

CLAIMS

1. A method for processing seismic data, the method comprising:
accessing the seismic data that describes seismic energy that propagated through
5 one or more layers of media, including a water layer, to a plurality of measurement
locations in the water layer,
wherein the seismic data comprises pressure data that describes time-variant
pressures at one or more of the plurality of measurement locations in the water layer;
transforming the pressure data from a discrete space time domain to a space
10 Laplace domain; and
determining upgoing pressure data based on iteratively reducing a residual error
that is a function of the pressure data in the space Laplace domain and an integral
operator having an integrand that relates the upgoing pressure data to the pressure data
in the wavenumber frequency domain,
15 wherein determining the upgoing pressure data is performed in a discrete
domain comprising the plurality of measurement locations, and
wherein the method is performed by one or more computing devices.
2. The method of claim 1, wherein the seismic data comprises velocity data
20 that describes time-variant velocities of particles at a plurality of measurement locations
in the water layer.
3. The method of claim 2,
further comprising determining upgoing pressure data and downgoing pressure
25 data based on iteratively reducing a residual error that is a function of the pressure data
and the velocity data in the space Laplace domain and an integral operator that relates
the upgoing pressure data and the downgoing pressure data in the wavenumber
frequency domain to the pressure data and the vertical velocity data in the Laplace
domain, the integral operator given by

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) \mathbf{L}(\mathbf{k}_h, x_3, s) \begin{bmatrix} P^{up} \\ P^{dn} \end{bmatrix}(\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$, $P^{up}(\mathbf{k}_h, x_3, s)$ is the upgoing pressure in the wavenumber frequency domain, $P^{dn}(\mathbf{k}_h, x_3, s)$ is the downgoing pressure in the wavenumber frequency domain, j is an imaginary number, $\mathbf{L}$ is a composition matrix, s is a complex source frequency, and Γ is a complex vertical slowness.

4. The method of claim 1, wherein the discrete domain excludes a plurality of locations at which the seismic data was not measured, wherein the plurality of locations are caused by one or more of gaps between operating sensors at measurement locations of the plurality of measurement locations, or non-operating sensors at measurement locations other than the plurality of measurement locations.

5. The method of claim 1, wherein the one or more layers of media include a surface or subsurface of earth, further comprising using the processed seismic data to generate a map of the surface or subsurface of the earth.

6. The method of claim 1, wherein the integral operator further comprises

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) \sinh(s\Gamma x_3) \exp(-s\Gamma x_3) P^{up}(\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$, $P^{up}(\mathbf{k}_h, x_3, s)$ is upgoing pressure in the wavenumber frequency domain j is an imaginary number, s is a complex source frequency, Γ is a complex vertical slowness, and $\sinh(s\Gamma x_3) \exp(-s\Gamma x_3) P^{up}(\mathbf{k}_h, x_3, s)$ relates the upgoing pressure data to the pressure data in the wavenumber frequency domain.

7. The method of claim 1, wherein the one or more layers of media include a subsurface of earth, and wherein processing the seismic data is performed without using any information, other than the seismic data, about the subsurface of the earth.

5 8. An apparatus for processing seismic data, the apparatus comprising:
logic configured to access the seismic data that describes seismic energy that propagated through one or more layers of media, including a water layer, to a plurality of measurement locations in the water layer;
wherein the seismic data comprises pressure data that describes time-variant
10 pressures at one or more of the plurality of measurement locations in the water layer;
a computer system comprising a memory and one or more processors, the computer system configured to
transform the pressure data from a discrete space time domain to a space
Laplace domain; and
15 determine upgoing pressure data based on iteratively reducing a residual error that is a function of the pressure data in the space Laplace domain and an integral operator having an integrand that relates the upgoing pressure data to the pressure data in the wavenumber frequency domain;
wherein the computer system is configured to determine the upgoing pressure
20 data in a discrete domain comprising the plurality of measurement locations.

9. The apparatus of claim 8, wherein the seismic data comprises velocity data that describes time-variant velocities of particles at a plurality of measurement locations in the water layer.

