ARTIFACT REDUCTION IN METHOD OF ITERATIVE INVERSION OF GEOPHYSICAL DATA

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application 61/332,463, filed May 7, 2010, entitled ARTIFACT REDUCTION IN ITERATIVE INVERNSION OF GEOPHYSICAL DATA, the entirety of which is incorporated by reference herein.

FIELD OF THE INVENTION

[0002] The invention relates generally to the field of geophysical prospecting, and more particularly to geophysical data processing. Specifically, the invention pertains to reducing artifacts in iterative inversion of data resulting from approximations made in the inversion.

BACKGROUND OF THE INVENTION

[0003] Geophysical inversion [1,2] attempts to find a model of subsurface properties that optimally explains observed data and satisfies geological and geophysical constraints. There are a large number of well known methods of geophysical inversion. These well known methods fall into one of two categories, iterative inversion and non-iterative inversion. The following are definitions of what is commonly meant by each of the two categories:

- Non-iterative inversion – inversion that is accomplished by assuming some simple background model and updating the model based on the input data. This method does not use the updated model as input to another step of inversion. For the case of seismic data these methods are commonly referred to as imaging, migration, diffraction tomography or Born inversion.

- Iterative inversion – inversion involving repetitious improvement of the subsurface properties model such that a model is found that satisfactorily explains the observed data. If the inversion converges, then the final model will better explain the observed data and will more closely approximate the actual subsurface properties. Iterative inversion usually produces a more

accurate model than non-iterative inversion, but is much more expensive to compute.

[0004] Two iterative inversion methods commonly employed in geophysics are cost function optimization and series methods. Cost function optimization involves iterative minimization or maximization of the value, with respect to the model M, of a cost function $S(M)$ which is a measure of the misfit between the calculated and observed data (this is also sometimes referred to as the objective function), where the calculated data is simulated with a computer using the current geophysical properties model and the physics governing propagation of the source signal in a medium represented by a given geophysical properties model. The simulation computations may be done by any of several numerical methods including but not limited to finite difference, finite element or ray tracing. Series methods involve inversion by iterative series solution of the scattering equation (Weglein [3]). The solution is written in series form, where each term in the series corresponds to higher orders of scattering. Iterations in this case correspond to adding a higher order term in the series to the solution.

[0005] Cost function optimization methods are either local or global [4]. Global methods simply involve computing the cost function $S(M)$ for a population of models $\{M_1, M_2, M_3, \ldots\}$ and selecting a set of one or more models from that population that approximately minimize $S(M)$. If further improvement is desired this new selected set of models can then be used as a basis to generate a new population of models that can be again tested relative to the cost function $S(M)$. For global methods each model in the test population can be considered to be an iteration, or at a higher level each set of populations tested can be considered an iteration. Well known global inversion methods include Monte Carlo, simulated annealing, genetic and evolution algorithms.

Local cost function optimization involves:

1. selecting a starting model,

2. computing the gradient of the cost function $S(M)$ with respect to the parameters that describe the model,

3. searching for an updated model that is a perturbation of the starting model in the gradient direction that better explains the observed data.

This procedure is iterated by using the new updated model as the starting model for another gradient search. The process continues until an updated model is found which satisfactorily explains the observed data. Commonly used local cost function inversion methods include gradient search, conjugate gradients and Newton's method.

[0006] As discussed above, iterative inversion is preferred over non-iterative inversion, because it yields more accurate subsurface parameter models. Unfortunately, iterative inversion is so computationally expensive that it is impractical to apply it to many problems of interest. This high computational expense is the result of the fact that all inversion techniques require many compute intensive forward and/or reverse simulations. Forward simulation means computation of the data forward in time, and reverse simulation means computation of the data backward in time.

[0007] Due to its high computational cost, iterative inversion often requires application of some type of approximation that speeds up the computation. Unfortunately, these approximations usually result in errors in the final inverted model which can be viewed as *artifacts* of the approximations employed in the inversion.

[0008] What is needed is a general method of iteratively inverting data that allows for the application of approximations without generating artifacts in the resulting inverted model. The present invention satisfies this need.

