green’s functions mentioned above can be applied in geophysical fields such as seismic wave propagation, imaging and scattering, and so on.
Quality factor inversion from pre-stack CMP data using envelope peak instantaneous frequency matching

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ABSTRACT

Supposing the source wavelet as the constant-phase, attenuation is obtained from pre-stack seismic data (CMP) using envelope peak instantaneous frequency (EPIF) matching. Seismic wave energy decays and inverts into heat while propagating through the earth due to the visco-elasticity of the media. Visco-elasticity attenuation is usually measured by the quality factor $Q$. Matheney and Nowack proposed the IF matching (IFM) method that iteratively modifies the causal attenuation operator to derive the $Q$-curve when the EPIF of the reference pulse matches that of the observed value at the receiver. Pre-stack seismic data is not processed by NMO correction, so the frequency contents are not destroyed, and the $Q$ estimation is available. Based on Mathneey and Nowack’s work, we propose a method for estimating $Q$ from pre-stack data using EPIF matching analysis.

According to the correlation of adjacent traces of the seismic records, the event positions (namely layers information) can be found from near offset traces. The reference wavelets are picked from a near offset trace. We isolate seismic waves of different offset traces of different layers using a moving cosine roll-off window and calculate the EPIF, which is served as observation signals. The EPIF is a matrix in which events number as the row number and total traces number as the column number. The EPIF of the observation signals match the EPIF of the attenuated reference signals to minimize the EPIF least-squares function using the optimization algorithm. Test of synthetic pre-stack CMP data indicates the validity of the method. EPIFM overcomes some disadvantages of the logarithm spectral ratios (LSR), such as the requirement of selecting variable frequency bands. It's stable to estimate $Q$ from pre-stack CMP records using the EPIFM analysis because the error of each iterative step is the average effect of all offsets.
Estimating Seismic Signatures Based on Multivariate Scale Mixture of Gaussians Model

Bing Zhang and Jin-Huai Gao

ABSTRACT

We propose a new method for estimating the seismic signatures. Suppose a source signature can be modeled by the formula with three free parameters (scale, frequency and phase), we can transform the estimation of the seismic signatures into determining the three parameters. The phase of the signature is estimated by constant-phase rotation to the seismic signal, the other two parameters are obtained by the higher-order Statistics (HOS) (fourth-order cumulant) matching method. In order to derive the estimator of the higher-order Statistics (HOS), a multivariate scale mixture of Gaussians (MSMG) model is applied to formulating the multivariate joint probability density function (PDF) of the seismic signal. By this way, we can represent HOS as a polynomial function of second-order statistics to improve the anti-noise performance and accuracy. In addition, the proposed method can work well for short time series.

Keywords: seismic signatures, estimation, cumulant, MSMG model.
The wave nature for a particle can be shown by the Schrödinger equation in quantum physics. However, whether the linear wave equation admits a particle-like (no diffraction) solution has been debated for many years. For wave propagation on a string, we can construct a d’Alembert solution, which has no diffraction. However, in higher dimensions, this is not the case. Bateman attempted in early 1900s unsuccessfully. Continued theoretical interest in this problem and the subsequent effort has generated a plethora of localized solutions, including the ‘quasi-photon’ solution to the wave equation (e.g., Gaussian packets), Kaiser’s physical wavelet based on the analytical signal transform, the Bateman-Hillion solution, Durnin’s Bessel beam, and the X-wave solution etc. Understanding the diffraction of localized waves is essential in building efficient and accurate seismic wave propagators. Starting from the localized wave packet solution to the linear wave equation given by Perel and Sidorenko (2007), we investigate the general physics of wave packet propagation and its diffraction using the finite difference method. In a homogeneous or a linear gradient medium, the wave packet with smaller aspect ratio $e$ (i.e., planar phase front), the longitudinal dimension over the transversal dimension, diffracts less than the one with larger $e$ (curved phase front). The number of oscillations filled within the wave packet is roughly given by $p$ and large $p$ achieves better diffraction property but to a limited extent. In the gradient medium, the propagation of the wave packet with small $e$ essentially represents rigid advection of the initial wave packet with rotation, which bears similarity to the high-frequency asymptotic curvelet propagation. In heterogeneous media, if the beam width exceeds the scale length of the heterogeneity distortion in the phase front is expected and this is true in general for other beams like the Gaussian beam as well. The reflection and transmission of a single wave packet is studied when the wave is incident upon an infinite planar boundary from the medium with lower velocity. If $e$ is small, both the reflected and refracted wave packets are similar to the incident one. However, for moderate to small $e$, the refracted wave packet may experience significant diffraction but the reflected one can still bear resemblance to the incident packet.
A scheme for offset VSP migration in local phase space

