CLAIMS

1. An optical seismic surveying system comprising:

a multibeam laser source including a plurality of laser sources and a Diffractive Optical Element, said plurality of laser sources configured to direct respective laser beams toward a single common focal point, said Diffractive Optical Element being located at said single common focal point, said Diffractive Optical Element configured to split each of said laser beams into a plurality of laser beams and to direct said laser beams toward an instantaneous area of interest, said laser beams impinging on said instantaneous area of interest and producing a laser spot assemblage, said laser spot assemblage including a plurality of laser spots;

an imager, directed toward said instantaneous area of interest, said imager including an optical arrangement and an imaging sensor, said imager configured to acquire a plurality of defocused images of speckle patterns produced by diffused reflections of said laser spots from said instantaneous area of interest toward said imager, each speckle pattern corresponding to a respective laser spot and thus to a respective sensing point in said instantaneous area of interest; and

a processor, coupled with said imager, said processor configured to determine a relative displacement between corresponding speckle patterns in sequential pairs of images, said processor further configured to determine a respective time signal for each sensing point representing vibrations thereat from said relative displacement between speckles patterns respective of each sensing point.

2. The seismic surveying system according to claim 1, wherein said a reference frame associated with said Diffractive Optical Element exhibits an axial orientation relative to a reference frame associated with said multibeam laser source.

3. The seismic surveying system according to claim 1, wherein said optical arrangement at least includes at least one cylindrical lens, thereby compressing a field of view of said imager.

4. The seismic surveying system according to claim 1, wherein said optical arrangement includes a rectangular aperture and a narrow pass filter, and

wherein said optical arrangement is telecentric.

5. The seismic surveying system according to claim 1, wherein said optical arrangement includes an apertures matrix.

6. The seismic surveying system according to claim 1, further including a tracking module, coupled with said processor and configured to provide information relating to position and orientation of said seismic surveying system and information relating to motion of said seismic surveying system.

7. The seismic surveying system according to claim 6, wherein said system scans an area of interest

8. The seismic surveying system according to claim 7, wherein said system employs one of along-track scanning and step-stare scanning.

9. The system according to claim 7, wherein said processor compensating effects of common motion on displacement of each of said speckle patterns.

10. The system according to claim 9, wherein said compensating said effects of common motion includes the following:

$$\vec{s}(t) = \vec{S}(t) - M\left[M^{T}M\right]^{-1}M^{T}\vec{S}(t)$$

wherein $\vec{s}(t)$ relates to displacement of a speckle pattern corresponding to laser spots only due to seismic vibration, $\vec{S}(t)$ relates to displacement of said speckle pattern corresponding to both common motion and seismic vibrations and M is a motion compensation matrix.

11. The seismic surveying system according to claim 6, wherein said tracking module includes a platform motion detector and a platform location detector,

wherein, said platform location detector provides information relating to said position of said system in a reference coordinate system, and

wherein said platform motion detector provides information relating to linear and angular motion of said system.

12. The seismic surveying system according to claim 11, wherein said platform location detector includes a Global Positioning System receiver operable to receive signals from GPS satellites and produce information relating to said position of said system.

13. The seismic surveying system according to claim 11, wherein said platform motion detector is an Inertial Measurement Unit, which includes accelerometers providing information relating to linear acceleration of said system and gyroscopes, which provide information relating to angular acceleration of said system.

14. The seismic surveying system according to claim 1, wherein said processor further determines a distance between said imager and each of said plurality of laser spots.

15. The seismic surveying system according to claim 14, wherein said distance between said imager and a laser spot is determined from shift of a speckle pattern corresponding to said laser spot, said shift of a speckle pattern caused by a known angular displacement of a laser beam corresponding to said laser spot, and

Wherein said distance is determined according to:

$$S \cong \frac{M}{P} \cdot \alpha \cdot \left(Z \cdot \frac{L - R}{L - Z} + R \right)$$

where S is a speckle pattern shift in units of pixels, M is a magnification of said imager, P is a size of a pixel, α is an angle between directions of said multibeam laser source, Z is a range from a waist of said beam to a rotation axis of said multibeam laser source, L is distance between said imager and said instantaneous area of interest, and R is a range between said imager and a focal plane of said imager.

16. The seismic surveying system according to claim 1, wherein said processor further generates a seismic image of an area of interest on

which representations of objects detected in said area of interest are superimposed on a map or an image of said area of interest.

17. The seismic surveying system according to claim 1, wherein said processor further configured to produce a seismic map of an area of interest from time signals corresponding to each sensing point and to detect objects in said area of interest from said seismic map.

18. The seismic surveying system according to claim 17, wherein said processor further configured to generate a seismic image of said area of interest, said seismic image being at least one of an image and a geographical map of said area of interest with symbols representing detected underground objects superimposed thereon, at corresponding locations.