SUMMARY OF THE INVENTION

[0009] A physical properties model gives one or more subsurface properties as a function of location in a region. Seismic wave velocity is one such physical property, but so are (for example) density, p-wave velocity, shear wave velocity, several anisotropy parameters, attenuation (q) parameters, porosity, permeability, and resistivity. The invention is a method for reducing artifacts in a subsurface physical property model caused by an approximation, other than source encoding, in an iterative, computerized geophysical data inversion process, said method comprising varying the approximation as the iterations progress. In one particular embodiment, the invention is a computer-implemented method for

inversion of measured geophysical data to determine a physical properties model for a subsurface region, comprising:

(a) assuming a physical properties model of the subsurface region, said model providing values of at least one physical property at locations throughout the subsurface region;

(b) selecting an iterative data inversion process having a step wherein a calculation is made of an update to the physical properties model that makes it more consistent with the measured geophysical data;

(c) making in said calculation an approximation that either speeds up the selected iterative data inversion process other than by source encoding, or that works an accuracy tradeoff;

(d) executing, using the computer, one cycle of the selected iterative data inversion process with said approximation and using the physical properties model;

(e) executing, using the computer, a next iterative inversion cycle, wherein a selection is made to either change some aspect of the approximation or not to change it;

(f) repeating (e) as necessary, changing the approximation in some or all of the iteration cycles, until a final iteration wherein a selected convergence criterion is met or another stopping condition is reached; and

(g) downloading the updated physical properties model from the final iteration or saving it to computer storage.

[0010] In some embodiments of the invention, one or more artifact types are identified in inversion results as being caused by the approximation, and the aspect of the approximation that is changed in some or all iteration cycles is selected for having an effect on artifacts of the one or more identified artifact types. The effect on artifacts may be such that artifacts from one approximation do not add constructively with artifacts from another iteration cycle that uses an approximation with a changed aspect.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The present invention and its advantages will be better understood by referring to the following detailed description and the attached drawings in which:

[0012] Fig. 1 is a flow chart showing basic steps in a general method disclosed herein;

[0013] Fig. 2 is a flow chart showing basic steps in a particular embodiment of the method of Fig. 1 wherein the objective function is approximated by encoding and summing the sources;

[0014] Figs. 3-5 pertain to an example application of the invention embodiment of Fig. 2:

[0015] Fig. 3 shows the seismic velocity model from which seismic data were computed for the example;

[0016] Fig. 4 shows inversion of data from the seismic velocity model in Fig. 3 using the inversion method summarized in Fig. 2;

[0017] Fig. 5 shows inversion of data from the seismic velocity model in Fig. 3 using the inversion method summarized in Fig. 2 without the step in which the code used to encode the sources is changed between iterations;

[0018] Fig. 6 is a flow chart showing basic steps in a particular embodiment of the method of Fig. 1 wherein the approximation is varying the size of the grid cells used in the numerical inversion so as to use a fine grid only where needed;

[0019] Figs. 7-9 pertain to an example application of the invention embodiment of Fig. 6:

[0020] Fig. 7 is the seismic velocity model from which seismic data were computed for the example;

[0021] Fig. 8 shows an inversion of data from the seismic velocity model in Fig. 7 using the inversion method summarized in Fig. 6;

[0022] Fig. 9 is an inversion of data from the seismic velocity model in Fig. 7 using the inversion method summarized in Fig. 6 without the step in which the depth of the artificial reflection generator is changed between iterations;

[0023] Fig. 10 is a flow chart showing basic steps in a particular embodiment of the method of Fig. 1, wherein the approximation is using only a subset of measured data;

[0024] Figs. 11-13 pertain to an example application of the invention embodiment of Fig. 10:

[0025] Fig. 11 shows the seismic velocity model from which seismic data were computed for the example;

[0026] Fig. 12 shows an inversion of data from the seismic velocity model in Fig. 11 using the inversion method summarized in Fig. 10; and

[0027] Fig. 13 shows an inversion of data from the seismic velocity model in Fig. 11 using the inversion method summarized in Fig. 10 without the step in which the subset of measured data is changed randomly between iterations.

[0028] Due to patent constraints, Figs. 3-5, 7-9, and 11-13 are gray-scale conversions of color displays.

