

Aug. 12, 1969

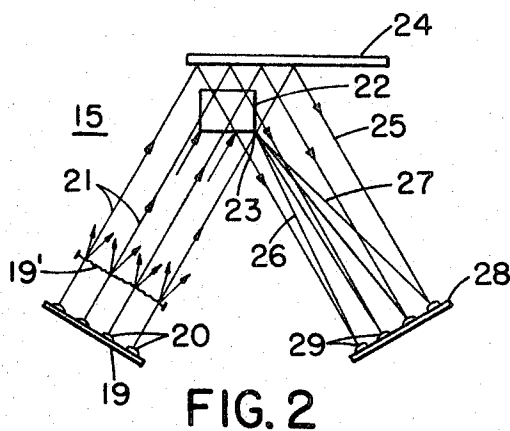
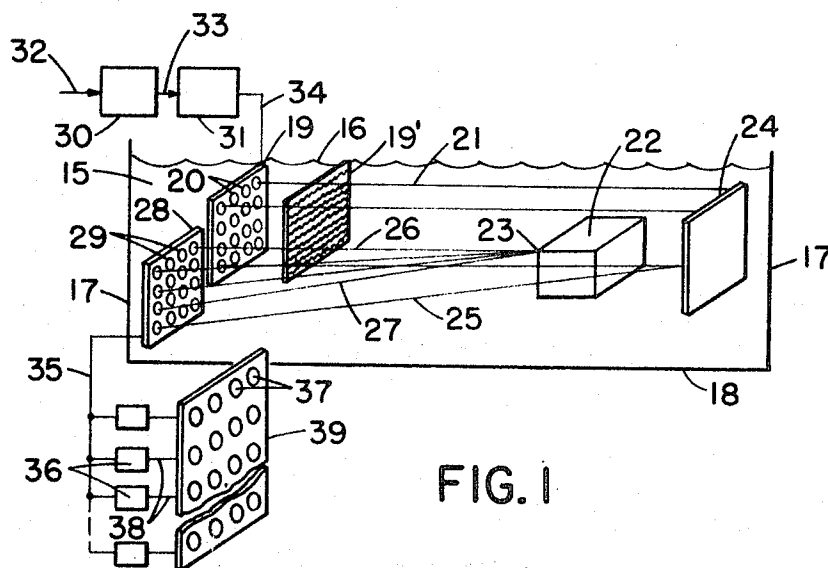
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3,461,420