25 10. The apparatus of claim 9,
further comprising the computer system to determine the upgoing pressure data and downgoing pressure data based on iteratively reducing a residual error that is a function of the pressure data and the velocity data in the space Laplace domain and an
30 integral operator that relates the upgoing pressure data and the downgoing pressure data

in the wavenumber frequency domain to the pressure data and the vertical velocity data in the Laplace domain, the integral operator given by

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) L(\mathbf{k}_h, x_3, s) \left[\begin{smallmatrix} P^{up} \\ P^{dn} \end{smallmatrix} \right](\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$,
5 $P^{up}(\mathbf{k}_h, x_3, s)$ is the upgoing pressure in the wavenumber frequency domain, $P^{dn}(\mathbf{k}_h, x_3, s)$ is the downgoing pressure in the wavenumber frequency domain, j is an imaginary number, L is a composition matrix, s is a complex source frequency, and Γ is a complex vertical slowness.

10 11. The apparatus of claim 8, wherein the discrete domain excludes a plurality of locations at which the seismic data was not measured, wherein the plurality of locations are caused by one or more of: gaps between operating sensors at measurement locations of the plurality of measurement locations, or non-operating sensors at measurement locations other than the plurality of measurement locations.

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12. The apparatus of claim 8, wherein the one or more layers of media include a surface or subsurface of earth, further comprising a visualization engine configured to use the processed seismic data to generate a map of the surface or subsurface of the earth.

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13. The apparatus of claim 8, wherein the integral operator further comprises

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) \sinh(s\Gamma x_3) \exp(-s\Gamma x_3) P^{up}(\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$,
25 $P^{up}(\mathbf{k}_h, x_3, s)$ is upgoing pressure in the wavenumber frequency domain, j is an imaginary number, s is a complex source frequency, Γ is a complex vertical slowness,

and $\sinh(s\Gamma x_3) \exp(-s\Gamma x_3) P^{up}(\mathbf{k}_h, x_3, s)$ relates the upgoing pressure data to the pressure data in the wavenumber frequency domain.

14. The apparatus of claim 8, wherein the one or more layers of media
5 include a subsurface of earth, and wherein the computer system is configured to process the seismic data without using any information, other than the seismic data, about the subsurface of the earth.

15. One or more non-transitory computer-readable storage media storing
10 instructions for processing seismic data which, when executed by one or more processors, cause the one or more processors to perform a method comprising:

accessing the seismic data that describes seismic energy that propagated through one or more layers of media, including a water layer, to a plurality of measurement locations in the water layer,

15 wherein the seismic data comprises pressure data that describes time-variant pressures at one or more of the plurality of measurement locations in the water layer;

transforming the pressure data from a discrete space time domain to a space Laplace domain; and

determining upgoing pressure data based on iteratively reducing a residual error
20 that is a function of the pressure data in the space Laplace domain and an integral operator having an integrand that relates the upgoing pressure data to the pressure data in the wavenumber frequency domain;

wherein determining the upgoing pressure data is performed in a discrete domain comprising the plurality of measurement locations, and

25 wherein the method is performed by one or more computing devices.

16. The one or more non-transitory computer-readable storage media of claim 15, wherein the seismic data comprises velocity data that describes time-variant velocities of particles at a plurality of measurement locations in the water layer.

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17. The one or more non-transitory computer-readable storage media of claim 16,

further comprising determining upgoing pressure data and downgoing pressure data based on iteratively reducing a residual error that is a function of the pressure data and the velocity data in the space Laplace domain and an integral operator that relates the upgoing pressure data and the downgoing pressure data in the wavenumber frequency domain to the pressure data and the vertical velocity data in the Laplace domain, the integral operator given by

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) \mathbf{L}(\mathbf{k}_h, x_3, s) \begin{bmatrix} P^{up} \\ P^{dn} \end{bmatrix}(\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$, $P^{up}(\mathbf{k}_h, x_3, s)$ is the upgoing pressure in the wavenumber frequency domain, $P^{dn}(\mathbf{k}_h, x_3, s)$ is the downgoing pressure in the wavenumber frequency domain, j is an imaginary number, $\mathbf{L}$ is a composition matrix, s is a complex source frequency, and Γ is a complex vertical slowness.

