“There are always times when those who do science need to pause and reflect ...”

Sven Treitel

Pitfalls and Challenges of Seismic Imaging (Beyond Conventional Seismic Imaging)

Evgeny Landa

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"Socrates, my master, is my friend but a greater friend is truth."

Plato

« Гамбургский счет »
В соответствии с легендой, метод оценки научных достижений известен, как "Гамбургский счет". Этот термин появился в 1928 году в произведении Виктора Шкловского, известного русского литературного критика, и связан с соревнованиями борцов. В то время борьба была скорее представлением, чем спортом...

«Все борцы обманывают в соревнованиях и могут проигрывать по указанию организаторов. Но один раз в году борцы собираются в Гамбурге и соревнуются по настоящему, без зрителей. Это долгое, тяжелое и не очень красивое соревнование. Но это единственный путь определить их истинный класс». 
"Socrates, my master, is my friend but a greater friend is truth."

Plato

Pitfalls and Challenges of Seismic Imaging
OUTLINES

• Pitfalls in seismic inversion

• Quantum seismic imaging: is it possible?

• Seismic diffractions - the abandoned stepchildren of traditional imaging

• Road ahead
“Большинство людей, если вы перечислите им все факты один за другим, предскажут вам результат. Они могут мысленно сопоставить факты и сделать вывод, что должно произойти то-то. Но лишь немногие, узнав результат, способны проделать умственную работу, которая дает возможность проследить, какие же причины привели к этому результату. Вот эту способность я называю ретроспективными, или аналитическими, рассуждениями (рассуждении назад).”

Этюд в багровых тонах,
Sir Arthur Conan Doyle (1887)
Inversion, is a mathematical tool for interpreting indirect measurements, inferring properties of the Earth’s interior from surface observations.

**Forward problem:** \[ Data = \text{Some}_\_\text{function}(Model) \]

**Inverse problem:** \[ Model = \text{Some}_\_\text{function}^{-1}(Data) \]

- The pure mathematical community takes an analytical, “just-solve-the-equation” approach (*not that it is easy!*)
- The second community focuses on optimization-based approach, which may not always give as much information as an analytical solution would
- Since stable analytical solutions to inverse problems generally do not exist *optimization is better than nothing*
Some problems can behave “impolitely”. Let us consider a linear system of equations:

\[
\begin{align*}
    x + 10y &= 11 \\
    10x + 101y &= 111
\end{align*}
\]

The unique solution is easy to find: \( x=1; \ y=1 \). Let us slightly change the right hand side of the first equation:

\[
\begin{align*}
    x + 10y &= 11.1 \\
    10x + 101y &= 111
\end{align*}
\]

Solution now is: \( x = 11.1; \ y = 0 \).

Small change of the input data led to sharp change of the solution.

*What practical value the solution of similar system can have? And the natural first answer - NONE.*
Oscar Perron’s paradox

• Suppose the largest natural number is \( N \)

• Then, if \( N > 1 \) we have \( N^2 > N \) contradicting the definition

• Hence, the largest natural number is equal to 1!

• We arrive at this absurd conclusion because we assumed that the largest natural number exists.
Well-posed problems should satisfy the following conditions:

1. A solution exists
2. The solution is unique
3. The solution depends continuously on the data

(=Jacques Hadamard=)

Verification of these conditions is often not a trivial task because the solutions obtained may not be a priori as absurd as in Perron’s paradox. An apparently reasonable result can mistakenly create an illusion that the problem is solved.
Geophysical inversion

What doesn’t it mean?

• **Inversion ≠ Data fitting**

“… a good fit is a necessary but by no means sufficient condition for success. By itself, a good fit does not guarantee that an inversion is correct. This occurs, in my opinion, more often than we would like to think”.

Sven Treitel
Non-uniqueness of the inverse kinematic problem

Three layer model

Location (m)

Depth (m)

Velocity m/sec

1

2

3
Two kinematically equivalent models
Difference between two models (zoom)
Geophysical inversion

What does it mean?