[0029] The invention will be described in connection with its preferred embodiments. However, to the extent that the following detailed description is specific to a particular embodiment or a particular use of the invention, this is intended to be illustrative only, and is not to be construed as limiting the scope of the invention. On the contrary, it is intended to cover all alternatives, modifications and equivalents that may be included within the scope of the invention, as defined by the appended claims.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0030] The present invention is a method for reducing artifacts caused by the application of approximations during iterative inversion of geophysical data. Geophysical inversion attempts to find a model of subsurface properties that optimally explains observed geophysical data. The example of seismic data is used throughout to illustrate the inventive

method, but the method may be advantageously applied to any method of geophysical prospecting and any type of geophysical data. The data inversion is most accurately performed using iterative methods. Unfortunately iterative inversion is often prohibitively expensive computationally. The majority of compute time in iterative inversion is spent performing expensive forward and/or reverse simulations of the geophysical data (here forward means forward in time and reverse means backward in time). The high cost of these simulations is partly due to the fact that each geophysical source in the input data must be computed in a separate computer run of the simulation software. Thus, the cost of simulation is proportional to the number of sources in the geophysical data, typically on the order of 1,000 to 10,000 sources for a geophysical survey. In typical practice, approximations are applied during the inversion to reduce the cost of inversion. These approximations result in errors, or artifacts, in the inverted model. This invention mitigates these artifacts by changing some aspect of the approximation between iterations of inversion so that the artifact during one iteration does not add constructively with the artifact in other iterations. Therefore the artifact is reduced in the inverted model.

[0031] Some common approximations made during iterative inversion that result in artifacts include:

1. Processing applied to the measured data
2. Inaccurate boundary conditions in the simulation
3. Approximations in the simulation (e.g. low order approximations of derivatives used in the simulator or the size of the grid cells used in the calculation)
4. Approximations in the parameterization of the model (e.g. use of a spatial grid of parameters that is too coarse to accurately represent variations in the model).

Two iterative inversion methods commonly employed in geophysics are cost function optimization and series methods. The present invention can be applied to both of these methods. A summary of each of these methods follows next.

Iterative Cost Function Optimization

[0032] Cost function optimization is performed by minimizing the value, with respect to a subsurface model M, of a cost function $S(M)$ (sometimes referred to as an *objective*

function), which is a measure of misfit between the observed (measured) geophysical data and corresponding data calculated by simulation of the assumed model. A simple cost function S often used in geophysical inversion is:

$$S(M)=\sum_{g=1}^{N_g}\sum_{r=1}^{N_r}\sum_{t=1}^{N_t}\left|\psi_{calc}(M,g,r,t,w_g)-\psi_{obs}(g,r,t,w_g)\right|^N \qquad (1)$$

where

N = norm for cost function (typically the least squares or L2-Norm is used in which case $N = 2$),

M = subsurface model,

g = gather index (for point source data this would correspond to the individual sources),

N_g = number of gathers,

r = receiver index within gather,

N_r = number of receivers in a gather,

t = time sample index within a data record,

N_t = number of time samples,

ψ_{calc} = calculated geophysical data from the model M,

ψ_{obs} = measured geophysical data, and

w_g = source signature for gather g, i.e. source signal without earth filtering effects.

[0033] The gathers in Equation 1 can be any type of gather that can be simulated in one run of a forward modeling program. For seismic data, the gathers correspond to a seismic shot, although the shots can be more general than point sources [**5**]. For point sources, the gather index g corresponds to the location of individual point sources. For plane wave sources, g would correspond to different plane wave propagation directions. This

generalized source data, ψ_{obs}, can either be acquired in the field or can be synthesized from data acquired using point sources. The calculated data ψ_{calc} on the other hand can usually be computed directly by using a generalized source function when forward modeling (e.g. for seismic data, forward modeling typically means solution of the anisotropic visco-elastic wave propagation equation or some approximation thereof). For many types of forward modeling, including finite difference modeling, the computation time needed for a generalized source is roughly equal to the computation time needed for a point source. The model M is a model of one or more physical properties of the subsurface region. Seismic wave velocity is one such physical property, but so are (for example) p-wave velocity, shear wave velocity, several anisotropy parameters, attenuation (q) parameters, porosity, and permeability. The model M might represent a single physical property or it might contain many different parameters depending upon the level of sophistication of the inversion. Typically, a subsurface region is subdivided into discrete cells, each cell being characterized by a single value of each parameter.

[0034] One major problem with iterative inversion is that computing ψ_{calc} takes a large amount of computer time, and therefore computation of the cost function, S, is very time consuming. Furthermore, in a typical inversion project this cost function must be computed for many different models M.

