CLAIMS

1. In a process for generating an image of a subterranean formation using marine seismic techniques in which one or more sources are activated above a subterranean formation, the reflections from the subterranean formation recorded as pressure data and vertical velocity data measured at each receiver coordinate of a seismic data acquisition system, the pressure data having a pressure-signal component and pressure-sensor noise and the vertical-velocity data having a vertical-velocity signal component and particle-motion-sensor noise, the specific improvement consisting of:

computing approximate vertical-velocity data from the pressure data and the vertical-velocity data measured at each receiver coordinate of the seismic data acquisition system;

computing a filter that gives a minimum difference between the vertical-velocity data and the approximate vertical-velocity data at each receiver coordinate;

computing noise-corrected vertical-velocity data composed of the vertical-velocity signal component and an approximate particle-motion-sensor noise convolved with the filter at each receiver coordinate, the approximate particle-motion-sensor noise composed of the pressure-sensor noise;

separating the pressure data into up-going pressure data and down-going pressure data based on the noise-corrected vertical-velocity data; and

using the up-going pressure data in generating an image of the subterranean formation without receiver ghost effects and the particle-motion-sensor noise, thereby enhancing the image of the subterranean formation.

2. The process of claim 1 wherein computing the approximate vertical-velocity data further comprises:

computing an approximate frozen free-surface profile that approximates the profile of the free surface above the receivers;

computing reflectivity and normal derivative at the receiver coordinates based on the approximate frozen free-surface profile;

computing a monopole matrix based on the reflectivity at the receiver coordinates;

computing a dipole matrix based on the normal derivative at the receiver coordinates;

computing an inverse of the monopole matrix;

computing a normal derivative of the pressure wavefield at the receiver coordinates based the inverse of the monopole matrix, the dipole matrix and the pressure data recorded at each receiver coordinate;

computing an approximate normal particle velocity at the receiver coordinates based on the normal derivatives of the pressure wavefield at the receiver coordinates; and

computing the approximate vertical-velocity data at the receiver coordinates based on the approximate normal particle velocity at the receiver coordinates and orientation of the receivers.

3. The process of claim 2, wherein computing the approximate frozen free-surface profile further comprises:

for each receiver coordinate,

computing up-going and down-going pressure wavefields at zero depth based on measured pressure and vertical-velocity data above a low-frequency range,

computing up-going and down-going pressure wavefields at an observation level between receiver depths and zero depth based on the up-going and down-going pressure wavefields at zero depth,

computing extrapolated up-going and down-going wavefields at a series of extrapolation points between the observation level to a distance above zero depth,

computing an image value at each extrapolation point based on the extrapolated up-going and down-going wavefields at each extrapolation point, and

determining a maximum image value; and

computing an interpolation function based on the maximum image values at the receiver coordinates.

4. The process of claim 3, wherein computing the approximate frozen free-surface profile further comprises computing a frozen free-surface extension.

5. The process of claim 2, wherein in computing reflectivity and normal derivative at receiver coordinates further comprises:

computing a unit normal vector of the approximate frozen free-surface profile;

computing reflectivity of the approximate frozen free-surface profile based on the unit normal vector at points along the approximate frozen free-surface profile;

computing reflectivity at the receiver coordinates based on the reflectivity of the approximate frozen free-surface profile; and

computing normal derivative of the reflectivity at the receiver coordinates.

6. The process of claim 1, wherein computing the filter further comprises:

computing a cross-correlation matrix based on the vertical-velocity data and the approximate vertical-velocity data;

computing an auto-correlation matrix based on the vertical-velocity data; computing an inverse of the auto-correlation matrix; and

computing the filter as the product of the inverse auto-correlation matrix and the cross-correlation matrix.

7. The process of claim 1, wherein the filter that gives the minimum difference further comprises computing the filter that gives the minimum difference between the vertical-velocity data subtracted from the approximate vertical-velocity data convolved with the filter.

8. The process of claim 1, wherein computing the noise-corrected vertical-velocity data further comprises adding the difference to the vertical-velocity data to generate the noise-corrected vertical-velocity data at each receiver coordinate.

9. The process of claim 1, wherein the noise-corrected vertical-velocity data further comprises the vertical-velocity data subtracted from the approximate vertical-velocity data convolved with the filter at each receiver coordinate.

