

$$\phi_{shaped} = \frac{(S * d^{meas}) \otimes (S * d^{simulated})}{\| (S * d^{meas}) \| \| (S * d^{simulated}) \|}$$

where S is the shaping function that has a spectrum similar to impedance spectra (Lazaratos et. al, 2011).

[0042] Krebs et al. (PCT Patent Publication No. WO/2008/042081) have shown that inversion speed may be greatly increased by using source encoding, and simultaneously inverting many sources in a single encoded gather. A preferred embodiment disclosed in this publication changes the encoding from one iteration to the next. Routh et al. have shown that the cross-correlation objective function is particularly advantageous in simultaneous encoded-source inversion when the fixed receiver assumption is not satisfied. (U.S. Provisional Patent Application Serial Number 61/418,694)

Synthetic Example

[0043] The advantages of the shaped cross-correlation objective function can be demonstrated with a synthetic example. From the observed shot gather (Fig. 11A) and predicted shot gather at convergence (Fig. 11B) before shaping, and the same two quantities after shaping (Figs. 11C and 11D), it can be seen in Fig. 12 that after shaping the cross-correlation function is peaked and less oscillatory after shaping (121) than before shaping (122). Figure 12 shows the normalized cross-correlation as a function of lag, with the zero-lag corresponding to index 3000 on the "x"-axis. The reduction of oscillatory nature can potentially help optimization algorithms that are global in nature in finding the maxima of the objective function such as simulated annealing, genetic algorithm, evolutionary algorithms etc. Another interesting aspect is that one can work with the envelope of the cross-correlation objective function as the quantity to be maximized. The envelope typically has much less oscillation compared to the function itself.

[0044] 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.

References

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- 30 Van Riel, P., and Hendrik, W. J. D., "Method of estimating elastic and compositional parameters from seismic and echo-acoustic data," U.S. Patent No. 6,876,928 (2005).

CLAIMS

1. A computer-implemented method for accelerating convergence of iterative inversion of seismic data to obtain a model of one or more physical parameters in a subsurface region, comprising using local cost function optimization, wherein an assumed or current model is updated to reduce misfit between the seismic data and model-simulated data, wherein the frequency spectrum of the updated model is controlled in a first iteration and thereafter to match a known or estimated frequency spectrum for the subsurface region.

2. The method of claim 1, wherein said one or more physical parameters is P-impedance, and wherein the frequency spectrum of the updated model in each iteration is controlled to match the known or estimated frequency spectrum by applying a spectral-shaping filter in the first iteration to both the seismic data and to a source wavelet used to generate the model-simulated data, wherein the source wavelet before application of the spectral-shaping filter is chosen to have a frequency spectrum $W(f)$ that satisfies $D(f) \approx I_p(f)W(f)$, where $D(f)$ is an average frequency spectrum of the seismic data, f is frequency, and $I_p(f)$ is an average frequency spectrum of P-impedance in the subsurface region or is approximated by a frequency spectrum of a different elastic parameter of the subsurface region, and wherein said known or estimated frequency spectrum for the subsurface region is $I_p(f)$.

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3. The method of claim 2, wherein the spectral-shaping filter satisfies

$$H(f) = \{f^{1/2} I_p(f)\} / \{A^{1/2}(f) D(f)\}$$

where $A(f)$ is a frequency-dependent factor determined such that

$$G(f) = A(f) W(f) D(f)$$

where $G(f)$ is a frequency spectrum of a gradient of the cost function with respect to one of the one or more physical parameters.

4. The method of claim 1, wherein updating the assumed or current model comprises computing a gradient of the cost function with respect to one of the one or more physical

parameters, and then applying a spectral-shaping filter to the gradient in at least the first iteration; and wherein the model-simulated data are generated using a source wavelet having a frequency spectrum $W(f)$ that satisfies $D(f) \approx f I_p(f) W(f)$, where $D(f)$ is an average frequency spectrum of the seismic data, f is frequency, and $I_p(f)$ is an average frequency spectrum of P-impedance in the subsurface region or is approximated by a frequency spectrum of a different elastic parameter of the subsurface region; and wherein said known or estimated frequency spectrum is $I_p(f)$.

5. The method of claim 4, wherein the spectral-shaping filter $H(f)$ is determined by dividing a known or estimated frequency spectrum $S(f)$ in the subsurface region for said one of the one or more physical parameters by the gradient's spectrum before shaping $G(f)$.

6. The method of claim 4, wherein the spectral-shaping filter varies with time.

7. The method of claim 1, wherein the known or estimated frequency spectrum for the subsurface region is obtained by averaging spectra of well logs from the subsurface region.

8. The method of claim 7, wherein models of at least two physical parameters are simultaneously obtained, and a known or estimated frequency spectrum for each physical parameter is obtained by averaging spectra of well logs measuring or corresponding to that physical parameter.

