

PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Marine Seismic Exploration System

We, TEXAS INSTRUMENTS INCORPORATED, a Corporation organized according to the laws of the State of Delaware, United States of America, of 13500 North Central Expressway, Dallas, Texas, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to marine seismic exploration, and more particularly, to the automatic shot-to-seismometer spacing determination to make possible normal movement correction of marine seismic data. In a more specific aspect, the invention relates to concurrent recording of first breaks and reflection data in reproducible form.

A marine seismogram is generally obtained by towing a streamer or floating cable, with which are associated groups of seismometers. An explosive charge is set off in the water and a portion of the waves travel into the earth and are reflected back to the seismometers from boundaries where a change of velocity occurs. Due to the variation in distance between the shot and each group of seismometers, the energy reflected from the same subsurface layer arrives at each group of seismometers at a different time. This "normal moveout" of the energy across the spread must be corrected for in order to obtain a meaningful interpretation of the seismogram. To do so requires a knowledge of the distance between the shot and each group of receivers. Unlike seismic exploration work on land, the location of the shot and each seismometer group in marine work is never known precisely with respect to any fixed point. Water break amplifiers have been used in conventional recording operations where visual seismic records are pro-

duced to amplify that portion of the shot energy which takes the most direct path through the water to the seismometer group and to produce a sharply breaking pulse upon receiving such energy. The distance from the shot to the seismometer group can then be determined from this water travel time and the seismic wave velocity in water. Since the cable or streamer is being towed it is generally taut at all times. However, depending on wind and the prevailing currents, it is seldom straight over its entire length. Because of streamer tautness it is not necessary to have a water break amplifier for every seismometer group along the cable but because of the curvature it is necessary to have one for various groups which are evenly spaced over the entire length of the cable. The assumption may then be made that any curvature between groups for which water break amplifiers exist is negligible.

The output pulses from the water break amplifiers recorded photographically as wiggle-trace recordings have been employed by an interpreter who would make the necessary calculations to determine the shot-to-detector distances. Thereafter he would apply the resultant information to the normal moveout computations.

In accordance with patent specification No. 1,064,038, seismic reflection data is recorded in digital form so that the resultant reproducible record can be fed directly into a data processing unit wherein the normal moveout corrections can be carried out automatically. However, in marine operations where the shot-to-detector distances are not accurately known, the normal moveout computations are rendered ambiguous and unreliable.

According to one aspect of the present invention, we provide, in a marine seismic exploration system wherein detectors spaced

along a towed member move along a traverse at a predetermined depth, the method which comprises:—

- 5 (a) producing a seismic disturbance at a marine shot location,
- (b) detecting acoustic energy generated by said seismic disturbance at a set of spaced points in the vicinity of said location to produce a corresponding set
- 10 of electrical signals,
- (c) sequentially sampling the amplitudes of said signals,
- (d) converting the sampled electrical amplitudes into digital signals,
- 15 (e) magnetically recording said digital signals on a real time base referenced to the time occurrence of said seismic disturbance,
- (f) converting the first break energy in each of the signals associated with a sub set of said detectors into a waveform persisting over a period greater than the digital sampling interval, and
- 20 (g) recording the waveforms on said time base.

According to another aspect of the present invention, we provide, in a marine seismic exploration system wherein a disturbance is created in water for generating seismic signals and detectors are spaced along a towing member adapted to move along a traverse at a predetermined depth, the system comprising:—

- 35 (a) analog-to-digital conversion means responsive to the output signals from each of said detectors concurrently to produce digital functions representative of said signals from said detectors said output signals being electrical analogs of the seismic disturbance,
- 40 (b) a recorder responsive to the output of said conversion means to produce reproducible recordings of said functions,
- 45 (c) signal channels individually connected to a selected subgroup of said detectors and having means for producing persistent output signals beginning in response to respective first breaks in the signals from said subgroup, and,
- 50 (d) circuit means for applying said persistent output signals from said signal channels to said conversion means concurrently to record in reproducible form the time occurrences of said first break energy.
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According to yet another aspect of the present invention, we provide in a marine seismic exploration system wherein a disturbance is created in water for generating seismic signals and detectors are spaced along a towing member adapted to move along a traverse at a predetermined depth, the system comprising:—