Iterative Series Inversion

[0035] Besides cost function optimization, geophysical inversion can also be implemented using iterative series methods. A common method for doing this is to iterate the Lippmann-Schwinger equation [3]. The Lippmann-Schwinger equation describes scattering of waves in a medium represented by a physical properties model of interest as a perturbation of a simpler model. The equation is the basis for a series expansion that is used to determine scattering of waves from the model of interest, with the advantage that the series only requires calculations to be performed in the simpler model. This series can also be inverted to form an iterative series that allows the determination of the model of interest, from the measured data and again only requiring calculations to be performed in the simpler model. The Lippmann-Schwinger equation is a general formalism that can be applied to all types of geophysical data and models, including seismic waves. This method begins with the two equations:

$$\mathbf{LG} = -\mathbf{I} \tag{2}$$

$$\mathbf{L}_0\mathbf{G}_0 = -\mathbf{I} \tag{3}$$

where **L**, $\mathbf{L}_0$ are the actual and reference differential operators, **G** and $\mathbf{G}_0$ are the actual and reference Green's operators respectively and **I** is the unit operator. Note that **G** is the measured point source data, and $\mathbf{G}_0$ is the simulated point source data from the initial model. The Lippmann-Schwinger equation for scattering theory is:

$$\mathbf{G} = \mathbf{G}_0 + \mathbf{G}_0\mathbf{VG} \tag{4}$$

where $\mathbf{V} = \mathbf{L} - \mathbf{L}_0$ from which the difference between the true and initial models can be extracted.

[0036] Equation 4 is solved iteratively for **V** by first expanding it in a series (assuming $\mathbf{G} = \mathbf{G}_0$ for the first approximation of **G** and so forth) to get:

$$\mathbf{G} = \mathbf{G}_0 + \mathbf{G}_0\mathbf{VG}_0 + \mathbf{G}_0\mathbf{VG}_0\mathbf{VG}_0 + \cdots \tag{5}$$

Then **V** is expanded as a series:

$$\mathbf{V} = \mathbf{V}^{(1)} + \mathbf{V}^{(2)} + \mathbf{V}^{(3)} + \cdots \tag{6}$$

where $\mathbf{V}^{(n)}$ is the portion of **V** that is n^{th} order in the residual of the data (here the residual of the data is $\mathbf{G} - \mathbf{G}_0$ measured at the surface). Substituting Equation 6 into Equation 5 and collecting terms of the same order yields the following set of equations for the first 3 orders:

$$\mathbf{G} - \mathbf{G}_0 = \mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0 \tag{7}$$

$$0 = \mathbf{G}_0\mathbf{V}^{(2)}\mathbf{G}_0 + \mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0 \tag{8}$$

$$0 = \mathbf{G}_0\mathbf{V}^{(3)}\mathbf{G}_0 + \mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0\mathbf{V}^{(2)}\mathbf{G}_0 + \mathbf{G}_0\mathbf{V}^{(2)}\mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0 + \mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0 \tag{9}$$

and similarly for higher orders in **V**. These equations may be solved iteratively by first solving Equation 7 for $\mathbf{V}^{(1)}$ by inverting G_0 on both sides of $V^{(1)}$ to yield:

$$\mathbf{V}^{(1)} = \mathbf{G}_0^{-1}(\mathbf{G} - \mathbf{G}_0)\mathbf{G}_0^{-1} \tag{10}$$

$\mathbf{V}^{(1)}$ from Equation 10 is then substituted into Equation 8 and this equation is solved for $\mathbf{V}^{(2)}$ to yield:

$$\mathbf{V}^{(2)} = -\mathbf{G}_0^{-1}\mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0\mathbf{V}^{(1)}\mathbf{G}_0\mathbf{G}_0^{-1} \tag{11}$$

and so forth for higher orders of **V**.