9. The method of claim 1, wherein models of at least two physical parameters are simultaneously obtained, and the frequency spectrum of each updated model in the first iteration and thereafter is controlled to match a known or estimated frequency spectrum of the corresponding physical parameter in the subsurface region.

10. The method of claim 9, wherein updating the assumed or current model of a particular physical parameter (denoted by index i) comprises computing a gradient with respect to that

particular physical parameter (∇_i) of the cost function, and then applying a spectral-shaping filter to the gradient, wherein the spectral-shaping filter is tailored to the particular physical parameter and its known or estimated frequency spectrum, $S_i(f)$, in the subsurface region.

5 11. The method of claim 10, wherein the spectral-shaping filter is determined by dividing $S_i(f)$ by the gradient's spectrum before shaping.

12. The method of claim 10, wherein the spectral-shaping filter varies with time.

10 13. The method of claim 2, wherein the spectral-shaping filter is derived according to a criterion that the spectrum of a gradient of the cost function with respect to one of the one or more physical parameters, after application of the spectral-shaping filter to both the seismic data and to a source wavelet used to generate the model-simulated data, should match the known or estimated frequency spectrum for the subsurface region.

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14. The method of claim 1, wherein the one or more physical parameters are selected from a group consisting of P-impedance, S-impedance, density, P-velocity, and S-velocity.

15. The method of claim 1, wherein the model-simulated data are generated using a seismic source wavelet having a frequency spectrum $W(f)$ satisfying, to within a proportionality constant, the following equation:

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$$D(f) = I_p(f)W(f)$$

where f is frequency, $D(f)$ is average frequency spectrum of the seismic data, and $I_p(f)$ is average frequency spectrum for P-impedance in the subsurface region or an approximation thereof based on a frequency spectrum of another elastic parameter.

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16. The method of claim 15, wherein $D(f)$ and $I_p(f)$ are average spectra, meaning averaged over the subsurface region.

17. A computer program product, comprising a non-transitory computer usable medium having a computer readable program code embodied therein, said computer readable program code adapted to be executed to implement a method for inverting seismic data to obtain a
5 model of one or more physical parameters in a subsurface region, said method comprising using iterative inversion with local cost function optimization, wherein an assumed or current model is updated to reduce misfit between the seismic data and model-simulated data, wherein the updated model's frequency spectrum in each iteration is controlled to match an input known or estimated frequency spectrum for the subsurface region.

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18. The method of claim 1, wherein the cost function is a cross-correlation between the seismic data and the model-simulated data, and the optimization maximizes the cost function after the frequency spectrum control is applied to the seismic data and the model simulated data.

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19. The method of claim 18, wherein source encoding is used on the seismic data and in the model simulation, and a plurality of encoded sources are simultaneously inverted.

20. The method of claim 19, wherein the encoding is changed for at least one iteration of the inversion.

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21. The method of claim 1, wherein the cost function is an envelope function of a cross-correlation between the seismic data and the model-simulated data, and the optimization maximizes the cost function.

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22. The method of claim 21, wherein source encoding is used on the seismic data and in the model simulation, and a plurality of encoded sources are simultaneously inverted.

23. The method of claim 22, wherein the encoding is changed for at least one iteration of the inversion.

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where S is the shaping function that has a spectrum similar to impedance spectra (Lazaratos et. al, 2011).

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CLAIMS

1. A computer-implemented method for accelerating convergence of iterative inversion of seismic data to obtain a model of one or more physical parameters in a subsurface region, comprising using local cost function optimization, wherein an assumed or current model is updated to reduce misfit between the seismic data and model-simulated data, wherein the frequency spectrum of the updated model is controlled in a first iteration and thereafter to match a known or estimated frequency spectrum for the subsurface region, wherein the controlling of the frequency spectrum comprises applying a spectral-shaping filter to both the seismic data and to a source wavelet used to generate the model-simulated data, or to a gradient of the cost function in at least a first iteration, said spectral-shaping filter being derived according to a criterion that the spectrum of a gradient of the cost function with respect to one of the one or more physical parameters, after application of the spectral-shaping filter to both the seismic data and to a source wavelet, should match the known or estimated frequency spectrum for the subsurface region.
2. The method of claim 1, wherein updating the assumed or current model comprises computing a gradient of the cost function with respect to one of the one or more physical parameters, and then applying a spectral-shaping filter to the gradient in at least the first iteration; and wherein the model-simulated data are generated using a source wavelet having a frequency spectrum $W(f)$ that satisfies $D(f) \approx f I_p(f) W(f)$, where $D(f)$ is an average frequency spectrum of the seismic data, f is frequency, and $I_p(f)$ is an average frequency spectrum of P-impedance in the subsurface region or is approximated by a frequency spectrum of a different elastic parameter of the subsurface region; and wherein said known or estimated frequency spectrum is $I_p(f)$.
3. The method of claim 2, wherein the spectral-shaping filter $H(f)$ is determined by dividing a known or estimated frequency spectrum $S(f)$ in the subsurface region for said one of the one or more physical parameters by the gradient's spectrum before shaping $G(f)$, where $G(f)$ is a frequency spectrum of the gradient of the cost function with respect to one of the one or more physical parameters.
4. The method of claim 2, wherein the spectral-shaping filter varies with time.
5. The method of claim 1, wherein the known or estimated frequency spectrum for the subsurface region is obtained by averaging spectra of well logs from the subsurface region.

