

Claims

What is claimed is:

1. A method for deghosting seismic data from a marine seismic survey, the method
5 comprising:
 - obtaining the seismic data from the marine seismic survey, wherein a source for the marine seismic survey comprises multiple sub-sources towed at two or more different depths and fired at distinct fire-time delays;
 - sorting the seismic data into common receiver gathers;
 - 10 transforming the common receiver gathers from horizontal source coordinates to horizontal wavenumbers;
 - constructing a matrix operator for a selected frequency; and
 - applying an inversion procedure to a system of equations based on the matrix operator to generate source-deghosted seismic data at the selected frequency.
- 15 2. The method of claim 1, wherein the matrix operator comprises an inverse spatial Fourier transform operator, a time-delay phase-shift operator per sub-source, and a ghost operator per sub-source.
- 20 3. The method of claim 2, wherein the matrix operator further comprises a summation over all sub-sources of a product of the ghost operator per sub-source and the time-delay phase-shift operator per sub-source.
4. The method of claim 2, wherein the ghost operator per sub-source comprises a
25 sinusoidal of a product of a vertical wave number and the depth of the sub-source.
5. The method of claim 1, wherein each sub-source of the multiple sub-sources has a fire-time delay that is distinct in that the fire-time delay for the sub-source is different from the fire-time delays of other sub-sources.

6. The method of claim 5, wherein the matrix operator comprises a time-delay phase-shift operator per sub-source, and wherein the time-delay phase-shift operator per sub-source comprises a phase shift that is proportional to the fire-time delay of the sub-source.
7. The method of claim 1, wherein the matrix operator comprises a summation over all sub-sources of a product of a ghost operator per sub-source and a time-delay phase-shift operator per sub-source, each sub-source has a fire-time delay that is different from the fire-time delays of other sub-sources, the time-delay phase-shift operator per sub-source comprises a phase shift that is proportional to the fire-time delay of the sub-source, and the ghost operator per sub-source comprises a sinusoidal of a product of a vertical wave number and the depth of the sub-source.
8. The method of claim 1, wherein an expression of the system of equations comprises a first vector of seismic data that is equal to a vector product of the matrix operator and a second vector of seismic data, wherein the inversion procedure solves for the second vector of seismic data.
9. An apparatus ~~method~~ for deghosting seismic data from a marine seismic survey, the apparatus comprising:
memory configured to store processor-executable code and data;
a processor configured to execute the computer-readable code so as to modify the data;
computer-readable code configured to sort seismic data from a marine seismic survey into common receiver gathers, wherein a source for the marine seismic survey comprises multiple sub-sources towed at two or more different depths and fired at distinct fire-time delays;
computer-readable code configured to transform the common receiver gathers from horizontal source coordinates to horizontal wavenumbers;

computer-readable code configured to construct a matrix operator for a selected frequency; and

computer-readable code configured to apply an inversion procedure to a system of equations based on the matrix operator to generate source-deghosted seismic data at
5 the selected frequency.

10. The apparatus of claim 9, wherein the matrix operator comprises an inverse spatial Fourier transform operator, a time-delay phase-shift operator per sub-source, and a ghost operator per sub-source.

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11. The apparatus of claim 10, wherein the matrix operator further comprises a summation over all sub-sources of a product of the ghost operator per sub-source and the time-delay phase-shift operator per sub-source.

15 12. The apparatus of claim 10, wherein the ghost operator per sub-source comprises a sinusoidal of a product of a vertical wave number and the depth of the sub-source.

13. The apparatus of claim 10, wherein each sub-source of the multiple sub-sources has a fire-time delay that is distinct in that the fire-time delay for the sub-source is
20 different from the fire-time delays of other sub-sources.

14. The apparatus of claim 13, wherein the time-delay phase-shift operator per sub-source comprises a phase shift that is proportional to the fire-time delay of the sub-source.

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15. The apparatus of claim 9, wherein the matrix operator comprises a summation over all sub-sources of a product of a ghost operator per sub-source and a time-delay phase-shift operator per sub-source, each sub-source has a fire-time delay that is different from the fire-time delays of other sub-sources, the time-delay phase-shift
30 operator per sub-source comprises a phase shift that is proportional to the fire-time

delay of the sub-source, and the ghost operator per sub-source comprises a sinusoidal of a product of a vertical wave number and the depth of the sub-source.

16. The apparatus of claim 9, wherein an expression of the system of equations
5 comprises a first vector of seismic data that is equal to a vector product of the matrix operator and a second vector of seismic data, wherein the inversion procedure solves for the second vector of seismic data.

17. At least one tangible computer-readable storage medium with executable code
10 stored thereon which, when executed by one or more processors, performs steps comprising:

obtaining the seismic data from the marine seismic survey, wherein a source for the marine seismic survey comprises multiple sub-sources towed at two or more different depths and fired at distinct fire-time delays;

15 sorting the seismic data into common receiver gathers;

transforming the common receiver gathers from horizontal source coordinates to horizontal wavenumbers;

constructing a matrix operator for a selected frequency; and

applying an inversion procedure to a system of equations based on the matrix
20 operator to generate source-deghosted seismic data at the selected frequency.

18. The at least one tangible computer-readable storage medium of claim 17,
wherein the matrix operator comprises an inverse spatial Fourier transform operator, a time-delay phase-shift operator per sub-source, and a ghost operator per sub-source.

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19. The at least one tangible computer-readable storage medium of claim 18,
wherein the matrix operator further comprises a summation over all sub-sources of a product of the ghost operator per sub-source and the time-delay phase-shift operator per sub-source.

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20. The at least one tangible computer-readable storage medium of claim 17, wherein each sub-source of the multiple sub-sources has a fire-time delay that is distinct in that the fire-time delay for the sub-source is different from the fire-time delays of other sub-sources.