Equation 10 involves a sum over sources and frequency which can be written out explicitly as:

$$\mathbf{V}^{(1)} = \sum_{\omega}\sum_{s}\mathbf{G}_0^{-1}(\mathbf{G}_s - \mathbf{G}_{0s})\mathbf{G}_{0s}^{-1} \tag{12}$$

where $\mathbf{G}_s$ is the measured data for source s, $\mathbf{G}_{0s}$ is the simulated data through the reference model for source s and $\mathbf{G}_{0s}^{-1}$ can be interpreted as the downward extrapolated source signature from source *s*. Equation 10 when implemented in the frequency domain can be interpreted as follows: (1) Downward extrapolate through the reference model the source signature for each source (the $\mathbf{G}_{0s}^{-1}$ term), (2) For each source, downward extrapolate the receivers of the residual data through the reference model (the $\mathbf{G}_0^{-1}(\mathbf{G}_s\text{-}\mathbf{G}_{0s})$ term), (3) multiply these two fields then sum over all sources and frequencies. The downward extrapolations in this recipe can be carried out using geophysical simulation software, for example using finite differences.

Example Embodiment

[0037] The flowchart of Fig. 1 shows basic steps in one embodiment of the present inventive method. In step **110**, an approximation is selected that will improve some aspect of the inversion process. The improvement may be in the form of a speedup rather than increased accuracy. Examples of such approximations include use of an approximate objective function or use of an approximation in the simulation software. These approximations will often be chosen to reduce the computational cost of inversion. However, rather than a computational speed-up, the improvement may instead work an accuracy trade-off, i.e. accept more inaccuracy in one aspect of the computation in return for more accuracy in some other aspect. In step **140**, an update to an assumed physical properties model **120** is generated based on the measured data **130**. In step **140** the approximation chosen in **110** is used to perform the update computations. Using iterative local cost function optimization as

an example of iterative inversion, the "update computations" as that term is used herein include, without limitation, computing the objective (cost) function, the objective function gradient, and all forward modeling required to accomplish the preceding. Step **140** produces an updated physical properties model **150**, which should be closer to the actual subsurface properties than were those of the assumed physical properties model **120**. Conventionally this updated physical properties model **150** would be further improved by feeding it and the measured data **130** back into the update method in step **140** to produce a further improved physical properties model. This conventional iterative inversion method has the disadvantage that any artifacts in the inversion that result from the approximation chosen in step **110** will likely reinforce constructively in the inversion and contaminate the final inverted result.

[0038] Rather than directly returning to step **140**, the present inventive method interposes step **160** in which some aspect of the approximation chosen in step **110** is changed in a manner such that the artifact caused by the approximation will change and therefore not be reinforced by the iterations of step **140**. By this means the artifact resulting from the approximation chosen in step **110** will be mitigated.

Examples of approximations and corresponding artifacts

[0039] The following table contains examples of step **110**, i.e. of approximations that might advantageously be used in data inversion, and that are suitable (step **160**) for application of the present invention. The first column of the table lists approximations that could be used with this invention. The second column lists the artifact associated with each approximation. The last column lists a feature of the approximation that could be varied between iterations to cause a change in the artifact between iterations that will cause it to add incoherently to the final inverted model and thus be mitigated.

Approximation	**Artifact**	**Features to vary**
Encoded simultaneous source seismic data [6]	Cross-talk noise between the encoded sources	Vary the encoding of the sources [ref. 6, claim 3]
Use of a subset of measured data	Footprints of source position in the inverted models caused by source	Vary randomly the subset of measured data

	positions	
Imperfect absorbing boundary condition in the simulator	Inaccuracy at the edges of the inverted models caused by artificial reflections from the edges	Vary the thickness of the absorbing boundary layer
Use of reflecting boundaries in the simulator	Inaccuracy at the edges of the inverted models caused by artificial reflections from the edges	Vary the reflecting boundary condition type (e.g. vary between Dirchlet or Neumann boundary conditions)
Use of random boundary conditions in the simulator [7]	Inaccuracy at the edges of the inverted models caused by artificial reflections from the edges	Vary the distribution of the random boundary
Spatial variation of size of grid cells in a finite difference simulator	Errors at the boundaries between changes in the grid cell size caused by artificial reflections from those boundaries	Vary the location of the boundaries separating regions with different grid cell sizes
Spatial variation of the accuracy of the simulation operator	Errors at the boundaries between changes in the simulator's operator accuracy caused by artificial reflections from those boundaries	Vary the location of the boundaries separating regions with different operator accuracies
Use of a grid cell size in the simulation that is too coarse to accurately represent variations in the	Spatial discretization errors	Vary the grid cell size or the origin of the grid

model		
Use of a large time step in a time domain simulator	Discretization errors	Vary the time step interval

The above list is not exhaustive. The list includes examples only of approximations that reduce computation time. Sometimes it is advantageous to trade inaccuracy in one area to gain more accuracy in another. An example of such an accuracy tradeoff type of approximation is to use less accurate absorbing boundary conditions in the forward modeling in order to make the gradient computations more accurate. Absorbing boundary conditions are needed to solve the differential equation(s) governing the wave propagation, e.g. the anisotropic visco-elastic wave propagation equation (or some approximation thereof) in the case of seismic data, or Maxwell's equations in the case of electromagnetic data. In general, an accuracy tradeoff involves sacrificing accuracy in one aspect of the method in return for increased accuracy in another aspect.