19. The seismic surveying system according to claim 1, wherein said multibeam laser source is a pulsed multibeam laser source, and

wherein said imager is synchronized with said pulsed multibeam laser source.

20. The seismic surveying system according to claim 1, wherein said laser sources in said multibeam laser source are divided into a plurality of groups of laser sources, each group includes at least one laser source, where each said group of laser sources is sequentially activated, and

Wherein said imager synchronously acquires images of said speckle patterns respective of each of said laser spots thereby increasing a detection resolution of said seismic surveying system.

21. The seismic surveying system according to claim 1, further including at least another imager, each of said imager and said at least another imager being sensitive at a respective wavelength, and

wherein said laser sources in said multibeam laser source are divided into a plurality of groups of laser sources, each group includes at least one laser source, each said group of laser sources is associated with a respective unique wavelength corresponding to a sensitivity of said imager and said another imager.

22. A seismic surveying method comprising the procedures of:

directing by a multibeam laser source a plurality of laser beams toward an instantaneous area of interest, said laser beams producing an assemblage of laser spots on said instantaneous area of interest;

acquiring a plurality of defocused images of speckle patterns produced by diffused reflections of said laser spots from an instantaneous area of interest, each speckle pattern corresponding to a respective laser spot and thus to a respective sensing point in said instantaneous area of interest;

determining relative displacements between corresponding speckle patterns in pairs of sequential images of received speckle patterns by:

estimating a course spatial displacement between said corresponding speckle patterns in each sequential pair of images;

aligning each pair of sequential images with each other according to said course spatial displacement estimation;

determining a fine relative spatial displacement between said corresponding speckle patterns in each pair of sequential images;

estimating a total relative spatial displacement between each pair of sequential images by combining said estimated coarse relative spatial displacement and said determined fine relative spatial displacement with a highest cross-correlation value; and

determining a respective time signal for each sensing point representing vibrations thereat from total relative displacements between speckle patterns respective of each sensing point.

23. The seismic surveying method according to claim 22, wherein said procedure of determining a fine spatial displacement between each pair of sequential images includes the sub-procedures of:

determining a frequency domain representation of each course aligned image;

for each sequential pair of images, applying a selected fine spatial displacement to one image at a selected resolution employing said frequency domain representation; and

for each sequential pair of finely displaced images, determining a cross-correlation value there between and repeating from said procedure applying a selected fine spatial displacement until a stop criterion is met.

24. The seismic surveying method according to claim 23, wherein said applying a selected fine relative spatial displacement between a pair of sequential images at a selected resolution is achieved by applying a phase shift to a frequency representation of one of said images,

where said phase shift corresponds to said selected fine relative spatial displacement at said selected resolution, by multiplying each element in said frequency domain representation by a selected complex phase shift coefficient.

25. The seismic surveying method according to claim 22, wherein said procedure of estimating a course spatial displacement between each sequential pair of images includes the sub-procedures of:

cross-correlating each of said sequential pair of images of said received speckle patterns, thereby generating a plurality of cross-correlation images;

for each one of said plurality of cross-correlation images, estimating a location of said cross-correlation peak in sub-pixel resolution, said location of said cross-correlation peak corresponds to said coarse relative spatial displacement estimation.

26. The seismic surveying method according to claim 25, wherein said procedure of estimating said cross-correlation peak location in sub-pixel resolution is achieved by employing pixel values of the cross-correlated image as sample points and fitting a selected function to these sample points, and

wherein a location of a maximum of said function corresponds to a location of said cross-correlation peak.

27. The seismic surveying method according to claim 22, further including the procedure of determining a distance between said imager and each of said laser spots.

28. The seismic surveying method according to claim 27, wherein said distance between said imager and a laser spot is determined from a shift of a speckle pattern corresponding to said laser spot, said shift of said speckle pattern caused by a known angular displacement of a laser beam corresponding to said laser spot, and

wherein said distance is determined according to:

$$S \cong \frac{M}{P} \cdot \alpha \cdot \left(Z \cdot \frac{L-R}{L-Z} + R \right)$$

where S is said shift in said speckle pattern in units of pixels, M is a magnification of said imager, P is a size of a pixel, α is an angle between directions of said multibeam laser source, Z is a range from a waist of said beam to the rotation axis of the multibeam laser source, L is a distance between said imager and said instantaneous area of interest, and R is the range between said imager and a focal plane of said imager.

29. The seismic surveying method according to claim 22, further including the procedures of:

producing a seismic map of an area of interest from time signals corresponding to each sensing point; and

detecting objects in said area of interest from said seismic map;

30. The seismic surveying method according to claim 29 further including the procedure of generating a seismic image of an area of interest, said seismic image being at least one of an image and a geographical map of said area of interest, with symbols representing detected underground objects superimposed thereon, at corresponding locations.