WAVELET RECONSTRUCTION PROCESS OF INCREASED RESOLUTION

Filed Jan. 3, 1967

6 Sheets-Sheet 1



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WAVELET RECONSTRUCTION PROCESS OF INCREASED RESOLUTION

Filed Jan. 3, 1967

6 Sheets-Sheet 2

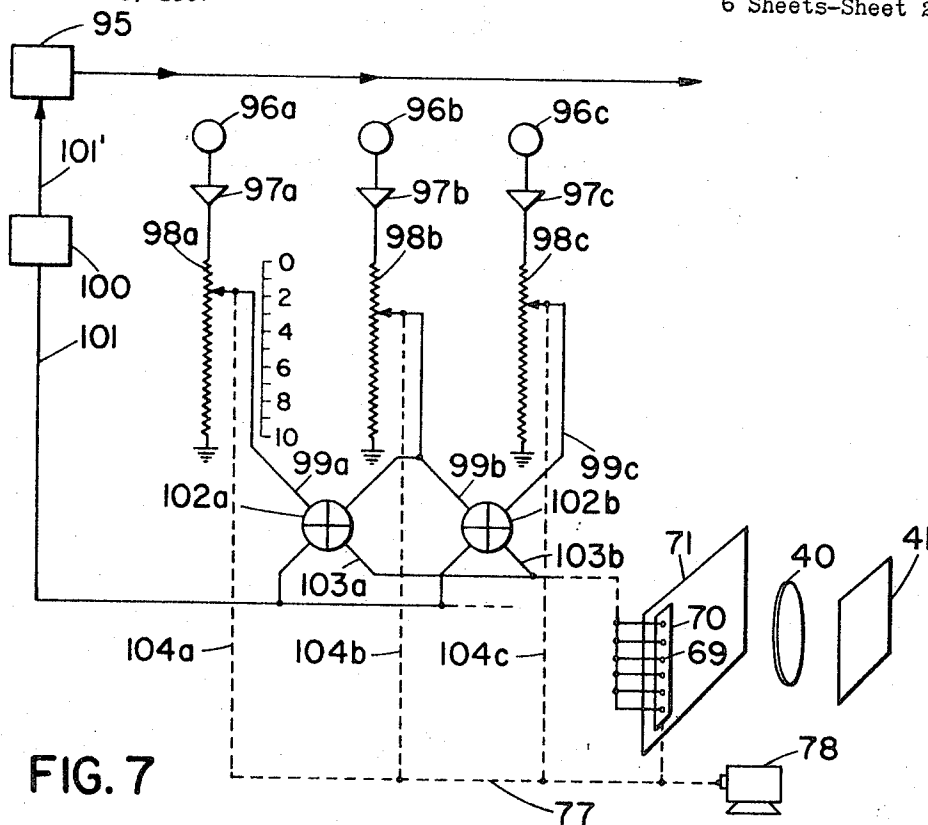


FIG. 7

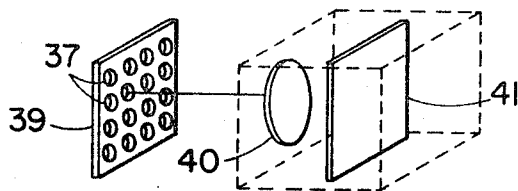


FIG. 3

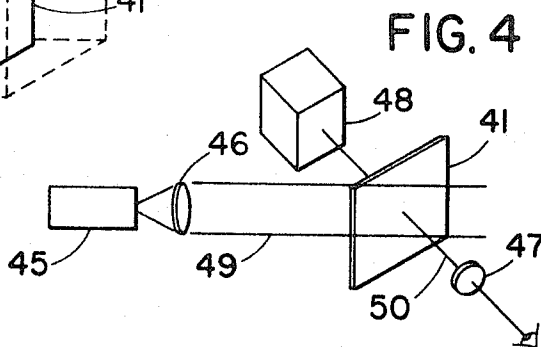


FIG. 4

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Filed Jan. 3, 1967

6 Sheets-Sheet 3

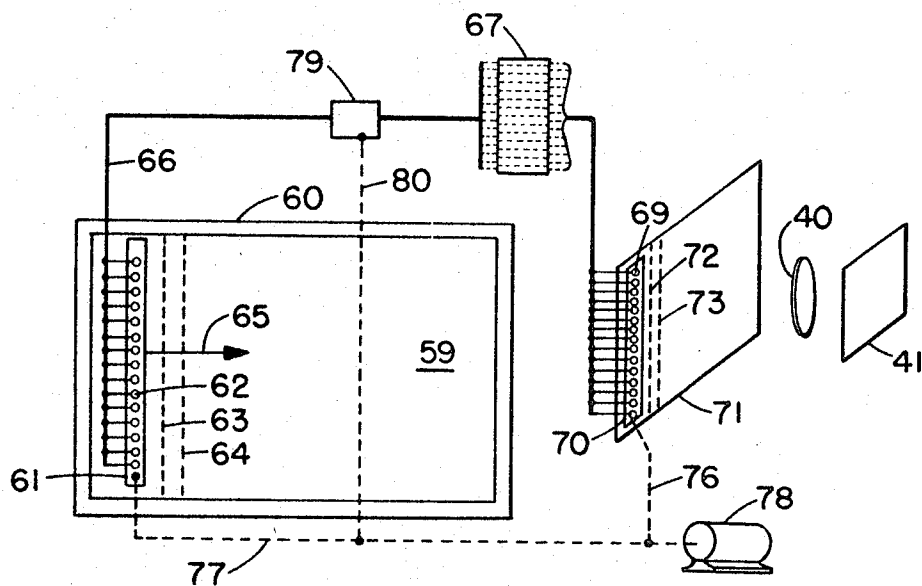


FIG. 5

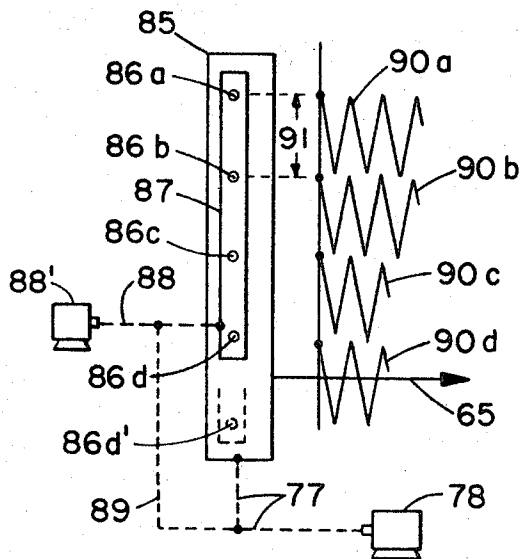


FIG. 6

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6 Sheets-Sheet 4

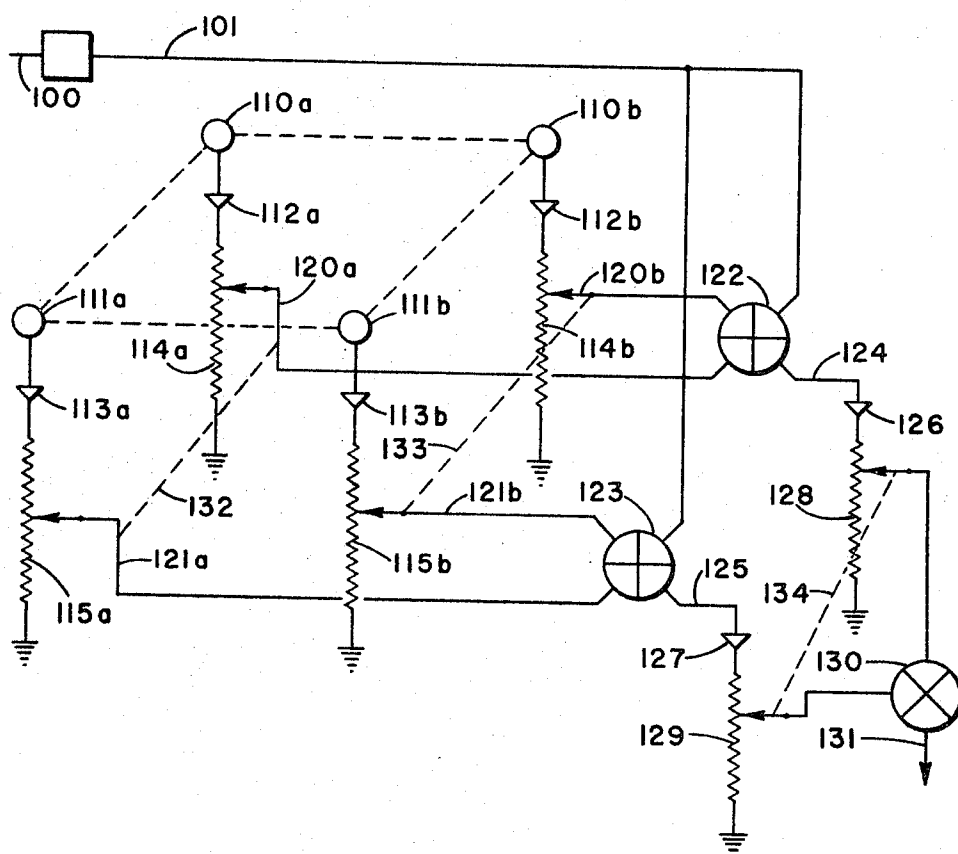


FIG. 8

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WAVELET RECONSTRUCTION PROCESS OF INCREASED RESOLUTION

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6 Sheets-Sheet 6

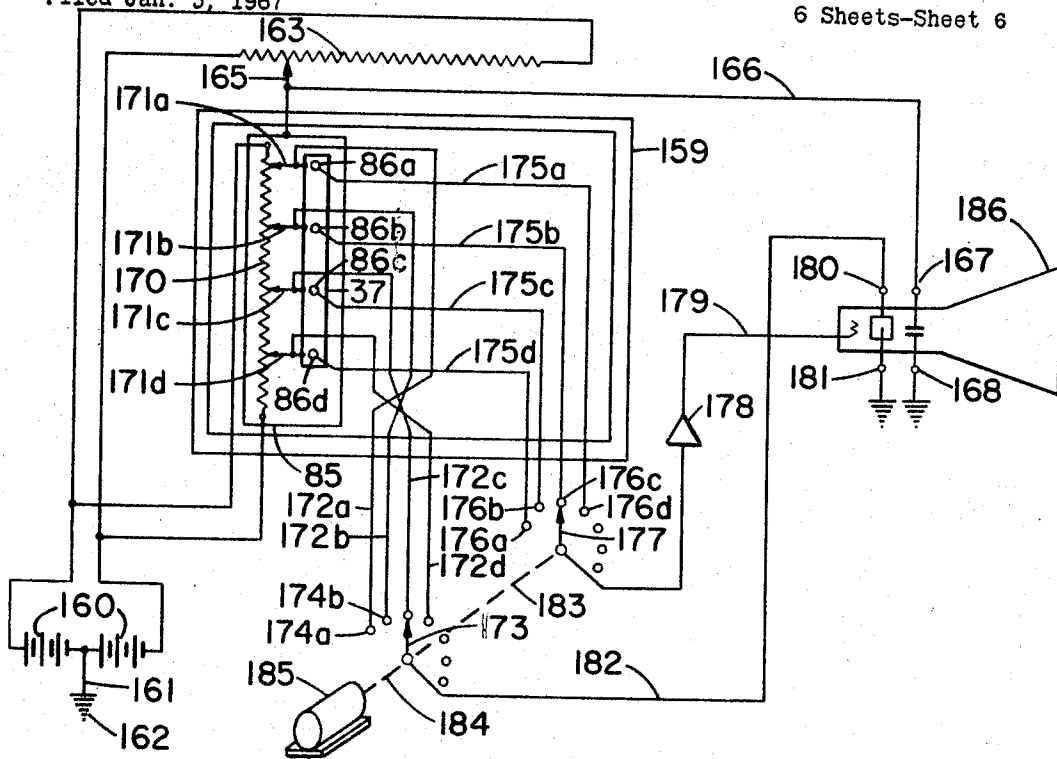


FIG. 11

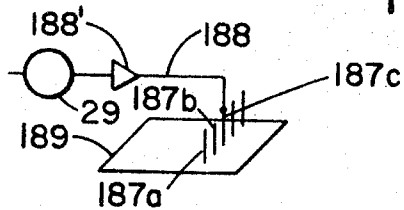


FIG. 12

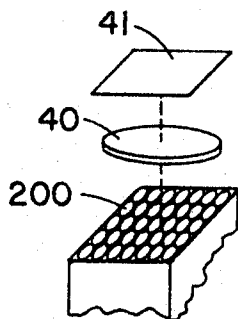


FIG. 14

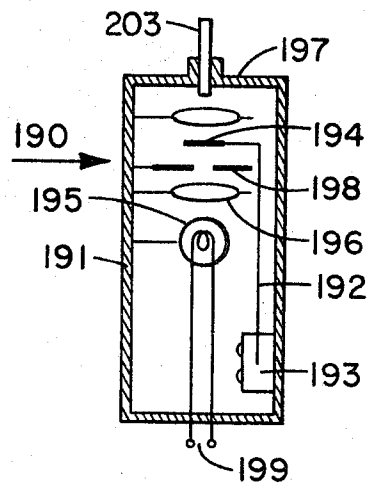


FIG. 13

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3,461,420

WAVELET RECONSTRUCTION PROCESS OF INCREASED RESOLUTION

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Continuation-in-part of application Ser. No. 512,689, Dec. 9, 1965. This application Jan. 3, 1967, Ser. No. 606,690