Test Example 1 – Encoded Objective Function

[0040] Figures 2-5 represent a synthetic example of performing inversion using an approximation to the objective function in which the seismic sources in the measured data are encoded then summed; see U.S. Application Publication No. 2010-0018718 by Jerome Krebs et al. This approximation speeds up the inversion, because the encoded objective function can be evaluated using one run of the simulation software rather than running it once for each source as is the case for conventional inversion. Figure 2 is a self-explanatory flow chart that focuses Fig. 1 on this particular embodiment, with step **210** showing the encoding approximation.

[0041] The geophysical properties model in this example is just a model of the acoustic wave velocity. Figure 3 shows the base velocity model, i.e., the "unknown" model that will be inverted for and which was used to generate the data to be inverted for this example. The shading indicates the velocity at each depth and lateral location, as indicated by the "color" bar to the right. Figure 4 shows the inversion resulting from application of this invention as summarized by the flow chart in Fig. 2. In this example the sources are encoded

by randomly multiplying them by either plus or minus one. The encoding of the sources is changed, in step **260**, by changing the random number seed used to generate the codes used to encode the sources. Note the good match to the base model shown in Fig. 3.

[0042] Figure 5 shows the result of applying the inversion method outlined in the flowchart in Fig. 2, but eliminating the inventive feature of step **260**. Note the inversion in Fig. 5 is dominated by crosstalk noise (the speckled appearance of the inversion), whereas this crosstalk noise artifact is largely invisible in the inversion resulting from the present invention (Fig. 4).

[0043] Encoding of simultaneous sources was previously disclosed (and claimed) in U.S. Application Publication No. 2010-0018718 by Jerome Krebs et al. along with the technique of varying the encoding from one iteration to the next; see paragraph 62 and claim 3 in that patent publication. However, U.S. Application Publication No. 2010-0018718 by Jerome Krebs et al. neither appreciates nor discloses that the encoding invention is a specific example of the generic invention disclosed herein.

Test Example 2 – Approximation that generates an artificial reflection

[0044] Figures 6-9 illustrate a synthetic example of performing inversion using an approximation to the simulator that generates an artificial reflection. An example of such an approximation is using a finite difference simulator such that the size of the cells in the grid are changed with depth from the surface. This approximation speeds up the inversion, because the grid in the simulator could be adjusted to optimize it in a depth varying manner. Typically smaller grid cells are required for the shallow portion of a finite difference simulator than are required deeper in the model. The artifact generated by this approximation is an artificial reflection at the boundaries between changes in the grid cell size.

[0045] Figure 6 is a flow chart for the embodiment of the present invention illustrated in this example. In this example, a variable grid simulator was not actually used to generate the artificial reflector. Instead (step **610**) an artificial reflection is generated by placing a fictitious discontinuity in the density model at 500 meters depth. This discontinuous density model was used by the simulator for model updating, but a constant density model was used to generate the measured data (**630** in Fig. 6). Inversion is then performed in a manner such

that only the velocity model is updated (**640**), so that the fictitious density discontinuity remains throughout the iterations of inversion.

[0046] The geophysical properties model in this example is just a model (**620**) of the acoustic wave velocity. Figure 7 shows the base velocity model (the model that will be inverted for and which was used to generate the data to be inverted) for this example. The shading indicates the velocity at each depth. Figure 8 shows the inversion resulting from application of the present invention as summarized by the flow chart of Fig. 6. In this example, in step **660**, the depth of the fictitious density contrast is randomly changed using a normal distribution centered on 500 meters and with a variance of 100 meters. Note the good match to the base model shown in Fig. 7. In Figs. 7-9 and 11-13, velocity is plotted as a dimensionless relative velocity equal to the inverted velocity divided by an initial velocity, the latter being the starting guess for what the velocity model is expected to be.