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ABSTRACT

Vertical seismic profiles (VSP) have the potential to obtain high-resolution image of complex structure near wells. In this paper, we mainly present a prestack depth migration scheme for the primary wavefield of multi-offset VSP in local phase space, which includes two steps: the extrapolation of wavefields and the imaging of the extrapolated wavefields. Firstly, Gabor-Daubechies tight frame based extrapolator (G-D extrapolator) and its high-frequency asymptotic expansion are used to extrapolate the wavefield of source and that of VSP, which have the characteristic of localization in both space and propagation direction and is applicable for simulating more accurate wavefields in laterally heterogeneous media. And further the corresponding validity conditions and the error are investigated. Secondly, considering the propagating angle of the upgoing and downgoing wavefields, a correlation imaging condition in local angle domain is presented based on the premise of local planar reflection. A synthetic example shows that by applying the high-frequency asymptotic expansion of G-D extrapolator, the computation efficiency is improved by about 30% and the error remains in the permissible range. The synthetic and real data tests display that applying the correlation imaging condition in local angle domain can effectively weaken migration artifacts and random noise without increasing the computation complexity.

Key words: VSP migration, local phase space, imaging condition, migration artifact
Multi-scale simulation of Diffracted Tsunami Waves off Hokkaido in Tohoku 2011 Earthquake

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ABSTRACT

On 11 March 2011, a large tsunami attacked the northeast coast of Japan because of the Tohoku earthquake. Parts of Hokkaido Island facing the Japanese Sea was flooded due to diffracted tsunami waves, which great surprised the local populace. In this presentation we will study the influence of Hokkaido Island and the tsunami waves diffracting around it. It is well known from wave theory that diffracted waves require very high resolution, due to the sharp decay of the waves around the object. Therefore one would need adapted mesh refinement to solve this problem correctly. The high resolution bottom seafloor topography near the Japanese coast less than 100 meters is employed in the simulation and also the adaptive mesh refinement method is used to study the multi-scale of the tsunami wave. We are particularly interested in the diffraction waves coming at the Otaru and to study the maximum height of the waves around the coast of northern Hokkaido.

Keywords: Tsunami, diffraction wave, adaptive mesh refinement method
Seismic diffractions are the response of important small scale elements in the subsurface such as faults, karsts, fractures and other geologic discontinuities, which are probably interesting zones for oil and gas reservoir. Traditional seismic imaging methods giving considerations only to reflections may guarantee quality and resolution. However, regarding the diffractive wavefield component as noise would lose useful information diffractions contain. Recently diffractions have received more attention. The main challenge of diffraction analysis and imaging is that real diffractions are typically one or two orders of magnitude weaker than specular reflections. Thus, it is not easy to distinguish diffracted events in full dataset or diffraction image in full seismic image. There are several methods to separate diffractions from full wavefields before or after imaging. Landa et al. (2008) found that diffractions and reflections are distinct in post-migration dip-angle domain. In this domain after migration with correct velocity, reflections appear as concave-shaped events (smile) while diffractions are flat. According to these different phenomenon, they separate and image diffractions with Radon Transform. In this paper we extend Landa’s idea for extracting diffractions. Firstly we produce dip angle domain common imaging gathers (CIG) with Kirchhoff PSTM. As usual, summation of the CIGs bring out final seismic image. Making use of the Cigs, we distinguish the true-angle of events dip based on the assumption that specular reflections energy are much larger than diffractions. Stacking the energy of true reflector-dip angle, we obtain specular reflections imaging with less noise and diffractions. On the contrary, stacking the energy of pseudo strata-dip angle, diffractions are separated and imaged. Synthetic model such as Marmousi and real data have illustrated our method not only improves the resolution of traditional reflections image, but also separates and images diffractions. Faults and caves are objectively distinguished and detected.

![Figure 1](image1.png)

**Figure 1.** (a) specular reflections imaging of Marmousi model (b) diffractions imaging of Marmousi model