10. The process of claim 1 executed on a programmable computer programmed to execute the method.

11. The process of claim 1, wherein the vertical-velocity data forms a geophysical data product, further comprising recording the geophysical data product on a physical, non-volatile computer-readable medium suitable for importing onshore.

12. The process of claim 11, further comprising performing geophysical analysis onshore on the geophysical data product.

13. A computer system that removes particle-motion-sensor noise from vertical-velocity data, the system comprising:

one or more processors;

one or more data-storage devices; and

a routine stored in one or more of the data-storage devices that when executed by the one or more processors controls the system to carry out

computing approximate vertical-velocity data from pressure data and vertical-velocity data at each receiver coordinate of a seismic data acquisition system, the pressure data having a pressure-signal component and pressure-sensor noise and the vertical-velocity data having a vertical-velocity signal component and vertical-velocity-sensor noise;

computing a filter to give a minimum difference between the vertical-velocity data and the approximate vertical-velocity data at each receiver coordinate;

computing noise-corrected vertical-velocity data composed of the vertical-velocity signal component and an approximate particle-motion-sensor noise convolved with the filter at each receiver coordinate, the approximate particle-motion-sensor noise based on the pressure-sensor noise;

separating the pressure data into up-going pressure data and down-going pressure data based on the noise-corrected vertical-velocity data; and

using the up-going pressure data in generating an image of the subterranean formation without receiver ghost effects and the particle-motion-sensor noise, thereby enhancing the image of the subterranean formation.

14. The computer system of claim 13 wherein computing the approximate vertical-velocity data further comprises:

computing an approximate frozen free-surface profile that approximates the profile of the free surface above the receivers;

computing reflectivity and normal derivative at the receiver coordinates based on the approximate frozen free-surface profile;

computing a monopole matrix based on the reflectivity the receiver coordinates;

computing a dipole matrix based on the normal derivative the receiver coordinates;

computing an inverse of the monopole matrix;

computing a normal derivative of the pressure wavefield at the receiver coordinates based the inverse of the monopole matrix, the dipole matrix and the pressure data recorded at each receiver coordinate;

computing an approximate normal particle velocity at the receiver coordinates based on the normal derivatives of the pressure wavefield at the receiver coordinates; and

computing the approximate vertical-velocity data at the receiver coordinates based on the approximate normal particle velocity at the receiver coordinates and orientation of the receivers.

15. The computer system of claim 14, wherein computing the approximate frozen free-surface profile further comprises:

for each receiver coordinate,

computing up-going and down-going pressure wavefields at zero depth based on measured pressure and vertical-velocity data above a low-frequency range,

computing up-going and down-going pressure wavefields at an observation level between receiver depths and zero depth based on the up-going and down-going pressure wavefields at zero depth,

computing extrapolated up-going and down-going wavefields at a series of extrapolation points between the observation level to a distance above zero depth,

computing an image value at each extrapolation point based on the extrapolated up-going and down-going wavefields at each extrapolation point, and

determining a maximum image value; and

computing an interpolation function based on the maximum image values at the receiver coordinates.

16. The computer system of claim 15, wherein computing the approximate frozen free-surface profile further comprises computing a frozen free-surface extension.

17. The computer system of claim 14, wherein in computing reflectivity and normal derivative at receiver coordinates further comprises:

computing a unit normal vector of the approximate frozen free-surface profile;

computing reflectivity of the approximate frozen free-surface profile based on the unit normal vector at points along the approximate frozen free-surface profile;

computing reflectivity at the receiver coordinates based on the reflectivity of the approximate frozen free-surface profile; and

computing normal derivative of the reflectivity at the receiver coordinates.

18. The computer system of claim 13, wherein computing the filter further comprises:

computing a cross-correlation matrix based on the vertical-velocity data and the approximate vertical-velocity data;

computing an auto-correlation matrix based on the vertical-velocity data;

computing an inverse of the auto-correlation matrix; and

computing the filter as the product of the inverse auto-correlation matrix and the cross-correlation matrix.

19. The computer system of claim 13, wherein the filter that gives the minimum difference further comprises computing the filter that gives the minimum difference between the vertical-velocity data subtracted from the approximate vertical-velocity data convolved with the filter.

20. The computer system of claim 13, wherein computing the noise-corrected vertical-velocity data further comprises adding the difference to the vertical-velocity data to generate the noise-corrected vertical-velocity data at each receiver coordinate.

21. The computer system of claim 13, wherein the noise-corrected vertical-velocity data further comprises the vertical-velocity data subtracted from the approximate vertical-velocity data convolved with the filter at each receiver coordinate.