[0047] Figure 9 shows the result of applying the inversion method outlined in the flowchart of Fig. 6, but eliminating the inventive feature that is step **660**. It may be noted that the inversion in Fig. 9 has a clearly visible artificial reflection **910** at 500 meters depth, whereas this artificial reflection is largely invisible in the inversion that used the present inventive method (Fig. 8).

Test Example 3 – Random subsets of measured data

[0048] Figures 10-13 represent a synthetic example of performing inversion using an approximation to the measured data. An example of such an approximation is using a subset of the measured data (**1010** in Fig. 10). This approximation reduces the amount of measured data, which speeds up the inversion, because the computational time of the inversion is directly proportional to the number of measured data. In a typical inversion, all of the measured data are needed to maintain a high horizontal resolution, and thus in typical practice this approximation is not used. The artifact generated by this approximation is footprints in the inverted models caused by sparse source positions and degradation of the horizontal resolution. Figure 10 is a flow chart that focuses the steps of Fig. 1 on the embodiment of the invention used in this example. In this example, a subset of the measured data (**1030** in Fig. 10) is used in the inversion, e.g. a subset of 5 data among 50 measured data.

[0049] The geophysical properties model in this example is just a model of the acoustic wave velocity. Figure 11 is the base velocity model (the model that will be inverted for and which was used to generate the data to be inverted) for this example. The shading indicates the velocity at each depth. Figure 12 is the inversion resulting from application of this invention as summarized by the flow chart in Fig. 10. In this example, in step **1060**, a subset of the measured data is randomly selected as inversion iteration increases. This results in a different subset of the data being used in each iteration cycle. Figure 12 shows a good match to the base model shown in Fig. 11 using ten percent of the measured data.

[0050] Figure 13 shows the results of applying the inversion method outlined in the flowchart in Fig. 6, but eliminating the inventive, artifact-reducing step **1060**. It may be noted that the inversion in Fig. 13 has artificial footprints at deeper parts below 2000 meters and short wavelength noises in the overall inverted model, whereas these footprint noises are mitigated in the inversion using the present inventive method (Fig. 12), and the short wavelength noises are invisible.

[0051] It should be understood that the flow charts of Figs. 2, 6 and 10 represent examples of specific embodiments of the invention that is described more generally in Fig. 1.

[0052] The foregoing patent application is directed to particular embodiments of the present invention for the purpose of illustrating it. It will be apparent, however, to one skilled in the art, that many modifications and variations to the embodiments described herein are possible. All such modifications and variations are intended to be within the scope of the present invention, as defined in the appended claims. Persons skilled in the art will readily recognize that in practical applications of the invention, at least some of the steps in the present inventive method (typically steps **140-160**, and often generating the model in **120**) are performed on a computer, i.e. the invention is computer implemented. In such cases, the resulting updated physical properties model of the subsurface may either be downloaded or saved to computer storage.

References

1. Tarantola, A., "Inversion of seismic reflection data in the acoustic approximation," *Geophysics* **49**, 1259-1266 (1984).

2. Sirgue, L., and Pratt G. "Efficient waveform inversion and imaging: A strategy for selecting temporal frequencies," *Geophysics* **69**, 231-248 (2004).

3. Weglein, A. B., Araujo, F. V., Carvalho, P. M., Stolt, R. H., Matson, K. H., Coates, R. T., Corrigan, D., Foster, D. J., Shaw, S. A., and Zhang, H., "Inverse scattering series and seismic exploration," *Inverse Problems* **19,** R27-R83 (2003).

4. Fallat, M. R., Dosso, S. E., "Geoacoustic inversion via local, global, and hybrid algorithms," *Journal of the Acoustical Society of America* **105**, 3219-3230 (1999).

5. Berkhout, A. J., "Areal shot record technology," *Journal of Seismic Exploration* **1**, 251-264 (1992).

6. Krebs, Jerome et al., "Iterative Inversion of Data from Simultaneous Geophysical Sources", U.S. Patent Application Publication No. 2010-0018718 (01-28-2010).

7. Clapp, R. G., "Reverse time migration with random boundaries," SEG International Exposition and Meeting (Houston), Expanded Abstracts, 2809-2813 (2009).