31. The method according to claim 22, further including the procedure of compensating effects of common motion on displacement of each of said speckle patterns.

32. The system according to claim 31, wherein said compensating said effects of common motion includes the following:

$$\vec{s}(t) = \vec{S}(t) - M\left[M^{T}M\right]^{-1}M^{T}\vec{S}(t)$$

wherein $\vec{s}(t)$ relates to displacement of a speckle pattern corresponding to laser spots only due to seismic vibration, $\vec{S}(t)$ relates to displacement of said speckle pattern corresponding to both common motion and seismic vibrations and M is a motion compensation matrix.

CLAIMS

1. An optical seismic surveying system comprising:

a multibeam laser source including a plurality of laser sources and a Diffractive Optical Element, said plurality of laser sources configured to direct respective laser beams toward a single common focal point, said Diffractive Optical Element being located at said single common focal point, said Diffractive Optical Element configured to split each of said laser beams into a plurality of laser beams and to direct said laser beams toward an instantaneous area of interest, said laser beams impinging on said instantaneous area of interest and producing a laser spot assemblage, said laser spot assemblage including a plurality of laser spots;

an imager, directed toward said instantaneous area of interest, said imager including an optical arrangement and an imaging sensor, said imager configured to acquire a plurality of defocused images of speckle patterns produced by diffused reflections of said laser spots from said instantaneous area of interest toward said imager, each speckle pattern corresponding to a respective laser spot and thus to a respective sensing point in said instantaneous area of interest; and

a processor, coupled with said imager, said processor configured to determine a relative displacement between corresponding speckle patterns in sequential pairs of images, said processor further configured to determine a respective time signal for each sensing point representing vibrations thereat from said relative displacement between speckles patterns respective of each sensing point.

2. The seismic surveying system according to claim 1, wherein said optical arrangement comprises one or more of:

(i) at least one cylindrical lens, thereby compressing a field of view of said imager,

(ii) a rectangular aperture and a narrow pass filter, and wherein said optical arrangement is telecentric, and

(iii) an apertures matrix.

3. The seismic surveying system according to claim 1, further including a tracking module, coupled with said processor and configured to provide information relating to position and orientation of said seismic surveying system and information relating to motion of said seismic surveying system.

4. The seismic surveying system according to claim 1, wherein said system is configured to employ one of along-track scanning and step-stare scanning.

5. The system according to claim 3, wherein said processor compensating effects of common motion on displacement of each of said speckle patterns.

6. The seismic surveying system according to claim 3, wherein said tracking module includes a platform motion detector and a platform location detector,

wherein, said platform location detector provides information relating to said position of said system in a reference coordinate system, and

wherein said platform motion detector provides information relating to linear and angular motion of said system.

7. The seismic surveying system according to claim 6, wherein said platform location detector includes a Global Positioning System receiver operable to receive signals from GPS satellites and produce information relating to said position of said system.

8. The seismic surveying system according to claim 6, wherein said platform motion detector is an Inertial Measurement Unit, which includes accelerometers providing information relating to linear acceleration of said system and gyroscopes, which provide information relating to angular acceleration of said system.

9. The seismic surveying system according to claim 1, wherein said processor:

(i) further determines a distance between said imager and each of said plurality of laser spots, and/or

(ii) further generates a seismic image of an area of interest on which representations of objects detected in said area of interest are superimposed on a map or an image of said area of interest, and/or

(iii) further configured to produce a seismic map of an area of interest from time signals corresponding to each sensing point and to detect objects in said area of interest from said seismic map, and/or

(iv) further configured to generate a seismic image of said area of interest, said seismic image being at least one of an image and a geographical map of said area of interest with symbols representing detected underground objects superimposed thereon, at corresponding locations.

10. The seismic surveying system according to claim 1, wherein said processor further determines a distance between said imager and each of said plurality of laser spots, wherein said distance between said imager and a laser spot is determined from shift of a speckle pattern corresponding to said laser spot, said shift of a speckle pattern caused by a known angular displacement of a laser beam corresponding to said laser spot, and

Wherein said distance is determined according to:

$$S \cong \frac{M}{P} \cdot \alpha \cdot \left(Z \cdot \frac{L-R}{L-Z} + R \right)$$

where S is a speckle pattern shift in units of pixels, M is a magnification of said imager, P is a size of a pixel, α is an angle between directions of said multibeam laser source, Z is a range from a waist of said beam to a rotation axis of said multibeam laser source, L is distance between said imager and said instantaneous area of interest, and R is a range between said imager and a focal plane of said imager.

