

2010EM327

~~AMENDED CLAIMS~~

1. A method for correcting measured data from a marine seismic survey to eliminate surface-related multiples, said measured data being pressure data either measured by pressure sensor receivers located in the water or calculated from measured particle velocity data, said method comprising:

(a) using a computer to simulate the measured data ("simulated data") with a forward model that includes a water propagation operator between source locations and receiver locations and a term representing primary impulse responses;

(b) updating the primary impulse responses by iterative optimization to minimize a difference between the measured data and the simulated data; and

(c) using the updated primary impulse responses to correct the measured data for multiple reflections, or for further processing to interpret for indications of hydrocarbon potential.

2. The method of claim 1, wherein the measured data are corrected for multiple reflections either (i) by using the updated primary impulse responses to determine simulated multiple reflections, and then subtracting the simulated multiple reflections from the measured data, or (ii) by convolving the updated primary impulse responses with a wavelet.

3. The method of claim 1, wherein the simulated data comprise direct arrival waves, primary reflections, and up-going and down-going multiple reflections, and wherein the forward model further comprises a source wavelet matrix and a surface reflector matrix; and the measured data in the iterative optimization are expressed as a data matrix comprising the measured data after transformation to frequency domain.

4. The method of claim 3, further comprising also updating the source wavelet matrix in the iterative optimization.

2010EM327

5. The method of claim 3, further comprising dividing the data matrix into a near offset part having missing or receiver-saturated data and a remainder part, and also updating the near offset part in the iterative optimization.

6. The method of claim 3, wherein the water propagation operator depends on acoustic wave propagation velocity in water and is therefore known, and the surface reflector matrix is also known, and therefore both quantities are held fixed in the iterative optimization.

7. The method of claim 1, further comprising an initial step of conditioning the measured seismic data or a selected part thereof by dip filtering, interpolation, up/down separation, or another method.

8. The method of claim 1, further comprising using the updated primary impulse responses to determine simulated direct arrival waves and primary reflections.

9. The method of claim 8, wherein the iterative optimization is terminated when a difference between a sum of the simulated direct arrival waves, primary reflections, and up-going and down-going multiple reflections equals the measured data to within a preselected tolerance.

10. The method of claim 8, further comprising subtracting the simulated direct arrival waves from the measured data using adaptive subtraction.

11. The method of claim 1, wherein the forward model is expressed as or is mathematically equivalent to:

$$P = W^T S + X_0 S + P S^{-1} R W X_0 S$$

where

$P = P(z_1, z_0)$ is the measured data after transformation to frequency domain and expressed in detail hiding operator notation, being a frequency slice from a matrix cube

2010EM327

$p(t, x_r, x_s)$, where x_r is receiver position and x_s is source position and t is seismic wave travel time from source to receiver;

$W^+ = W^+(z_1, z_0)$ is the water propagation operator, i.e. a matrix operator that describes propagation of a wavefield from surface depth level z_0 to water depth level at which the receivers are located z_1 ;

W is the transposed matrix of W^+ ;

$R = R(z_0, z_0)$ represents a surface reflector matrix, and equals $-I$ for complete reflection from an air-water interface, where I is the identity matrix;

$S = S(z_0)$ is a source wavelet matrix; and

$X_0 = X_0(z_1, z_0)$ are the primary impulse responses, expressed as Green's functions.

12. The method of claim 11, wherein the source wavelet is assumed constant for all shots, and therefore the matrix S reduces to a scalar constant S .

13. The method of claim 12, wherein the forward model is divided into an up-going part and a down-going part, which are expressed as, or mathematically can be reduced to:

$$P^+ = W^+ S + P^+ R W X_0,$$

and

$$P^- = X_0 S + P^- R W X_0,$$

where P is separated into an up-going wavefield P^+ and a down-going wavefield P^- using data from particle motion detectors.

14. The method of claim 1, wherein the measured data are from either an ocean bottom cable seismic survey or a deep-towed seismic streamer survey.

15. The method of claim 1, further comprising using the estimated primary impulse responses to determine simulated multiple reflections in measured particle velocity data; and correcting the measured particle velocity data by subtracting the simulated multiple reflections.

2010EM327

16. A method for producing hydrocarbons from a subsurface offshore region, comprising:
- conducting an ocean bottom cable or deep-towed streamer survey of the subsurface offshore region;
 - removing multiple reflections from the survey's data using a method of claim 1;
 - interpreting the survey's data after multiple removal for subsurface conditions indicative of hydrocarbon potential;
 - drilling a well into the subsurface offshore region based at least in part on the interpretation of the survey's data, and producing hydrocarbons from the well.
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 correcting measured data from a marine seismic survey to eliminate surface-related multiples, said measured data being pressure data either measured by pressure sensor receivers located in the water or calculated from measured particle velocity data, said method comprising:
- (a) simulating the measured data ("simulated data") with a forward model that includes a water propagation operator between source locations and receiver locations and a term representing primary impulse responses;
 - (b) updating the primary impulse responses by iterative optimization to minimize a difference between the measured data and the simulated data; and
 - (c) downloading or saving the updated primary impulse responses to computer memory or data storage.
18. The computer program product of claim 17, wherein said method further comprises:
- using the updated primary impulse responses to determine simulated multiple reflections; and
 - correcting the measured data by subtracting the simulated multiple reflections.

2010EM327

19. The method of claim 1, wherein the measured data and the simulated data are encoded according to source, receiver, or both.
20. The method of claim 19, wherein the encoding is changed for at least one iteration.
21. The method of claim 19, wherein the measured data are encoded in data processing or are acquired in encoded form from a survey in which the survey sources were operated with encoded pilot signals.
22. The method of claim 19, further comprising applying linear or nonlinear filtering to the updated primary impulse responses between iterations.