primary and ghost arrivals causes notches, or gaps, in the frequency content the detectors record.

[0006] The traces may be used to determine the subsurface (i.e., earth structure below surface 24) and to determine the position and presence of reflectors 26. However, ghosts disturb the accuracy of the final image of the subsurface and, for at least this reason, various methods exist for removing ghosts, i.e., deghosting, from the results of a seismic analysis.

[0007] However, most existing methods are designed for handling seismic data recorded with horizontal streamers, i.e., seismic data collected at the same depth (datum) relative to the ocean surface. Recent developments require that processing methods handle seismic data collected with curved and/or slanted streamers, i.e., seismic data collected by receivers located at variable depths.

[0008] Accordingly, it would be desirable to provide systems and methods for 3D seismic processing which allow imaging of the subsurface geology based on marine seismic data recorded at different water depths.

SUMMARY

[0009] According to an exemplary embodiment, there is a method for deghosting seismic data collected with a seismic system, the seismic data being related to a subsurface of a body of water. The method includes receiving the seismic data recorded by detectors distributed along a variable-depth profile; calculating migrated (d_1) and mirror-migrated (d_2) gathers based on the seismic data, wherein the migrated and mirror-migrated gathers depend on a feature characterizing a configuration of the seismic system; applying a joint deconvolution model to the migrated and mirror-migrated gathers (d_1, d_2) to calculate a single

WHAT IS CLAIMED IS:

1. A method for deghosting seismic data collected with a seismic system, the seismic data being related to a subsurface of a body of water, the method comprising:

receiving the seismic data recorded by detectors distributed along a variable-depth profile;

calculating migrated ~~(d_1)~~ and mirror-migrated ~~(d_2)~~ gathers based on the seismic data, wherein the migrated and mirror-migrated gathers depend on a feature characterizing a configuration of the seismic system;

applying a joint deconvolution model to the migrated and mirror-migrated gathers ~~(d_1, d_2)~~ to calculate a single deghosted gather ~~(dg)~~; and

generating a final image of the subsurface based on the single deghosted gather ~~(dg)~~,

wherein the feature is not present in a gather after a step of stacking that is performed prior to generating the final image.

2. The method of Claim 1, wherein the feature is an offset between a seismic source of the seismic system and the detectors.

3. The method of Claim 1, wherein the feature is an angle of an incident wave to a corresponding detector.

4. The method of any one of claims 1 to 3, wherein the step of applying a deconvolution model comprises:

defining a reflectivity ~~(r)~~ as a sum of a set of polynomials ~~(T_i)~~ multiplied by corresponding coefficients ~~(a_i)~~;

parameterizing ghost ~~(g_{min})~~ and mirror ghost ~~(g_{max})~~ operators;

defining a cost function ~~(C)~~ based on the reflectivity ~~(r)~~ and the ghost ~~(g_{min})~~ and mirror ghost ~~(g_{max})~~ operators; and

minimizing the cost function ~~(C)~~ to determine the coefficients ~~(a_i)~~ and the ghost ~~(g_{min})~~ and mirror ghost ~~(g_{max})~~ operators.

5. The method of Claim 4, further comprising:

calculating the reflectivity ~~(r)~~; and

calculating a ghost model ~~(g_1)~~ and a mirror ghost model ~~(g_2)~~,

wherein the ghost model ~~(g_1)~~ is given by a convolution of the ghost operator ~~(g_{min})~~ with the reflectivity ~~(r)~~ and then subtracting the reflectivity ~~(r)~~, and

the mirror ghost model ~~(g_2)~~ is given by the convolution of the mirror ghost operator ~~(g_{max})~~ with the reflectivity ~~(r)~~ and then subtracting the reflectivity ~~(r)~~.

6. The method of Claim 5, wherein the ghost operator ~~(g_{min})~~ is a causal, minimum-phase operator and the mirror ghost operator ~~(g_{max})~~ is an anti-causal, maximum-phase operator.

7. The method of Claim 5 or 6, further comprising:

computing a deghosted gather ~~(dg_1)~~ based on the migrated gather ~~(d_1)~~ and the ghost model ~~(g_1)~~; and

computing a deghosted mirror gather ~~(dg_2)~~ based on the mirror migrated gather ~~(d_2)~~ and the mirror ghost model ~~(g_2)~~.

8. The method of Claim 7, further comprising:

calculating the single deghosted gather ~~(dg)~~ based on the deghosted gather ~~(dg_1)~~ and the deghosted mirror gather ~~(dg_2)~~.