11. The seismic surveying system according to claim 1, wherein said multibeam laser source is a pulsed multibeam laser source, and

wherein said imager is synchronized with said pulsed multibeam laser source.

12. The seismic surveying system according to claim 1, wherein said laser sources in said multibeam laser source are divided into a plurality of groups of laser sources, each group includes at least one laser source, where each said group of laser sources is sequentially activated, and

Wherein said imager synchronously acquires images of said speckle patterns respective of each of said laser spots thereby increasing a detection resolution of said seismic surveying system.

13. The seismic surveying system according to claim 1, further including at least another imager, each of said imager and said at least another imager being sensitive at a respective wavelength, and

wherein said laser sources in said multibeam laser source are divided into a plurality of groups of laser sources, each group includes at least one laser source, each said group of laser sources is associated with a respective unique wavelength corresponding to a sensitivity of said imager and said another imager.

14. A seismic surveying method comprising the procedures of:

directing by a multibeam laser source a plurality of laser beams toward an instantaneous area of interest, said laser beams producing an assemblage of laser spots on said instantaneous area of interest;

acquiring a plurality of defocused images of speckle patterns produced by diffused reflections of said laser spots from an instantaneous area of interest, each speckle pattern corresponding to a respective laser spot and thus to a respective sensing point in said instantaneous area of interest;

determining relative displacements between corresponding speckle patterns in pairs of sequential images of received speckle patterns by:

estimating a course spatial displacement between said corresponding speckle patterns in each sequential pair of images;

aligning each pair of sequential images with each other according to said course spatial displacement estimation;

determining a fine relative spatial displacement between said corresponding speckle patterns in each pair of sequential images;

estimating a total relative spatial displacement between each pair of sequential images by combining said estimated coarse relative spatial displacement and said determined fine relative spatial displacement with a highest cross-correlation value; and

determining a respective time signal for each sensing point representing vibrations thereat from total relative displacements between speckle patterns respective of each sensing point.

15. The seismic surveying method according to claim 14, wherein said procedure of determining a fine spatial displacement between each pair of sequential images includes the sub-procedures of:

determining a frequency domain representation of each course aligned image;

for each sequential pair of images, applying a selected fine spatial displacement to one image at a selected resolution employing said frequency domain representation; and

for each sequential pair of finely displaced images, determining a cross-correlation value there between and repeating from said procedure applying a selected fine spatial displacement until a stop criterion is met.

16. The seismic surveying method according to claim 14, wherein said procedure of estimating a course spatial displacement between each sequential pair of images includes the sub-procedures of:

cross-correlating each of said sequential pair of images of said received speckle patterns, thereby generating a plurality of cross-correlation images;

for each one of said plurality of cross-correlation images, estimating a location of said cross-correlation peak in sub-pixel resolution, said location of said cross-correlation peak corresponds to said coarse relative spatial displacement estimation.

17. The seismic surveying method according to claim 14, further including the procedure of determining a distance between said imager and each of said laser spots.

18. The seismic surveying method according to claim 17, wherein said distance between said imager and a laser spot is determined from a shift of a speckle pattern corresponding to said laser spot, said shift of said speckle pattern caused by a known angular displacement of a laser beam corresponding to said laser spot, and

wherein said distance is determined according to:

$$S \cong \frac{M}{P} \cdot \alpha \cdot \left(Z \cdot \frac{L-R}{L-Z} + R \right)$$

where S is said shift in said speckle pattern in units of pixels, M is a magnification of said imager, P is a size of a pixel, α is an angle between directions of said multibeam laser source, Z is a range from a waist of said beam to the rotation axis of the multibeam laser source, L is a distance between said imager and said instantaneous

area of interest, and R is the range between said imager and a focal plane of said imager.

19. The seismic surveying method according to claim 14, further including the procedures of:

producing a seismic map of an area of interest from time signals corresponding to each sensing point; and

detecting objects in said area of interest from said seismic map;

20. The seismic surveying method according to claim 19 further including the procedure of generating a seismic image of an area of interest, said seismic image being at least one of an image and a geographical map of said area of interest, with symbols representing detected underground objects superimposed thereon, at corresponding locations.

21. The method according to claim 14, further including the procedure of compensating effects of common motion on displacement of each of said speckle patterns.

22. The system according to claim 21, wherein said compensating said effects of common motion includes the following:

$$\vec{s}(t) = \vec{S}(t) - M\left[M^T M\right]^{-1} M^T \vec{S}(t)$$

wherein $\vec{s}(t)$ relates to displacement of a speckle pattern corresponding to laser spots only due to seismic vibration, $\vec{S}(t)$ relates to displacement of said speckle pattern corresponding to both common motion and seismic vibrations and M is a motion compensation matrix.