Int. Cl. G01s 9/66

U.S. Cl. 340—1

32 Claims 10

ABSTRACT OF THE DISCLOSURE

An object in an optically opaque medium is irradiated by continuous-wave energy that the medium transmits efficiently, such as sound waves in water, for example. This produces over a detection area an interference pattern of direct and reflected waves, which is translated into a proportional exposure on photographic film. Viewing the developed film as a hologram in coherent (laser) light reveals the object. When arrays of spaced point receivers and corresponding modulated point light sources are scanned so as to traverse every point of the detection and film areas, increased resolution is achieved, showing more details of the object.

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of my co-pending application Ser. No. 512,689, now Patent No. 3,400,363 entitled "Wavelet Reconstruction Process for Sonic, Seismic and Radar Exploration," filed Dec. 9, 1965.

BACKGROUND OF THE INVENTION

This invention pertains to the art of scanning or mapping the contour of three-dimensional objects or surfaces hidden from view. More particularly, the invention is directed to the use of coherent waves that can be transmitted through media which are opaque to visible radiation. Further, it is concerned with the utilization of principles of wavefront reconstruction for viewing the topography of a surface or object that can be irradiated with wave energy that is coherent in time and space, which object or surface can reflect and diffract this wave energy to an array of detectors. Specifically, this invention is directed to detecting and recording coherent wave energy and to ways of increasing the resolution of the resulting hologram when a limited number of detectors is in use. The wave energy can be acoustic or elastic in form, and the object or surface can be immersed in any contrasting medium such as water or earth, so long as it can reflect and diffract this energy.

For convenience the invention will be described in terms of its application in sonic exploration in a fluid medium such as water. Briefly described, as the energy source I use a generator of continuous sound waves of some desired frequency, preferably distributed over a two-dimensional plane surface. This creates a substantially parallel beam of sound energy that is coherent in time and space. Means such as a reflecting plane surface is placed in the path of this beam to direct part of the sonic energy to an areal detector, such as an array of transducer distributed over a two-dimensional plane. The areal detector acting as a transducer provides, as a corresponding distribution over its area or over a pattern or grid of points corresponding to the point transducers, voltages which can be used to control the illumination output either of a corresponding array of light emitters, such as glow lamps, for example, arranged in the same pattern as the detector transducers, or of a moving point or array

of point sources of light adapted to traverse all points in said pattern in sequence. The amount of light at each point in the luminous pattern is a direct function of the intensity of the sonic energy at the corresponding point in the areal detector pattern. A photographic transparency record or photograph is made of the average light intensity at each point in the lamp or grid pattern.

The source of sonic energy can be a multiplicity of point sound sources arranged in an areal array and supplied with electrical energy at a constant frequency. However, under certain circumstances, it is possible to use a point source of sonic energy forming a divergent beam of sound. If a two-dimensional source is used to provide a parallel beam, the grid or array spacings are preferably uniform, so that the sonic energy in the emitted beam will be coherent both in space and in time. Energy returned by the plane reflector to the detector array will thus represent a constant or regular pattern of intensity, depending upon the actual length of path, measured in sonic wave lengths in the surrounding medium, from the source to the plane reflector and thence to the areal detector, of each pencil of energy in the beam.

Now, if a three-dimensional object also exists in or is inserted into the beam, the object too will reflect and diffract some of the coherent energy back to the areal detector. Thus, the intensity of the sonic energy at each point of the areal detector array will be a combination of the regular pattern of the plane-reflected beam and of the irregular pattern of energy of the reflected and diffracted rays representative of the particular three-dimensional object. If the sonic energy in the plane-reflected beam were not present at the detector, the energy pattern of the object-reflected and diffracted waves would be representative of the object; but this pattern would be difficult to interpret, since these energy values would be scalar values. By modulating or combining these values with the regular pattern of values of the plane-reflected beam, the latter in a sense provides a phase reference, so that the object-reflected and diffracted waves, as detected, now contain phase information as well as amplitude data.

If these resultant values of amplitude of the sonic wave signal at each detector point are converted to corresponding luminous energy, or intensity, then a photograph of the areal pattern of this luminous intensity will be the equivalent of the optical "hologram" that is used in the wavefront reconstruction process with coherent light. As in the case of optical holography, this photographic record can be viewed in coherent light to present a visible display of a three-dimensional image of the reflecting object surface, for direct viewing or photographic recording in the normal sense.

Instead of positioning the source and receiver so that reflected waves are received from the object and from a plane reflector, it is possible to transmit energy from the source past the object to the detector. The detector then receives diffracted wave energy from the object, modulated by directly transmitted wave energy, to make a final presentation that can be viewed in the nature of a silhouette of the object irradiated by the sonic source.

Also, since the wave energy is generated at the primary source by appropriate transducers actuated from a common source of electrical frequency control, the modulating coherent wave motion at the detector array can be provided by a secondary source controlled from the same common frequency control as the primary wave-energy source. Or conversely, the modulation or biasing of the reflected or diffracted waves from the object can be provided by electrically combining signals from the electrical frequency source with each of the electrical outputs of the areal detector transducers that convert the

received sonic energy into corresponding electrical energy.

Also contemplated is the use of two similarly oriented but somewhat spaced apart detector arrays, each receiving sonic energy both from the object and from the modulation or reference beam. Two images can then be observed in the final image reconstruction step to form a stereo pair that will make possible a determination of the distance to and the size of the visualized object.

I contemplate still further applications of these principles, such as the mapping of three-dimensional reflecting surfaces in the earth by seismic waves generated by a coherent source of such waves. The wave-energy detectors can also be used in various arrays, and their outputs can be recorded either simultaneously or sequentially. Thus, by moving the detectors and recording their outputs while the initiation and transmission conditions are held constant, a record is obtained with more data points than there are detectors, with a resulting increase in the resolution of the method, showing more details of the object being visualized.

SUMMARY OF THE INVENTION

In other words, when a limited number of detectors and light sources are used in arrays for forming a hologram by translating the wave energy received over a detection area into a visible pattern on film, for illumination by coherent light to view an object, the resolution and thus the amount of visible detail in the object is limited. In accordance with this invention, this limitation is avoided by imparting a scanning motion to the receivers of the array, and to the corresponding array of light sources modulated by the respective receivers, so that each point of the entire detection and film areas is traversed, to produce the effect of an almost infinite number of detection points uniformly spread over the area. As an alternative, spaced-point data may be smoothed by an electrical interpolation procedure.

BRIEF DESCRIPTION OF THE DRAWINGS

These principles and their applications will be better understood by reference to the accompanying drawings illustrating certain preferred and other embodiments of the invention.