• How much the solution allows for reconstruction of important characteristic of the subsurface

• At the same time the importance of these characteristics is a factor external to the inversion problem...
Few lessons

- Inversion based on the best fit of observed and calculated data may lead to construction of several subsurface models with significantly different geological meaning.

- An overburden model constructed by the best fit does not guarantee a correct solution for the deeper part of the model.

- Refinement of the model parameterization may lead to a better fit but does not guarantee construction of a better subsurface model.

- The question we should always keep in mind is “How correct and realistic is our seismic images” rather than the question “How well does it fit my data”.
Tarantola took the view that the most general formulation of inverse problems can be obtained by using the language of probability and the *Bayesian approach:*

- Bayesian approach requests *knowledge of the statistical properties of the model* as well as *the statistical properties of the data*

- According to the Bayesian approach, *the data is used in inversion to constrain the a priori model,* and not the opposite as when *the inversion is constructed from the data* and the a priori model serves as a constraint.

- In practice our knowledge of statistical properties and a priori information are very poor: “*It is difficult to use Bayes’ theorem in seismic inversion and to be honest*”

- Our solutions are limited by the well known least squares method, assuming Gaussian distribution of noise
Monte Carlo Estimation and Resolution Analysis of Seismic Background Velocities

ZVI KOREN, 1, 2 KLAUS MOSEGAARD, 3 EVGENY LANDA, 4 PIERRE THORE 4 AND ALBERT TARANTOLA 5
Plate 1. Models representative of the five more likely regions in the model space. The estimated a posteriori probability of each model is 0.32, 0.08, 0.05, 0.05 and 0.04.
The present status of FWI

The so-called “full-waveform inversion” or FWI is “...technical bubble, and self-proclaimed seismic cure-all”

“... all the current approaches to so-called full-waveform inversion are:
(1) using the wrong data,
(2) using the wrong algorithms, and
(3) using the wrong Earth model, as well.”

“A timely and necessary antidote to indirect methods and so-called P-wave FWI»

A. WEGLEIN, TLE, 2013
“The truth is... seismic waves that propagate in the earth hardly satisfy any wave equations.”

Migration Velocity Inversion with Semblance Analysis
Goldin’s legacy

A good example of the inability of mathematics to solve a natural problem is “full-waveform inversion”.

Main problems:

1. The wave propagation equations are usually inadequate to describe the observed data.

2. The computational complexity of the problem. Chess game illustrates this problem.
Popper, Bayes and The Inverse Problem

ALBERT TARANTOLA, Nature, 2006

“Observations should only be used to falsify possible solutions, not to deduce any particular solution.”
• Today a large number of semi-heuristic algorithms and strategies exist, but they do not solve the inverse problem.

• Bayesian approach in principle provides a framework for combining the a priori model information with the information contained in the data to arrive at the a posteriori model distribution.

• In fact, the validation of our assumptions regarding the real model is the most crucial step in inversion.
What do we need to achieve alternative subsurface image?

• Develop a fundamentally new procedure that can construct the image without precise velocity information
“An idea which looks completely paradoxical at first, if analyzed to completion in all its details and in experimental situations, may in fact not be paradoxical”

Richard Feynman

Quantum seismic imaging: is it possible?
Feynman’s « path-integral » picture of the world:

• The world is kind of tapestry in which all kind of things can gone

• To predict the future you start with a known state in the past, allow everything to happen in the intermediate time and simply add up the contributions from all the histories

• Each history contributes certain probability amplitude. The amplitude is just an integral over time and space volume between past and the future
In classical Newton’s theory a particle have just a single trajectory

The classical path $\overrightarrow{x}(t)$ is singled out of all possible paths as the one having the least action $S$

$$S = \int_{t_a}^{t_b} dt \; L(x, x', t)$$

where $L$ – is the Lagrangian
Quantum mechanics

In Feynman’s path-integral approach, a particle does not have just a single history/trajectory as it would have in classical theory.