6. The method of claim 5, wherein models of at least two physical parameters are simultaneously obtained, and a known or estimated frequency spectrum for each physical parameter is obtained by averaging spectra of well logs measuring or corresponding to the physical parameter.

7. The method of claim 1, wherein models of at least two physical parameters are simultaneously obtained, and the frequency spectrum of each updated model in the first iteration and thereafter is controlled to match a known or estimated frequency spectrum of the corresponding physical parameter in the subsurface region.

8. The method of claim 7, wherein updating the assumed or current model of a particular physical parameter (denoted by index i) comprises computing a gradient with respect to that particular physical parameter (V_i) of the cost function, and then applying a spectral-shaping filter to the gradient, wherein the spectral-shaping filter is tailored to the particular physical parameter and a known or estimated frequency spectrum, $S_i(f)$, of the particular physical parameter in the subsurface region.

9. The method of claim 8, wherein the spectral-shaping filter is determined by dividing $S_i(f)$ by the gradient's spectrum before shaping.

10. The method of claim 8, wherein the spectral-shaping filter varies with time.

11. The method of claim 1, wherein the one or more physical parameters are selected from a group consisting of P-impedance, S-impedance, density, P-velocity, and S-velocity.

12. The method of claim 1, wherein the model-simulated data are generated using a seismic source wavelet having a frequency spectrum $W(f)$ satisfying, to within a proportionality constant, the following equation:

$$D(f) = I_p(f)W(f)$$

where f is frequency, $D(f)$ is average frequency spectrum of the seismic data, and $I_p(f)$ is average frequency spectrum for P-impedance in the subsurface region or an approximation thereof based on a frequency spectrum of another elastic parameter.

13. The method of claim 12, wherein $D(f)$ and $I_p(f)$ are average spectra, meaning averaged over the subsurface region.

14. A computer program product, comprising a non-transitory computer usable medium having a computer readable program code embodied therein, said computer readable program code adapted to be executed to implement a method for inverting seismic data to obtain a model of one or more physical parameters in a subsurface region, said method comprising using iterative inversion with local cost function optimization, wherein an assumed or current model is updated to reduce misfit between the seismic data and model-simulated data, wherein the updated model's frequency spectrum in each iteration is controlled to match an input known or estimated frequency spectrum for the subsurface region; wherein the controlling of the frequency spectrum in each iteration comprises applying a spectral-shaping filter to both the seismic data and to a source wavelet used to generate the model-simulated data, or to a gradient of the cost function in at least a first iteration, said spectral-shaping filter being derived according to a criterion that the spectrum of a gradient of the cost function with respect to one of the one or more physical parameters, after application of the spectral-shaping filter to both the seismic data and to a source wavelet, should match the known or estimated frequency spectrum for the subsurface region.

15. The method of claim 1, wherein the cost function is a cross-correlation between the seismic data and the model-simulated data, and the optimization maximizes the cost function after the frequency spectrum control is applied to the seismic data and the model simulated data.

16. The method of claim 15, wherein source encoding is used on the seismic data and in the model simulation, and a plurality of encoded sources are simultaneously inverted.

17. The method of claim 16, wherein the encoding is changed for at least one iteration of the inversion.

18. The method of claim 1, wherein the cost function is an envelope function of a cross-correlation between the seismic data and the model-simulated data, and the optimization maximizes the cost function.

19. The method of claim 18, wherein source encoding is used on the seismic data and in the model simulation, and a plurality of encoded sources are inverted in a single inversion.

20. The method of claim 19, wherein the encoding is changed for at least one iteration of the inversion.

21. The method of claim 1, wherein the source wavelet before application of the spectral-shaping filter is chosen to have a frequency spectrum $W(f)$ that satisfies $D(f) \approx f I_p(f) W(f)$, where $D(f)$ is an average frequency spectrum of the seismic data, f is frequency, and where said known or estimated frequency spectrum for the subsurface region $I_p(f)$, is an average frequency spectrum of P-impedance in the subsurface region or is approximated by a frequency spectrum of a different elastic parameter of the subsurface region.

22. The method of claim 21, wherein the spectral-shaping filter satisfies

$$H(f) = \{f^{1/2} I_p(f)\} / \{a^{1/2}(f) D(f)\}$$

where $A\{f\}$ is a frequency-dependent factor determined such that

$$G(f) = A\{f\} W(f) D(f)$$

where $G\{f\}$ is a frequency spectrum of a gradient of the cost function with respect to one of the one or more physical parameters.