22. A non-transitory computer-readable medium having machine-readable instructions encoded thereon that enables one or more processors of a computer system to perform the operations of

computing approximate vertical-velocity data from pressure data and vertical-velocity data at each receiver coordinate of a seismic data acquisition system, the pressure data having a pressure-signal component and pressure-sensor noise and the vertical-velocity data having a vertical-velocity signal component and vertical-velocity-sensor noise;

computing a filter to give a minimum difference between the vertical-velocity data and the approximate vertical-velocity data at each receiver coordinate;

computing noise-corrected vertical-velocity data composed of the vertical-velocity signal component and an approximate particle-motion-sensor noise convolved with the filter at each receiver coordinate, the approximate particle-motion-sensor noise based on the pressure-sensor noise;

separating the pressure data into up-going pressure data and down-going pressure data based on the noise-corrected vertical-velocity data; and

using the up-going pressure data in generating an image of the subterranean formation without receiver ghost effects and the particle-motion-sensor noise, thereby enhancing the image of the subterranean formation.

23. The non-transitory computer-readable medium of claim 22 wherein computing the approximate vertical-velocity data further comprises:

computing an approximate frozen free-surface profile that approximates the profile of the free surface above the receivers;

computing reflectivity and normal derivative the receiver coordinates based on the approximate frozen free-surface profile;

computing a monopole matrix based on the reflectivity the receiver coordinates;

computing a dipole matrix based on the normal derivative the receiver coordinates;

computing an inverse of the monopole matrix;

computing a normal derivative of the pressure wavefield at the receiver coordinates based the inverse of the monopole matrix, the dipole matrix and the pressure data recorded at each receiver coordinate;

computing an approximate normal particle velocity at the receiver coordinates based on the normal derivatives of the pressure wavefield at the receiver coordinates; and

computing the approximate vertical-velocity data at the receiver coordinates based on the approximate normal particle velocity at the receiver coordinates and orientation of the receivers.

24. The non-transitory computer-readable medium of claim 23, wherein computing the approximate frozen free-surface profile further comprises:

for each receiver coordinate,

computing up-going and down-going pressure wavefields at zero depth based on measured pressure and vertical-velocity data above a low-frequency range,

computing up-going and down-going pressure wavefields at an observation level between receiver depths and zero depth based on the up-going and down-going pressure wavefields at zero depth,

computing extrapolated up-going and down-going wavefields at a series of extrapolation points between the observation level to a distance above zero depth,

computing an image value at each extrapolation point based on the extrapolated up-going and down-going wavefields at each extrapolation point, and

determining a maximum image value; and

computing an interpolation function based on the maximum image values at the receiver coordinates.

25. The non-transitory computer-readable medium of claim 24, wherein computing the approximate frozen free-surface profile further comprises computing a frozen free-surface extension.

26. The non-transitory computer-readable medium of claim 23, wherein in computing reflectivity and normal derivative at receiver coordinates further comprises:

computing a unit normal vector of the approximate frozen free-surface profile;

computing reflectivity of the approximate frozen free-surface profile based on the unit normal vector at points along the approximate frozen free-surface profile;

computing reflectivity at the receiver coordinates based on the reflectivity of the approximate frozen free-surface profile; and

computing normal derivative of the reflectivity at the receiver coordinates.

27. The non-transitory computer-readable medium of claim 22, wherein computing the filter further comprises:

computing a cross-correlation matrix based on the vertical-velocity data and the approximate vertical-velocity data;

computing an auto-correlation matrix based on the vertical-velocity data;

computing an inverse of the auto-correlation matrix; and

computing the filter as the product of the inverse auto-correlation matrix and the cross-correlation matrix.

28. The non-transitory computer-readable medium of claim 22, wherein the filter that gives the minimum difference further comprises computing the filter that gives the minimum difference between the vertical-velocity data subtracted from the approximate vertical-velocity data convolved with the filter.

29. The non-transitory computer-readable medium of claim 22, wherein the noise-corrected vertical-velocity data further comprises adding the difference to the

vertical-velocity data to generate the noise-corrected vertical-velocity data at each receiver coordinate.

30. The non-transitory computer-readable medium of claim 22, wherein the noise-corrected vertical-velocity data further comprises the vertical-velocity data subtracted from the approximate vertical-velocity data convolved with the filter at each receiver coordinate.