In these drawings:

FIGURE 1 is a diagrammatic illustration of a body of water in cross section, with an embodiment of the invention shown diagrammatically in perspective in operation therein;

FIGURE 2 is a diagrammatic plan view of the transmitting and receiving apparatus of FIGURE 1;

FIGURE 3 is a diagrammatic illustration of the making of a hologram for optical viewing;

FIGURE 4 is a diagrammatic view of apparatus for reconstructing an image of the object to be viewed;

FIGURES 5 and 6 are diagrammatic illustrations of two embodiments in which a limited number of detectors are sequentially repositioned and their outputs are recorded, while keeping the wave energy field constant, to provide a hologram with the effect of more data points than detectors;

FIGURES 7 and 8 diagrammatically illustrate two methods by which the signals from relatively widely spaced detectors may be smoothed to minimize the effects of spacing;

FIGURES 9 and 10 diagrammatically illustrate how reproducibly recording the outputs of the detectors and the reference coherent signal permits later combination of the recorded data;

FIGURE 11 is a diagrammatic illustration of an adaptation of the embodiments of FIGURES 5 and 6 to recording by a cathode-ray tube;

FIGURE 12 is a diagrammatic illustration of the recording of detector outputs by electrographic means; and

FIGURES 13 and 14 show diagrammatically a type

of wave detector for modulating a self-contained light source and transmitting the resultant modulated light to a recorder.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings and particularly to FIGURE 1, I show therein a body of water 15, having a surface 16, lateral boundaries 17, and bottom 18. Although for illustrative purposes these boundaries are shown close in to the apparatus, they would in practice be at such a great distance as to minimize boundary reflections in the body of water 15.

Immersed in water 15 is a three-dimensional object 22 which it is desired to map, picture, display or observe. Also immersed in water 15 at some distance from object 22 is a source 19 of coherent sonic energy formed of a multiplicity of transducers 20 mounted in a plane supporting framework and arranged in a regularly spaced rectangular pattern or grid. Each of transducers 20 converts electrical signals into sonic waves in the water 15. These transducers may be electro-dynamic, piezo-electric, or similar devices such as are commercially available for underwater sonic signaling. As the sonic frequency must be maintained very constant, it is preferably provided by a quartz-crystal controlled device 30, or other well known clock signal source provided with electrical power over a lead 32, the constant-frequency output signal being taken by lead 33 to power amplifier 31 and thence by leads of a cable 34 to each of the individual transducer units 20. While I have shown here a two-dimensional array of source elements 20 such as to provide a plane wavefront of coherent wave energy, it is also satisfactory to use a point source of wave energy and to consider that it produces a spherical wavefront of coherent energy irradiating the object 22.

The aerial detector or receiver array 28 is preferably similarly formed, as a plane array of individual receiving transducers 29 supported by a suitable framework similar to array 19, for converting received sonic energy into corresponding electrical energy. Like transmitting transducers 20, individual transducers 29 are preferably mounted in their supporting framework regularly spaced in a rectangular grid. The spacing of units 29 in detector array 28 may be either the same as or different from the spacing of units 20 in array 19. It will be understood that the most detailed data will be provided by closely spacing a very large number of the units 29, but is the essence of this invention as will be subsequently explained, to achieve the resolution effects of an almost unlimited number of closely spaced detectors 29 by applying a scanning motion to a limited number of such detectors.

The individual receiving transducer units 29 are connected by leads of a cable 35 to as many individual amplifiers 36 as may be needed to provide one amplifier for each transducer unit, the respective output of which amplifiers 36 are carried by leads 38 to corresponding luminous sources 37. Each of luminous sources 37, which can be a glow tube, cathode ray device, or galvanometer with appropriate mask, as is well known in the art, provides an intensity of light output within a small area which varies directly with the voltage output of the corresponding one of the detector units 29, which latter voltage varies directly with the amplitude and polarity of the varying sonic pressure at the corresponding position in water 15. Luminous sources 37 are also arranged in a regularly spaced rectangular array or grid 39, with spacings which correspond, with any desired proportional scale, to the spacing of transducer units 29. Thus, at the luminous array 39, a distribution or pattern of light intensity over the entire grid of luminous sources 37 is formed, which to any desired linear scale represents the intensity pattern of sonic pressure in water 15 in the plane of detector array 28.

As is shown in FIGURE 3, the pattern of light on array or grid 39 is imaged by a lens 40 and recorded in conventional form on a photographic sheet or film 41. Since the pressure variations in water 15 are alternating in form due to the wave-form output of source array 19, it will be understood that a voltage bias is required in amplifiers 36, so that a varying uni-directional voltage is applied to each of luminous sources 37. Thus, the photographic exposure of film 41 must be such as to take this variation into account. It could be a very short exposure at a peak of intensity of the luminous array 39; or, by restricting the aperture of lense 40, it could be made as a time exposure that includes one or more complete cycles of variation of the luminous intensity, that is, one or more complete periods of the sonic signal of source array 19.

In FIGURE 2 is shown a plan view of the embodiment of FIGURE 1. As is apparent here, the source array 19 of individual transducers 20 sends out a substantially plane-wave beam 21. As will be understood, this requires the linear dimensions of the array 19 to be equivalent to a number of wave lengths of the sonic signal in water 15. Reflector 24 is a plane wall of any material with an acoustic impedance differing from water 15, so that it will reflect a substantial part of the sonic energy incident upon it, such material as rock, brick, metal or possibly wood serving this purpose. Also, the dimensions of reflector 24 should be comparable to the dimensions of detector array 28, which are also comparable or similar to the dimensions of source array 19. When detector units 29 are maintained in fixed positions, the spacing of individual unit sources 20 and detectors 29 should preferably be a fraction of the sonic wave length, such as from the order of $\frac{1}{10}$ or less of a wave length to a maximum of about a half wave length of the sonic signal in water 15. The smaller the spacing of the individual units, and thus the greater the total number of transmitting and receiving transducers 20 and 29, the higher will be the resolution of the resulting image on the film 41.

With source 19 continuously emitting acoustic energy in a beam 21, the reflector 24 reflects a beam of this energy 25 to detector 28. Also, three-dimensional object 22, from all points of its surface such as point 23, reflects and scatters or diffracts sonic energy incident upon it from source 19, some of this energy reaching detector 28 by paths 26 and 27. As will be understood, the more extensive and diffuse is the surface of object 22, the greater is the amount of scattered energy that it returns to detector 28; and energy from each scattering or diffracting point or small area of object 22 returns to the entire surface of detector 28. Thus, each individual transducer unit 29 receives energy from reflector 24 and from all diffracting or scattering points on the surface of object 22. The resultant sonic pressure, and corresponding light intensity of each individual luminous source 37, is thus the resultant of the sonic energy reaching each individual receiver unit 29 by all possible paths.

In FIGURE 4 I show how the photographic film or record 41 is used after it is exposed and developed. Film 41 now carries a pattern of transparent and opaque points or small areas, each representing a corresponding one of detecting transducers 29, and by its photographic density or blackness, representing the resultant intensity of sonic energy at the corresponding particular transducer 29. This is a standing-wave pattern of intensity. Due to the coherence of the sonic energy of source 19, every interval of time equal to the period of this energy provides an identical resultant pressure at receiver 28, which represents the reflection and diffraction pattern of energy from the object 22 modulated or modified by the reference energy received from source 19 via reflector 24. This film or record 41 can then be called a hologram, by similarity with the corresponding system of wavefront reconstruction in optics with coherent light. A description of the principles of wavefront construction with vis-

ible coherent light is given by Emmett N. Leith and Juris Upatnieks in Scientific American, June 1965, vol. 212, No. 6, in an article entitled, "Photography by Laser."

If a hologram is viewed while illuminated by coherent light, a real and/or a virtual image of an object will become visible to the eye or can be photographed. This is shown in FIGURE 4, where the laser 45 and lens 46 provide a beam 49 of coherent light in the visible range of the spectrum. Transparency or film 41 is placed in this beam. When the beam-illuminated film 41 is viewed from a proper position, such as along the line 50, a virtual image is formed at position 48. This image can be focused by a lens 47 and photographed, or it can be viewed by placing the eye of the observer at the position of lens 47.