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18. The one or more non-transitory computer-readable storage media of claim 15, wherein the discrete domain excludes a plurality of locations at which the seismic data was not measured, wherein the plurality of locations are caused by one or more of: gaps between operating sensors at measurement locations of the plurality of measurement locations, or non-operating sensors at measurement locations other than the plurality of measurement locations.

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19. The one or more non-transitory computer-readable storage media of claim 15, wherein the one or more layers of media include a surface or subsurface of earth, wherein the instructions, when executed, further cause using the processed seismic data to generate a map of the surface or subsurface of the earth.

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20. The one or more non-transitory computer-readable storage media of claim 15,

wherein the integral operator further comprises

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) \sinh(s\Gamma x_3) \exp(-s\Gamma x_3) P^{up}(\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic
5 function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$,
 $P^{up}(\mathbf{k}_h, x_3, s)$ is upgoing pressure in the wavenumber frequency domain, j is an
imaginary number, s is a complex source frequency, Γ is a complex vertical slowness,
and $\sinh(s\Gamma x_3) \exp(-s\Gamma x_3) P^{up}(\mathbf{k}_h, x_3, s)$ relates the upgoing pressure data to the
pressure data in the wavenumber frequency domain.

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21. The one or more non-transitory computer-readable storage media of claim 15, wherein the one or more layers of media include a subsurface of earth, and wherein the instructions, when executed, cause processing the seismic data without using any information, other than the seismic data, about the subsurface of the earth.

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22. A method for processing seismic pressure data and seismic velocity data, the method comprising:

accessing the seismic pressure data and the seismic velocity data that describe seismic energy that propagated through one or more layers of media, including a water
20 layer, to a plurality of measurement locations submerged in the water layer and without using artificial measurements that do not correspond to the plurality of measurement locations;

transforming the pressure data and the vertical velocity data from a discrete space time domain to a space Laplace domain; and

25 determining upgoing pressure data and downgoing pressure data based on iteratively reducing a residual error that is a function of the pressure data and the velocity data in the space Laplace domain and an integral operator having an integrand

that relates the upgoing pressure data and the downgoing pressure data to the pressure data and the vertical velocity data in the wavenumber frequency domain,

wherein the method is performed by one or more computing devices.

5 23. The method of claim 22, wherein determining the upgoing pressure data and the downgoing pressure data is performed in a discrete domain comprising the plurality of measurement locations.

10 24. The method of claim 23, wherein the plurality of measurement locations forms a discrete domain that excludes a plurality of locations at which the seismic data was not measured, wherein the plurality of locations are caused by one or more of: gaps between operating sensors at measurement locations of the plurality of measurement locations, or non-operating sensors at measurement locations other than the plurality of measurement locations.

15 25. The method of claim 22, wherein the one or more layers of media include a surface or subsurface of earth, further comprising using the processed seismic data to generate a map of the surface or subsurface of the earth.

20 26. The method of claim 22, wherein the one or more layers of media include a subsurface of earth, and wherein determining the upgoing pressure data and the downgoing pressure data is performed without using any information, other than the seismic data, about the subsurface of the earth.

25 27. The method of claim 22, wherein the integral operator further comprises:

$$\frac{1}{2\pi^2} \int_{\mathbf{k}_h \in \mathbb{K}} \chi_{\mathbb{K}}(\mathbf{k}_h) \mathbf{L}(\mathbf{k}_h, x_3, s) \left[\begin{matrix} P^{up} \\ P^{dn} \end{matrix} \right] (\mathbf{k}_h, x_3, s) \exp(-j\mathbf{k}_h \cdot \mathbf{x}_{l,h}) d\mathbf{k}_h$$

where $\mathbf{x}_{l,h}$ is a measurement location at depth x_3 , $\chi_{\mathbb{K}}(\mathbf{k}_h)$ is a characteristic function of horizontal wave vectors $\mathbf{k}_h$ in a domain of horizontal wave vectors $\mathbb{K}$, $P^{up}(\mathbf{k}_h, x_3, s)$ is the upgoing pressure in the wavenumber frequency domain,

$P^{dn}(k_h, x_3, s)$ is the downgoing pressure in the wavenumber frequency domain, j is an imaginary number, L is a composition matrix, s is a complex source frequency, and Γ is a complex vertical slowness.