Instead of only considering the classical trajectory, consider every possible path between \(a\) and \(b\). Each path contributes to the total amplitude. This amplitude is

\[
K(b, a) = \sum_{\text{all paths from } a \text{ to } b} A_i(x(t))
\]

where \(A\) is the contribution of each individual path

\[
A_i(x(t)) = \text{const} \ast \exp[iS_i(x(t)) / \hbar]
\]

\[W\]
Quantum mechanics and Newton’s physics

\[ w(x(t)) = \exp[iS(x(t))/\hbar] \]
\[ Q(t_0, x_0; \alpha) = \int dh \int dt U(t, h) \delta(t - \tau(x_0, t_0, h; \alpha)) \]

where \( U(t, h) \) is the recorded CDP gather for location \( x_0, h \) - is the offset to be summed over the measurement aperture. The quantity \( \tau = \tau(x_0, t_0, h; \alpha) \)

represents the time-integration path/trajectory, which is parametrized by a parameter \( \alpha \).
The conventional zero-offset stack is obtained by optimizing for $\alpha$, i.e.

$$Q_0(t_0, x_0) = Q(t_0, x_0; \alpha_0)$$
Path-integral stack

\[ Q_w = \int d\alpha w(\alpha) Q(\alpha) \]

Instead of stacking seismic data along only one time trajectory corresponding to the Fermat path our construction involves summation over all possible time trajectories.
Path-integral stack

The path-integral stack $Q_F$ approach the classical limit $Q_O$ for $\beta \to \infty$.

This can be shown by a stationary-phase approximation under the assumptions

$$Q(\alpha) \to 0, \text{ when } |\alpha - \alpha_0| \to \infty, S'(\alpha_0) = 0, S''(\alpha_0) \neq 0$$

$$Q_F \approx \exp \left[ i \beta S(\alpha_0) + i \mu \pi / 4 \right] \sqrt{\frac{2\pi}{\beta |S''(\alpha_0)|}} Q_0$$
The imaging consists of weighted summation along a representative sample of all possible travel time curves (paths) between the source and observation points.
Path-integral imaging

Zero-offset section
Path-integral imaging

Stacked section
Path-integral imaging

Path-summation section
Path-integral imaging

CMP

Near offset section
Path-integral imaging

CMP

Path Summation stack
Path-integral imaging

Path Summation cube
Path-integral imaging
Path-integral imaging

Path-summation time migration
Summary

• Quantum seismic imaging method provides a new framework for subsurface imaging without precise knowledge or selection of a velocity model.

• Quantum seismic imaging can be considered as a model-independent technique, since it does not involve any velocity or parameter estimation in a common sense.

• The image is constructed by summation over many possible trajectories.

• The quantum imaging converges to a standard imaging procedure only in trivial situations of a deterministic and known velocity model.
“Today many quantum physicists believe that quantum principles in fact apply on all scales. By combining the (quantum) approach with other (e.g. mechanical) systems, or by applying its basic ideas in different contexts, it may be possible to bring quantum effects ever closer to our everyday experience.”

Lvovskv, Ghobadi, Simon, Chandra and Prasad

“Observation of micro-macro entanglement of light.”

Nature, Physics, 2013
Path integrals have been introduced in seismic wave modeling (Lomax, 1999; Schlottmann, 1999).

**Bayesian approach, Monte Carlo and simulated annealing** methods can also be formulated and interpreted in terms of the Feynman path integral (Lemm et al., 2005, Lee et al., 2000).

**Interferometry** can be considered in the path integral framework.

“... physics ... has been reduced to calculating only the probability of an event, and not predicting exactly what happens... Yes. That’s the way it is: **Nature permits us to calculate only probabilities...**” (Feynman, 1988).
"Good continuous reflectors are for kids; unconformities are for men."