The virtual image 48 shows the surface of object 22 in three dimensions. The object 22 can be a stationary underwater object such as an obstacle to shipping, for example, a rock projection or a sunken ship's hull. Or, in some instances, it may be a moving object such as a submarine, provided the motion is not so rapid as to exceed a small fraction of the sonic wave length during the time of recording the pressure-wave pattern and the corresponding record film 41. Assuming that the sonic waves are of sufficient intensity to permit this, a series of record films 41 may be made in the manner of a moving picture, developed and viewed in sequence, to get a continuing picture of the movement of the object. If desired, the photographic record film 41 can be photochromic in nature, in which case the varying pattern of transparency forms during the making of the exposure, and the usual steps of photographic processing are not required. If the photochromic material is in the form of a movable strip or rotatable disc, which moves to a position for viewing as in FIGURE 4 as soon as it is exposed as in FIGURES 1 and 3, then the object 22 reflecting the sonic waves can be immediately visualized.

One of the principal differences between the technique of sonic or seismic wavelet reconstruction, as it has thus far been described, and optical wavelet reconstruction as it is known in the art, is in the nature of the receivers or detectors. In the optical case, the receiver is the photographic film or plate itself, and each point of the film becomes both a detector and a recorder. The spacing density of such detection and recording points depends only on the grain structure and resulting resolving power of the film and can thus be very high—of the order of thousands of lines per inch. This high resolving power provides fine detail in the recording and reproducing of the image of an object.

On the other hand, in sonic and seismic wavefront reconstruction, the detectors are separate from the recorders, and a great number of separate detectors, amplifiers, and optical transducers are required to make a correspondingly high resolution record as compared with the optical case. Fortunately, in the case of seismic waves, and for some purposes in the case of sonic waves, the geometry of the source, object, and receiver is fixed and constant within a sufficiently small fraction of the wave length of the illuminating sonic or seismic waves, during the making of one photographic film, so that the effect of object motion is negligible. In such instances, therefore, by keeping the source and object relationship fixed, the receivers 29 can be moved or scanned during the making of a single record, provided the optical transducers 37 are correspondingly moved with respect to the recording film 41. In other words, instead of recording all areas of a hologram simultaneously as is done in the optical case, they can be recorded sequentially. This scanning of the reception area by a receiver or receiver array can be done in stepwise fashion, or it can be a continuous movement of a group of detectors to sweep out an area.

One embodiment adapted for seismic or sonic operation is illustrated in FIGURE 5. Here a frame 60 has a

cross-bar 61 adapted to move perpendicular to itself in the direction of arrow 65 so as to sweep out an area 59. Mounted on the cross-bar 61 are a multiplicity of closely spaced sonic wave energy detectors 62. Each of detectors 62 is connected by a lead of a multiple conductor cable 66 to a corresponding amplifier 67 which can be one unit of a multi-channel amplifier system, or it can be a multiplexed single channel amplifier as is well known in the art. The amplified detector signal then goes to a corresponding luminous transducer 69 arranged in a line of closely spaced transducers on a cross-bar 70 mounted on a frame 71. Through drive means 76 and 77 cross-bars 70 and 61 are adapted to be driven by a motor means 78 in synchronism. Successive positions 63, 64 of cross-bar 61 correspond to positions 72, 73 of cross-bar 70. A lens 40 images the changing illumination pattern from light transducers 69 onto the film transparency record 41. Luminous sources 69 can be continuously connected to corresponding detectors 62, and the cross-bars 61 and 70 moved at a constant speed, preferably related to the frequency of the sonic signals and to the sensitivity of the film 41. Or a switch means 79 can be inserted, controlled by motor 78 through driving connection 80 so that at discrete spaced positions of the cross-bars 61 and 70 a connection is made between each detector 62 and the corresponding luminous source 69 for a specified time interval to produce the necessary photographic exposure of film 41.

In a stationary sonar system the detectors 62 can be moved by means of cables and guides in any way desired. For some applications, such as for example, mapping the sea floor from a moving vessel, the apparatus can be simplified. In that application the linear array of detectors 62 can be horizontal and aligned across the longitudinal axis of the transporting vessel, either attached to the vessel or towed behind it. The forward vessel motion provides the successive positions of the linear array in the scanning direction 65, until the proper number of successive positions for one hologram have been recorded. As the forward motion of the vessel continues, a new hologram will be recorded.

During the recording of each hologram, the position of the source 19 remains fixed; and it may also remain fixed for two or more sequentially recorded holograms, particularly if stereo pairs of holograms are being obtained. To accomplish this from a moving vessel, two separate sources or source arrays can be used alternately, arranged to float at the proper position and attached by cables to the towing vessel. When one source or array is in use, it is allowed to remain stationary by paying out its towing cable at the same rate as the vessel moves forward. Simultaneously, the alternate source or array that is not in use is being towed forward toward the vessel so as to bring it to the proper position for its sequential use as a stationary emitter.

As an alternative, and as will be discussed in connection with FIGURES 9 and 10, it may be preferred to use a single source moving with the vessel and to adjust the phase of the signal emitted from the source, which is combined with the detector signals, in such a way as to compensate for the changing phase due to the source motion.

Although towing or moving a transducer through the water generates a certain amount of noise, this is generally not a serious problem, as the receiver band width can be very narrow so that very little of this noise will be recorded. Also, in applying the invention it is reciprocal sense of moving the transmitter while keeping the receivers stationary, and allowing for or compensating for the source motion in the observed phases of the received waves, the problem of transducer noise due to movement through the water substantially disappears for the stationary receivers due to their separation from the source by appreciable distances.

In FIGURE 6 is shown a modification of the embodiment of FIGURE 5 in which a group of spaced trans-

ducers 86a, 86b, 86c, etc., are mounted on a bar 87 adapted to reciprocate or slide lengthwise or parallel with respect to a support or cross-bar 85, by a distance 91 equal to the detector spacing of the detectors 86a, etc., so that detector 86d, for example, reaches the position 86d'. The reciprocating motion of bar 87 can be provided by a drive 88 from a motor 88', or it can be accomplished by the same motor 78 which through the driving connection 77 moves bar 85 horizontally in the scanning direction 65 through a tie-in driving connection 89.

Now, as the cross-bar 35 moves sideways in a direction 65 perpendicular to itself, the bar 87 moves cyclically up and down, and each detector 86a, 86b, etc., sweeps out a corresponding zig-zag path 90a, 90b, etc., approximately as shown. The exact path can, of course, be varied, but will preferably be such that, considering the small finite size of each detector 86a, 86b etc., every unit area of a detection area to be scanned will be covered at least once. Thus, a minimum number of detectors can be used to provide a high-resolution, multiple data point, two-dimensional pattern hologram. Of course, the luminous sources 69 will be proportionally spaced and moved in accordance with the spacing and motion of the detectors 86 in making a hologram 41 by exposure of the moving light sources 69 through the lens 40.

In seismic exploration there are two principal environments, water and land. For seismic exploration in water, some moving-detector arrangement like those of FIGURES 5 and 6 can be used. On land, however, it is not convenient to move the detectors continuously and cyclically, and in fact it is not necessary to do so since the geometry of the source and the objects to be visualized is constant and unchanging. Rather, it is possible to move the detectors in steps by lifting up and replanting in new positions part of the detectors while the remainder remain in place, in a progressive manner sometimes known as "roll-along." Although this results in a somewhat discontinuous or spaced-point coverage of the detection area, it is proposed to fill in between recorded data points, so as to decrease any adverse effects associated with the spaced point—rather than continuous sampling, by an interpolation procedure.