CLAIMS

1. A method for reducing artifacts in an inverted subsurface physical property model caused by an approximation, other than source encoding, in an iterative geophysical data inversion process, wherein the model is updated at the end of each iteration cycle, said method comprising:

identifying an approximation, other than the source encoding, made in the course of:

(i) processing or selecting measured data to invert, or

(ii) parameterization of the model, or

(iii) simulation of synthetic data to compare to measured data; and

reducing the artifact by varying the approximation in consecutive iteration cycles such as to cause the artifact in the updates to add incoherently in leading to a final model as the inversion progresses from one iteration to a next wherein the inversion is performed using a computer.

2. The method of claim 1, wherein the iterative data inversion process comprises:

(a) selecting measured data to invert;

(b) processing the selected data as needed;

(c) selecting a physical properties model of a subsurface region, said model providing values of at least one physical property at locations throughout the subsurface region;

(d) selecting a computational grid, and using it and the selected physical properties model to generate synthetic data corresponding to the selected data from (b);

(e) comparing the synthetic data to the measured data from (b) and generating an update to the physical properties model that makes it more consistent with the measured; and

(f) repeating (a)-(e), selecting the updated model from the previous iteration as the selected model in (c) until a final iteration wherein a selected convergence criterion is met or another stopping condition is reached.

3. The method of claim 2, wherein one or more artifact types are identified in an updated subsurface physical property model as being caused by the approximation.

4. The method of claim 3, wherein varying the approximation comprises changing an aspect of the approximation and the aspect of the approximation that is changed is selected for having an effect on artifacts of the one or more identified artifact types.

5. The method of claim 4, wherein said effect is such that artifacts from one approximation do not add constructively with artifacts from another iteration cycle that uses an approximation with a changed aspect.

6. The method of claim 1, wherein the artifact is footprints of source position in the inverted model, and approximation is to select a subset of the measured geophysical data for inputting to the iterative inversion process, and varying the approximation is selecting a different subset.

7. The method of claim 6, wherein each different subset is selected randomly.

8. The method of claim 1, wherein the artifact is inaccuracy at edges of the inverted model caused by artificial reflections from the edges, and the approximation is imperfect absorbing boundaries in simulation of synthetic data in the iterative inversion process, and the variation of the approximation is to vary thickness of an absorbing boundary layer.

9. The method of claim 1, wherein the artifact is inaccuracy at edges of the inverted model caused by artificial reflections from the edges, and the approximation is using a

type of reflecting boundary condition in simulation of synthetic data in the iterative inversion process, and the variation of the approximation is using a different type of reflecting boundary condition.

10. The method of claim 1, wherein the artifact is inaccuracy at edges of the inverted model caused by artificial reflections from the edges, and the approximation is random boundary conditions in simulation of synthetic data in the iterative inversion process, and the variation of the approximation is varying distribution of the random boundary.

11. The method of claim 1, wherein the approximation is spatial variation of grid cell size in a finite difference simulator in the iterative inversion process, and the artifact is errors at boundaries between changes in grid cell size caused by artificial reflections from those boundaries, and the variation of the approximation is varying location of a boundary separating regions with different grid cell sizes.

12. The method of claim 1, wherein the approximation is spatial variation in simulator accuracy in the iterative inversion process, and the artifact is errors at boundaries between changes in simulator accuracy caused by artificial reflections from those boundaries, and the variation of the approximation is varying location of a boundary separating regions with different simulator accuracies.

13. The method of claim 1, wherein the artifact is spatial discretization errors, and the approximation is use of a grid cell size in simulation of synthetic data in the iterative inversion process, wherein the grid cell size is too coarse to accurately represent variations in the model, and the variation of the approximation is varying the grid cell size or origin of the grid.

14. The method of claim 1, wherein the artifact is discretization errors, and the approximation is use of discrete time steps in a time domain simulator in the iterative

inversion process, and the variation of the approximation is to use in one iteration a time step larger than time steps used in other iterations.

15. The method of claim 1, wherein the iterative geophysical data inversion process includes forward modeling of synthetic data and computing gradients of a cost function, and the approximation is using absorbing boundary conditions in the forward modeling, and the variation of the approximation is using less accurate absorbing boundary conditions in the forward modeling, thereby trading forward modeling accuracy for more accurate gradient computations.

16. The method of claim 1, wherein the approximation speeds up the iterative inversion process or works an accuracy trade-off.