Nigel Anstey

Diffraction imaging
• Reflection seismology is a method to estimate the properties of the Earth's subsurface from *reflected* seismic waves

• Specular *reflections* are the ones being used conventionally

• Specular *reflections* are generated by smooth interfaces
Что такое дифракция?
Как увидишь над пашнею радугу — 
Атмосферы родимой явление, 
Так подумаешь, мать твою за ногу 
И застынешь в немом изумлении.
Очарован внезапною прелестью, 
Елки, думаешь, где ж это, братцы, я? 
И стоишь так с отвисшей челюстью, 
Но потом понимаешь: ДИФРАКЦИЯ.

Игорь Иртеньев
« Возникает всегда когда каким либо путем часть волнового фронта встречается с препятствием »

Hecht

« Феномен результата отклонения от геометрической оптики »

Landau

« Никто никогда не был способен удовлетворительно определить разницу между интерференцией и дифракцией »

Feynman

- Occurs whenever a portion of a wavefront, be it sound, matter or light, is obstructed in some way

Hecht

- Phenomena which are the “consequence of deviations from geometrical optics”

Landau

- No-one has ever been able to define the difference between interference and diffraction satisfactorily

Feynman
Diffraction is direct indicator of small scale heterogeneities in the subsurface...

There are many evidences that diffractive component of the wavefield is a key ingredient in establishing resolution...
Seismic diffraction

Specular reflection

Edge diffraction

Tip diffraction
Seismic diffraction

Location

Depth

Time

- edge
- amplitude halved
- polarity reversed
Ways to separate diffractive and reflective components:

1. Weighted summation
2. Modified Kirchhoff migration
3. Plane wave destructor
4. Radon transform in the dip angle domain
5. Local Angle Domain (LAD)
Model with one reflector and a constant velocity. Three point scatterers are located directly on the reflector.
Prestack depth migration image of the full wavefield. Scatterers are almost invisible due to their weak amplitudes.
Depth migration of diffraction shot gathers. Three point scatterers are well imaged and can be reliably detected from interpreting the image. Two additional diffractors located at the left and right sides of the figure are caused by the edges of the interface.
Synthetic velocity model for a channelized reservoir
Zero-offset data

Time

In-line

Cross-line
Diffractive component

In-line Cross-line

Time
Migrated time slice of the full wavefield
Migrated time slice of the diffractive component
Meanders (satellite photo)
Stacked section

location

two way time

After Berkovich et al., 2009
Diffraction stacked section

After Berkovich et al., 2009
Migrated diffraction image

After Berkovich et al., 2009
Stacked section

Location

After Fomel, Landa and Taner, 2007
Diffraction stack

Location

After Fomel, Landa and Taner, 2007
Migrated diffraction stack

Location

After Fomel, Landa and Taner, 2007
Migrated full stack

Location

After Fomel, Landa and Taner, 2007
Velocity model
Zero-offset cube (channel time slice)
Migrated full field

Migrated diffractive component
Migrated full field

Migrated diffractive component

Diffractivity diagram
• Traditional seismic processing and imaging tends to highlight reflectors and obscure non-reflecting elements, such as small faults, edges, fractures and small scattering objects.

• Diffraction is a direct indicator of small and medium scale subsurface elements.

• Diffraction imaging method allows us finding objects less than seismic wavelength.
Is the future bright?...

Can we overcome the non-uniqueness, instability and uncertainty in our solutions?

• How far the geophysical inverse problem can be formalized?

• The gap between a solution as obtained for very refined mathematical assumptions and reality can be very large

• Does the level of mathematics really define the maturity of a science?

• Overcoming uncertainties…
«Я могу жить с сомнениями и в неопределенности, и не знать много. Я думаю, что намного интереснее жить не зная чего то, чем иметь ответы, которые могут быть ошибочными. »

Ричард Фейнман
“Do not shoot the pianist. He is doing his best”

A sign in western saloons of 19th century