That is, in the preparation of a hologram, where there are a limited number of independent data points resulting from a corresponding number of spaced detector positions, the recorded hologram will show a two-dimensional array of unit record areas arranged in a matrix. Since adjacent unit record areas will normally be of different optical density, the pattern of the matrix defined by the edges of the unit areas will be readily visible. It is proposed to filter or smooth the recorded hologram by plotting intermediate unit areas between the independent data points. The optical density of such intermediate areas is derived by a linear interpolation procedure as indicated in FIGURES 7 and 8.

In FIGURE 7 is shown, as a source of coherent seismic energy, a vibrator 95 and a line of detectors 96a, 96b, 96c, etc., each connected to one of amplifiers 97 and a corresponding one of potentiometers 98. The sliders 99 of potentiometers 98 go to adders 102, as does signal on lead 101 from signal source 100 which supplies signal also through lead 101' to vibrator source 95. Assume, as indicated, that the potentiometers have eleven positions from and including zero up to a maximum of ten. Then, eleven separate records can be made with the adjacent potentiometers 98a, 98b set as follows: (10, 0), (9, 1), (8, 2), (7, 3), (6, 4), (5, 5), and so on to (0, 10). At the same time, the adder 102b is providing eleven separate records of the traces 96b, 96c and so on. The outputs of the adders go via leads 103 to luminous sources 69. The cross-bar 70 on luminous display 71 is moved horizontally by means 77, 78 which also control the drive means 104 of the potentiometers.

In FIGURE 8 I show how this progressive overlap can be carried out with a relatively few detectors by a form of two-dimensional linear interpolation. The operation of

FIGURE 8 is similar to that of FIGURE 7 and can be briefly described as follows. In FIGURE 8 are four detectors, 110a, 110b, and 111a, and 111b arranged in a rectangle. Each is respectively connected to an amplifier 112, 113, and a potentiometer 114, 115. By adder 122 slider lead voltages 120a, 120b, respectively, from detectors 110a, 110b are added together and to the signal from source 100 over line 101, as was pointed out in connection with FIGURE 7. By choice of settings of potentiometers 114, the output lead 124 of adder 122 will represent the weighted sum of the two detector outputs. Correspondingly, sources 111a, 111b are connected respectively to amplifiers 113, potentiometers 115, and the sliders therefrom are connected by leads 121a and 121b to adder 123 corresponding to the connections shown for 110a, 110b. By inter-connecting sliders 120a, 121a and 120b, 121b by controls 132, 133 respectively, the outputs 124, 125 of adders 122, 123 will correspond to similar interpolation points between the spaced detectors 110a, 110b and 111a, 111b. Now, by providing amplifiers 126, 127, potentiometers 128, 129, and by controlling the sliders by means 134, their outputs can be added by adder 130. The output 131 of adder 130 then provides a signal which is the result of a two-dimensional interpolation between the four detectors. For each step position of potentiometers 114 and of potentiometers 115, it is desirable to run the potentiometers 128, 129 through their full range in the manner described in connection with FIGURE 7. At the same time, of course, a light source 69 energized by output 131 is moved to corresponding intermediate positions by the same drive means 77, 78, 89 that actuate potentiometer drives 132, 133, and 134.

By the use of such means as that described in connection with FIGURE 8, it is possible to increase the number of overlapped recorded unit areas by a factor approximately equal to the product of the number of interpolation steps in the two directions. This provides a low-pass filtering effect on the hologram which minimizes any adverse diffraction effects of the original data point matrix.

Up to now, a two-dimensional substantially parallel beam of sonic or seismic wave energy has been discussed. It is possible also to use single-point sources, and also to combine point sources into multiple-source patterns. This is shown in FIGURE 9 where a group of sources 141a, 141b, etc., simultaneously or sequentially feed a group of detectors 140a, 140b, etc. If it is not possible to get precise synchronism between separate sources 141a, 141b, etc., it is preferred to run each separately and record the resulting signals 143a, 143b, etc., on a magnetic tape 144 in either analog or digital form, along with a reference signal 142. Magnetic tape 144 thus includes a reference track 145, for signal phase determination, and signal tracks 146.

In playback, as is shown in FIGURE 10, signal tracks 146 are played out into a digital computer memory 153, using an analog-to-digital converter unit 151 if the signals are in analog form. It will be clear that the signals can also be combined in analog form as is well known in the art. Next, in accordance with the phase of signals on tracks 145a and 145b, the corresponding ones of separate tracks 146a and 146b in memory 153 are drawn out over leads 154, 155, added by circuit 156, and then replaced in memory 153 over lead 157 to be later added to further tracks 146c from a tape 144c (not shown) and so on. By recording on magnetic tape 144 the signals for separate vibrations from the individual sources 141, and adding them subsequently for the same phase of the input signal, the equivalent of a beam of input energy with all of the sources 141 acting in phase is obtained. Or if desired, corrections in phase for one or the other of the sources can be introduced to take account of transmission irregularities in the earth in the vicinity of such source.

The sums of the traces of the separate records 144 for

each of the sources 141 can then be combined as in FIGURE 7 and 8 to improve the optical properties of the hologram, including the step of adding bias signal of constant phase. The recording of the hologram can be by any desired means including a flying-spot recorder, multi-element optical array, etc. The intermediate step of reproducibly recording the detector signals and the corresponding reference signal can, of course, be used in any configuration of source and detectors.

While a two-dimensional array of detectors and sources is preferred, it is possible to make a record with a single line of detectors, and then in recording to print the same trace parallel to itself to produce a two dimensional record. This could be used where there is symmetry in the objects such that the information of most importance occurs as variations along a single line. Or, two or more cross-lines can be recorded and two or more pictures obtained which indicate subsurface structure along sections cut by the cross-lines of detectors.

In running a survey of this type, it is possible to use common depth point geometry—or split spreads as is well known in the seismic prospecting art, to get narrow and wide spacings of the holograms to apply the principle of stereoscopic viewing of the pairs of resulting transparencies. This effect is aided by using two or more different frequencies in the sources 141 for seismic surveying. Since low-frequency energy is transmitted more effectively to great depths than is high-frequency energy, a low-frequency coherent beam of seismic wave energy would be transmitted and received at widely spaced detector arrays to make a picture of deep reflecting horizons. On the other hand, higher-frequency seismic energy with more closely spaced detector arrays would be used to map shallow reflecting horizons.

The two or more different frequency coherent seismic wave energy beams can be generated and transmitted in sequence, displayed on the optical display means, and recorded photographically in sequence on different films. Conversely, the two or more different frequencies can be generated and transmitted simultaneously, in such a way that they are all present on a single photographic record. The pictorial record, which is the counterpart of the optical hologram can be a film recording of a pattern of luminous spots, each representing the level of coherent wave energy at each of the separate detectors. Or the luminous spots can represent the level of coherent seismic wave energy at a plurality of points in a matrix produced by a limited number of detectors, positioned sequentially at a plurality of positions. Likewise, the display means can be an array of separate self-luminous elements which is sequentially positioned at each of the positions of the sonic detectors.

In FIGURE 11 is shown a modification of the embodiment of FIGURES 5 and 6 using a cathode-ray tube in place of the luminous-point array means. In this figure, the frame 159 has a potentiometer 163 mounted along its length, and a slider contact 165 is mounted on the traveling bar 85 to contact potentiometer 163. Similarly bar 85 carries a potentiometer 170, with a plurality of slider contacts 171a, 171b, etc., at the positions of detectors 86a, 86b, etc. These sliders 171 are connected by leads 172 to separate contacts 174 of a switch 173, the output of which is taken by lead 182 to the vertical deflection plates 180 of a cathode-ray tube 186. The two potentiometers 163 and 170 are supplied with voltage from a battery 160, the center of which is grounded at 162 by lead 161. Slider 165 is connected by a lead 166 to the horizontal deflection plate 167 of tube 186. The other deflection plates 168 and 181 of the tube are grounded. Thus, when slider 165, for example, is at the mid-position of potentiometer 163, the voltage on vertical deflection plate 167 will be zero (or ground) potential, and the spot on the cathode-ray tube will be centered horizontally on the oscilloscope face in a similar manner, as the switch 173 makes contact in sequence

with contacts 174, the spot will move vertically to the respective positions indicative of the actual positions of the sliders 171.