9. The method of any one of Claims 1 to 8, further comprising:

stacking the single deghosted gather ~~(dg)~~ to eliminate the feature.

10. A computing device for deghosting seismic data collected with a seismic system, the seismic data being related to a subsurface of a body of water, the computing device comprising:

an interface for receiving the seismic data recorded by detectors distributed along a variable-depth profile; and

a processor connected to the interface and configured to,

calculate migrated ~~(d_1)~~ and mirror-migrated ~~(d_2)~~ gathers based on the seismic data, wherein the migrated and mirror-migrated gathers depend on a feature characterizing a configuration of the seismic system,

apply a joint deconvolution model to the migrated and mirror-migrated gathers ~~(d_1, d_2)~~ to calculate a single deghosted gather ~~(dg)~~, and

generate a final image of the subsurface based on the single deghosted gather ~~(dg)~~,

wherein the feature is not present in a gather after a step of stacking that is performed prior to generating the final image.

11. The computing device of Claim 10, wherein the feature is an offset between a vessel of the seismic system and the detectors.

12. The computing device of Claim 10, wherein the feature is an angle of an incident wave to a corresponding detector.

13. The computing device of any one of claims 10 to 12, wherein the processor is further configured to:

define a reflectivity ~~(r)~~ *as a sum of a set of polynomials* ~~(T_i)~~ *multiplied by* corresponding coefficients ~~(a_i)~~;

parameterize ghost ~~(g_{min})~~ and mirror ghost ~~(g_{max})~~ operators;

define a cost function ~~(C)~~ based on the reflectivity ~~(r)~~ and the ghost ~~(g_{min})~~ and mirror ghost ~~(g_{max})~~ operators; and

minimize the cost function ~~(C)~~ to determine the coefficients ~~(a_i)~~ and the ghost ~~(g_{min})~~ and mirror ghost ~~(g_{max})~~ operators.

14. The computing device of Claim 13, wherein the processor is further configured to:

calculate the reflectivity ~~(r)~~; and

calculate a ghost model ~~(g_1)~~ *and a mirror ghost model* ~~(g_2)~~,

wherein the ghost model ~~(g_1)~~ is given by a convolution of the ghost operator ~~(g_{min})~~ with the reflectivity ~~(r)~~ and then subtracting the reflectivity ~~(r)~~, and

the mirror ghost model ~~(g_2)~~ is given by the convolution of the mirror ghost operator ~~(g_{max})~~ with the reflectivity ~~(r)~~ and then subtracting the reflectivity ~~(r)~~.

15. The computing device of Claim 14, wherein the ghost operator ~~(g_{min})~~ is a causal, minimum-phase operator and the mirror ghost operator ~~(g_{max})~~ is an anti-causal, maximum-phase operator.

16. The computing device of Claim 14 or 15, wherein the processor is further configured to:

compute a deghosted gather ~~(dg_1)~~ based on the migrated gather ~~(d_1)~~ and the ghost model ~~(g_1)~~; and

compute a deghosted mirror gather ~~(dg_2)~~ based on the mirror migrated gather ~~(d_2)~~ and the mirror ghost model ~~(g_2)~~.

17. The computing device of Claim 16, wherein the processor is further configured to:

calculate the single deghosted gather ~~(dg)~~ based on the deghosted gather ~~(dg_1)~~ and the deghosted mirror gather ~~(dg_2)~~.

18. The computing device of any one of claims 10 to 17, wherein the processor is further configured to:

stack the single deghosted gather ~~(dg)~~ to eliminate the feature.

19. A non-transitory computer readable medium including computer executable instructions, wherein the instructions, when executed by a computer, implement a method for deghosting seismic data collected with a seismic system, the seismic data being related to a subsurface of a body of water, the method comprising:

receiving the seismic data recorded by detectors distributed along a variable-depth profile;

calculating migrated ~~(d_1)~~ and mirror-migrated ~~(d_2)~~ gathers based on the seismic data, wherein the migrated and mirror-migrated gathers depend on a feature characterizing a configuration of the seismic system;

applying a joint deconvolution model to the migrated and mirror-migrated gathers ~~(d_1, d_2)~~ to calculate a single deghosted gather ~~(dg)~~; and

generating a final image of the subsurface based on the single deghosted gather ~~(dg)~~,

wherein the feature is not present in a gather after a step of stacking that is performed prior to generating the final image.

20. The medium of Claim 19, wherein the feature is an offset between a seismic source of the seismic system and the detectors or an angle of an incident wave to a corresponding detector.