patent, a method for deghosting uses joint deconvolution for migration and mirror migration images to generate a final image of a subsurface. Deghosting is performed at the end of processing (during an imaging phase) and not at the beginning, as with traditional methods. Further, the '951 patent discloses that no datuming step is performed on the data.

[0009] Another method that addresses variable-depth data is disclosed by U.S. Patent Application Serial No. 13/334,776 (herein '776) authored by G. Poole. This method uses a surface datum $\tau - p$ model that represents input shot data. A transform from the $\tau - p$ model to a shot domain (offset-time) combines the operations of redatuming and reghosting. The use of variable-depth streamer data combined with reghosting ensures that a single point in the $\tau - p$ domain satisfies a range of different ghost lags, therefore, making use of variable-depth data notch diversity, which ensures effective receiver deghosting.

[0010] However, existing methods relate to pressure measurements made, for example, by hydrophones. Currently, the new streamer generation is capable of measuring not only pressure but also particle motion data, e.g., displacement, velocity, differential pressure, acceleration, etc. Thus, there is a need to process not only pressure measurements, but also particle motion data. Accordingly, it would be desirable to provide systems and methods with such capabilities.

SUMMARY

[0011] According to an embodiment, there is a method for improving accuracy of an image of a surveyed subsurface. The method includes receiving seismic data (D) recorded with seismic sensors located on marine towed streamers, wherein the seismic data includes pressure data (P) recorded with hydrophones and particle motion data (A) recorded with particle motion sensors; deghosting the seismic data (D) using a sparse

$\tau - p$ inversion algorithm together with a low-rank optimization scheme and a high-cut filter to calculate ghost-free wave-fields (U_0(t,x,y)) in the time-space domain; and processing the ghost-free wave-fields (U_0(t,x,y) to generate the image of the surveyed subsurface.

[0012] According to another embodiment, there is a computing device for improving accuracy of an image of a surveyed subsurface, the computing device including an interface configured to receive seismic data (D) recorded with seismic sensors located on marine towed streamers, wherein the seismic data includes pressure data (P) recorded with hydrophones and particle motion data (A) recorded with particle motion sensors; and a processor connected to the interface. The processor is configured to deghost the seismic data (D) using a sparse $\tau - p$ inversion algorithm together with a low-rank optimization scheme and a high-cut filter to calculate ghost-free wave-fields (U_0(t,x,y)) in the time-space domain; and process the ghost-free wave-fields (U_0(t,x,y) to generate the image of the surveyed subsurface.

[0013] According to still another embodiment, there is a non-transitory computer readable medium including computer executable instructions, wherein the instructions, when executed by a processor, implement instructions for improving accuracy of an image of a surveyed subsurface, the instructions implementing the method discussed above.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate one or more embodiments and, together with the description, explain these embodiments. In the drawings:

[0015] Figure 1 is a schematic diagram of a conventional seismic data acquisition system having a horizontal streamer;

WHAT IS CLAIMED IS:

1. A method for improving accuracy of an image of a surveyed subsurface, the method comprising:

receiving seismic data (D) recorded with seismic sensors located on marine towed streamers, wherein the seismic data includes pressure data (P) recorded with hydrophones and particle motion data (A) recorded with particle motion sensors;

deghosting the seismic data (D) using a sparse $\tau - p$ inversion algorithm together with a low-rank optimization scheme and a high-cut filter to calculate ghost-free wave-fields (U_0(t,x,y)) in the time-space domain; and

processing the ghost-free wave-fields (U_0(t,x,y) to generate the image of the surveyed subsurface.

2. The method of Claim 1, wherein the step of deghosting comprises:

applying band-pass filters (F) to particle motion data of the seismic data.

3. The method of Claim 1, wherein the step of deghosting comprises:

constructing an operator T in a $\tau - p$ domain, that when applied to ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain, produces estimates (D_{est}) of the seismic data; and

applying the low-rank optimization scheme to the operator T to reduce the dimension of the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain.

4. The method of Claim 3, further comprising:

using high-cut filtered data to obtain an initial result of the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain;

using the initial result of the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain to calculate a next ghost-free wave-field (U(f,px,py)) with a higher frequency; and

repeating the sparse $\tau - p$ inversion algorithm to calculate the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain.

5. The method of Claim 4, further comprising:

applying a reverse $\tau - p$ transform and an inverse Fourier transform to the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain to obtain the ghost-free wave-fields (U_0(t,x,y)) in the time space-domain.

6. The method of Claim 1, further comprising:

using only pressure data (P) to derive particle motion data (A).

7. The method of Claim 1, wherein the seismic data is acquired with a variable-depth streamer.

8. A computing device for improving accuracy of an image of a surveyed subsurface, the computing device comprising:

an interface configured to receive seismic data (D) recorded with seismic sensors located on marine towed streamers, wherein the seismic data includes

pressure data (P) recorded with hydrophones and particle motion data (A) recorded with particle motion sensors; and

a processor connected to the interface and configured to,

deghost the seismic data (D) using a sparse $\tau - p$ inversion algorithm together with a low-rank optimization scheme and a high-cut filter to calculate ghost-free wave-fields ($U_0(t,x,y)$) in the time-space domain; and

process the ghost-free wave-fields ($U_0(t,x,y)$ to generate the image of the surveyed subsurface.

9. The computing device of Claim 8, wherein the processor is further configured to:

apply band-pass filters (F) to particle motion data of the seismic data.

10. The computing device of Claim 8, wherein the processor is further configured to:

construct an operator T in a $\tau - p$ domain, that when applied to ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain, produces estimates (D_{est}) of the seismic data; and

apply the low-rank optimization scheme to the operator T to reduce the dimension of the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain.

11. The computing device of Claim 10, wherein the processor is further configured to:

use high-cut filtered data to obtain an initial result of the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain;

use the initial result of the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain to calculate a next ghost-free wave-field (U(f,px,py)) with a higher frequency; and

repeat the sparse $\tau - p$ inversion algorithm to calculate the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain.

12. The computing device of Claim 11, wherein the processor is further configured to:

apply a reverse $\tau - p$ transform and an inverse Fourier transform to the ghost-free wave-fields (U(f,px,py)) in the $\tau - p$ domain to obtain the ghost-free wave-fields (U_0(t,x,y)) in the time space-domain.

13. The computing device of Claim 8, wherein the processor is further configured to:

use only pressure data (P) to derive particle motion data (A).

14. The computing device of Claim 8, wherein the seismic data is acquired with a variable-depth streamer.

15. A non-transitory computer readable medium including computer executable instructions, wherein the instructions, when executed by a processor,

implement instructions for improving accuracy of an image of a surveyed subsurface, the instructions comprising:

receiving seismic data (D) recorded with seismic sensors located on marine towed streamers, wherein the seismic data includes pressure data (P) recorded with hydrophones and particle motion data (A) recorded with particle motion sensors;

deghosting the seismic data (D) using a sparse $\tau - p$ inversion algorithm together with a low-rank optimization scheme and a high-cut filter to calculate ghost-free wave-fields ($U_0(t,x,y)$) in the time-space domain; and

processing the ghost-free wave-fields ($U_0(t,x,y)$ to generate the image of the surveyed subsurface.