The outputs of detectors 86 representing received sonic or seismic waves are transmitted by leads 175 to contacts 176 of a second switch 177. This switch is driven in synchronism with switch 173 by motor 185 through driving connections 183 and 184. The signal from switch 177 amplified by amplifier 178 is transmitted over lead 179 to the z-axis control of the cathode-ray tube. Thus, as the spot is positioned vertically by the signal on lead 182, the brightness of the spot is controlled by the received-wave signal on lead 179. Transfer of the resulting pattern on the face of tube 186 by the lens 40 to photographic plate 41 (not shown in this figure), during one complete scan of potentiometers 163 and 170, produces the desired hologram.

In FIGURE 12 is shown another embodiment of this invention in which a graphic record is made directly from the signal output of the sonic or seismic detector units. Each detector unit 29 is connected by a lead 188 through an amplifier 188' to a corresponding one of an array of styli 187. These styli are sharp-pointed wires, preferably arranged in a pattern corresponding to the pattern arrangement of detector units 29, and placed in contact with a sheet 189 of electrically sensitive recording material. This can be any of the commercially available facsimile recording papers which are darkened by the passage of electric current from the contacting stylus to a conductive backing plate (not shown). The arrangement of the styli 187 may correspond to the arrangement of luminous sources 37 in the array 39, or they can be movable like the sources 69 or 86 of FIGURES 5 and 6.

As the detector units 29 or 62 receive sonic or seismic waves, corresponding electric currents pass from the styli 187 through the sheet 189 to produce various amounts of darkening of the sheet at the contact points of the styli. This darkening is a function of the intensity of the sonic or seismic wave energy detected by each corresponding detector 29 or 62. The resulting pattern of darkening of sheet 189 can then be photographically reduced to the form of a transparency 41 which constitutes the hologram for viewing in laser illumination.

In FIGURE 13 is shown diagrammatically and partially in cross-section a mechanical-optical device that is responsive to the intensity of wave energy to provide an optical output as a function of that intensity. The illustrated device 190 comprises a housing 191 having a tuned reed 192 mounted by means 193 on its interior wall. Reed 192 is tuned to the frequency of the sonic or seismic signal to be detected. On the free end of reed 192 is an opaque bar 194 across the axis of an optical system comprising a lamp 195, condensing lens 196 a mask 198 containing a central opening, a lens 197, and an optical fiber 203. Through a sealed connection, fiber 203 passes out through the wall of housing or container 191. Power can be supplied to lamp 195 from an external source via leads 199, or a self-contained battery (not shown) can be included within housing 191.

When housing 191 is subjected to vibration by the sonic or seismic energy waves in the surrounding medium, it will have an amplitude of vibration that is a function of the wave intensity. As case 191 moves, therefore, reed 192 vibrates with respect to it, and moves opaque mask 194 with respect to the opening of stationary mask 198 to allow light passage. The amount of light then passing through lens 197 and into fiber 203 is a direct function of the received-wave amplitude as it induces relative vibration between housing 191 and reed 192. In place of the seismically responsive reed 192, a pressure-sensitive diaphragm may be used, again preferably tuned to the frequency of the wave energy to be detected.

The optical fibers 203, which can be of glass or transparent plastic, may extend for a considerable distance and, as appears in FIGURE 14, may be joined with many

others from different corresponding transducers 190 to form a two-dimensional bundle 200. The light pattern of the various fiber ends of this bundle can be recorded by placing a photographic film 41 in direct contact with the fiber ends; or it can be imaged by lens 40 onto the film 41 to form the hologram for viewing in laser light.

It has been shown in a paper by B. R. Brown and A. W. Lohmann, entitled "Complex Spatial Filtering with Binary Masks," published in *Applied Optics*, vol. 5, No. 6, June 1966, pp. 967-969, that it is unnecessary in optical holography to have a precisely recorded pattern of light intensity that is accurately proportional to the wave intensity at corresponding points. That is, it has been found that a hologram prepared with a high contrast of density to transparency will show substantially the same optical image when viewed with a beam of coherent light as a hologram recorded with a quite different degree of contrast. Thus, a highly precise optical recording system is not required, so that masks 198 and 194 of FIGURE 13 may be designed in such a way that for very low amplitudes of reed vibration, substantially no light is transmitted to fiber 203, while above a certain minimum amplitude a fairly constant amount of light passes. Or, vibrating reed 192 can be adapted to make an electrical contact instead of modulating a light beam when its amplitude exceeds a specified value. The closing of this contact can then control the lighting of a light source 69 at a position in the array 71 corresponding to the position of the detector 190 in the receiving array 60. Thus, quite simple seismic or sonic-wave sensitive devices can be used to transduce sonic and seismic-wave energy amplitudes into optically recorded holograms.

Using a binary-spot presentation representative of the received-wave energy signals makes it possible to provide very simple recording apparatus. For example, the record equivalent to film 41 can be recorded on a photochromic material by an ultraviolet beam reflected by a mirror into a raster matrix, and the intensity of the beam can be controlled by electro-optical means, such as a Kerr cell, to be all on, or all off. Similarly, the amplifiers 67 of FIGURE 5, 97 of FIGURE 7, 112 of FIGURE 8, 178 of FIGURE 11 and 188' of FIGURE 12 need not be precisely linear amplifiers of high fidelity, but can be simple devices which pass no current as long as the signal is below a predetermined threshold value and pass full current for signals above that threshold.

Referring again to FIGURE 1, it is contemplated that this embodiment may be modified by placing between the source 19 and the object 22, a two-dimensional diffusing means 19'. This can, for example, be a plurality of randomly placed wave-energy scattering means, such as small spheres of varying sizes and the like. The purpose of diffuser 19' is to modify the wavefront originating at source 19 from its plane nature into a somewhat rough or more complex wavefront, so that its energy travels in many directions instead of essentially the single direction normal to the wavefront. Accordingly, after passing diffuser 19', energy reaches any particular point on the object 22 from many parts of the diffused wavefront, and as a further result the reflected and diffracted light from object 22 arrives at detector 28 from many directions. That is, a large area of the detector array and of the hologram receives energy from each point on the object, and the entire object contributes wave energy to each point on the receiver array and in the hologram. The diffuser 19', however, does not affect the coherence of the light itself, but on the contrary when the hologram is later viewed in coherent light, the reconstructed image contains even greater detail, while the effect of small defects or irregularities in the apparatus or recording and viewing system substantially disappears.

While my invention has thus been described with reference to the foregoing specific embodiments and illustrations, it will be apparent to those skilled in the art that there are still further modifications and embodiments

which can utilize the principles set forth. For example, it is possible to reproducibly record the detector signals and record the photographic record or hologram at a later time, provided that the reference-frequency signal is also recorded on the same recording medium as the signals from the object in the proper phase. This recording can be used for any of the embodiments shown in this application and in my earlier application S.N. 512,689, now Patent No. 3,400,363. Also, while I have described a system in which the source and the object are held fixed in position while the detectors and recording means are sequentially moved over a recording area, it will be clear that the object and detectors or receivers can be held fixed in position while the source is moved or repositioned. And, if intermediate recording of detector and reference signals is performed, both the source and detectors can be repositioned in a sequential manner. Various different patterns of movement or repositioning of the detectors or sources can be followed, and other means of recording the detected signals can be used besides those illustrated and described, so long as they follow the illustrated principles.

The scope of the invention, therefore, should not be considered as limited to the details of described embodiments.

I claim:

1. In the wavefront reconstruction method of visualizing an object in a visibly opaque medium including the steps of irradiating said object with coherent elastic wave energy from a source thereof, said energy being transmitted by said medium, receiving at a two-dimensional detector array some of said energy after it has been in part redirected by said object, and transducing the distribution of said energy over said detector array into a corresponding graphic record suitable for illumination with coherent visible radiation to form a visible image of said object, the improvement in which said transducing step comprises

sequentially recording on a graphic record surface a function of the outputs of the corresponding individual detectors in said array, while maintaining fixed the geometrical relationship of said source and said object.

2. The method as in claim 1 wherein said detectors are fixed in position in said array, and said sequential recording step comprises connecting individual detectors in sequence to corresponding individual graphic recording means acting on said record surface.

3. The method as in claim 1 wherein said detectors are movable in said array, and said sequential recording step comprises recording a function of the outputs of said detectors at correspondingly varying positions on said graphic record while moving said detectors in sequential intervals of time to positions defining said array.

4. In the wavefront reconstruction method of visualizing an object in a visibly opaque elastic-wave transmitting medium by the steps of irradiating said object with coherent elastic wave energy from a source thereof, detecting at space pattern of detectors said elastic wave energy after it has been at least in part redirected by said object, and graphically recording in a space pattern of spots similar to said space pattern of detectors the outputs of said detectors combined with wave energy of the same frequency and predetermined phase with respect to the energy of said source, the improvement comprising

placing a wave energy detector at a first position in the area in which wave energy intensity is to be recorded, irradiating said object with said coherent elastic-wave energy, recording the output of said detector in said first position in the form of a spot on a graphic medium in an arrangement corresponding to said first detector position, placing a wave energy detector at a second position in said area, irradiating said object, and

recording the output of said detector in said second position in the form of an additional spot on said graphic medium in an arrangement corresponding to said second detector position.

5. The method of claim 4 in which said detectors are placed at both said first and second positions before said recording steps, and only said recording steps are performed in sequence.

6. The method of claim 4 in which both said detector-placing and said recording steps are performed in sequence.

7. In apparatus for wavefront reconstruction in visualizing an irradiated object comprising a source of coherent elastic-wave energy for irradiating said object, said wave energy being redirected by said object to form a two-dimensional distribution of said wave energy, a plurality of elastic wave energy detectors responsive to said redirected energy, spaced in a receiving array and adapted to control corresponding radiant energy recording means, and means actuated by said recording means to product a two-dimensional graphic record corresponding to said two-dimensional distribution of coherent elastic wave energy, the improvement comprising,

means to modify the controlling of said radiant energy recording means by said detectors to record the outputs of at least some of said detectors sequentially.

8. Apparatus as in claim 7 in which said plurality of elastic-wave energy detectors are fixed in position in said array, and said sequential recording means includes means to sequentially connect said detectors to corresponding ones of said radiant energy recording means.

9. Apparatus as in claim 7 including means to sequentially change the positions of at least some of said detectors in said array.

10. Apparatus as in claim 9 wherein said detector position-changing means includes means to move said detectors by discrete distances between each recording of a sequence of recordings.

11. Apparatus as in claim 9 including also control means responsive to said detector position-changing means to control said radiant energy recording means as said detectors are sequentially changed in position.

12. Apparatus as in claim 7 in which said receiving array comprises a plurality of detectors equally spaced along a line to form a linear array, and including also means to move said linear array perpendicular to the direction of its length.

13. Apparatus as in claim 12 wherein said array-moving means comprises a vehicle to which said array is attached perpendicular to the direction of travel of said vehicle.

14. Apparatus as in claim 12 including also means to oscillate said linear array in the direction of its length while it is being moved perpendicular to said linear direction.

15. Apparatus as in claim 12 including also means to oscillate said linear array in the direction of its length by an amplitude of oscillation substantially equal to the spacing between said detectors, while said array is being moved perpendicular to its linear direction.

16. Apparatus as in claim 7 including means for reproducibly recording the output signals of said detectors, and means for reproducibly recording in association with said output signals a reference signal of the same frequency as said elastic-wave energy and of known phase relation thereto.

17. Apparatus as in claim 16 in which said reproducible recording means comprises a magnetic recorder.

18. Apparatus as in claim 7 including means to combine the outputs from a plurality of said spaced detectors in said array to produce a combination signal for recording at a corresponding point in said graphic record.

19. Apparatus as in claim 18 in which said plurality of detectors are arranged in a line in said array.

20. Apparatus as in claim 18 in which said plurality

of detectors are arranged in a two-dimensional spacing pattern over said receiving array.

21. Apparatus as in claim 7 in which said radiant energy recording means comprises a cathode-ray tube.

22. Apparatus as in claim 7 in which said receiving array comprises a pattern of spaced wave energy detectors and including means to move each of said detectors sequentially over a corresponding part of the detection area.

23. Apparatus as in claim 7 in which said recording means comprises an electro-sensitive recording medium and a plurality of recording styli each connected to and actuated by a respective one of said elastic wave detectors.

24. Apparatus as in claim 7 in which said recording means comprises means for recording an opaque spot for detector signals greater than a predetermined magnitude, and a translucent spot for signals less than said predetermined magnitude.

25. Apparatus as in claim 7 in which said detector means comprises means responsive to said elastic-wave energy intensity to modulate a light beam in accordance with the intensity of said elastic-wave energy incident on said detector, and optically transparent means to conduct said modulated light beam to a recording point.

26. Apparatus as in claim 25 in which said light-conducting means comprises a transparent optical fiber, and said recording means comprises a plurality of said fibers extending from a common recording area to a corresponding plurality of spaced detectors.

27. Apparatus as in claim 7 including means between said elastic-wave energy source and said object to diffuse said elastic-wave energy.

28. Apparatus as in claim 27 in which said diffusing means comprises a plurality of elastic-wave energy-scattering solid particles forming a layer extending across the path of said elastic-wave energy as it propagates from said source to said object and receiving array.

29. Apparatus as in claim 7 in which said source of coherent elastic-wave energy comprises a plurality of source units arranged in a two-dimensional array, and means for driving all of said source units simultaneously in phase and at the same frequency.

30. Apparatus as in claim 7 in which said source of coherent elastic-wave energy is a single transducer, and means for driving said transducer at a constant frequency to produce an expanding wavefront of energy irradiating said object.

31. In the wavefront reconstruction method of visualizing an object in a visibly opaque elastic-wave-transmitting medium by the steps of irradiating said object with coherent elastic-wave energy from a source thereof, detecting at a space pattern of detectors said elastic-wave energy after it has been at least in part redirected by said object, and graphically recording in a space pattern of spots similar to said space pattern of detectors the outputs of said detectors combined with wave energy of the same frequency and predetermined phase with respect to the energy of said source, the improvement in which said graphically recording step comprises

recording the output signals of said detectors in the form of reproducible traces, and simultaneously recording in the form of an associated reproducible trace a reference signal of the same frequency as said elastic-wave energy and having a known phase relation thereto,

simultaneously reproducing said reproducible detector signal traces and said associated reference signal trace,

adding said reproduced reference signal to each of said reproduced detector signals to provide a biased output signal, and

graphically recording said biased output signals in positions corresponding to the positions of said detectors in said space pattern.

32. The method of claim 31 including the further step of filtering said detector outputs with a filter tuned to the frequency of said source.

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