- 65 (a) analog-to-digital conversion means re-

sponsive to the output signals from each of said detectors concurrently to produce digital functions representative of the signals from said detectors, said output signals being electrical analogs of the seismic disturbance,

- 70 (b) a recorder responsive to the output of said conversion means to produce reproducible recordings of said functions,
- 75 (c) first break signal channels individually connected to a selected subgroup of said detectors and having a band pass filter whose low frequency cutoff is an octave above the dominant frequency of said detector output signals,
- 80 (d) shaping means responsive to the outputs of said channels for producing persistent output signals, beginning in response to the first breaks in the signals from said subgroup, and,
- 85 (e) circuit means for applying said output signals from said shaping means to said conversion means concurrently to record in reproducible form representations of the time occurrences of said first break energy.
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For a more complete understanding of the present invention and for further objects and advantages thereof, reference may now be had to the following description taken in conjunction with the accompanying drawings, in which:—

FIGURE 1 illustrates one embodiment of the present invention; 100

FIGURE 2 illustrates the first break shaping unit;

FIGURE 3 is a graph showing the frequency response of the unit of FIGURE 2; Figure 4 illustrates the shaped water break pulses; and 105

FIGURE 5 illustrates utilization of the data recorded in the system of FIGURE 1.

In FIGURE 1, a seismic detecting streamer 10 is towed behind the boat 11 along a predetermined course. Ideally, the streamer 10 as towed by cable 12 should extend along a straight line behind the boat 11. However, more generally, the water current as represented by the arrow 13 and wind as represented by the arrow 14, are effective to alter the position of the streamer 10 and boat 11 relative to the preset course. Often, the boat 11 halts during the time interval that a seismic recording is being obtained. Movement of streamer and boat during such intervals in general are in no way related to each other and the exact position of the various detectors relative to a given shot location is unknown. 110 115 120

Following a given shot, surveying apparatus on boat 11 may indicate the deviation of the boat from its desired course, thus requiring an abrupt change in direction to get back on course. As a result, a streamer 10 125

may follow a serpentine path through the water.

A shot 20 from a boat 21 is detonated to produce seismic waves which are detected by the detectors in the streamer 10. In the operation illustrated in FIGURE 1, the streamer 10 includes twenty-four detectors 31—54. The exploration program illustrated detonates the shot 20 at a point midway of the length of the streamer 10 and spaced laterally therefrom for broadside shooting operation. The irregularity in the lengths of the shot-seismometer distances r1—r24 is readily apparent.

A time break or shot instant signal is transmitted to the boat 11 from boat 21, as indicated by the radio transmission path 57. Recording instruments carried by boat 11 then serve to apply a time break signal and a timing or clock signal, by way of channel 60, to a multichannel preamplifier unit 59. Similarly, signals from detector 31 are applied to the multichannel amplifier unit 59 by way of channel 61. All of the signals from the detectors 31—54 similarly are applied to the unit 59, with the signal from the most remote detector being applied by way of channel 84. The signals applied to the unit 59 are then applied by way of channels 87 to a multiplexer and analog-to-digital converter section 89. The output of the analog-to-digital converter is then applied by way of recording heads 90 to a magnetic tape 91, driven at a uniform speed by a tape transport unit generically represented by a capstan 92. By this means, the time break and timing signal, as well as the set signals from the detectors 31—54, are stored in digital form on the tape 91.

In accordance with the present invention, signals forming a preselected sub set of signals are applied by way of channels 93 to a water break amplifier and shaper section 94. In the embodiment illustrated, the signals from detectors 31, 35, 40, 45, 50, and 54 are applied to section 94. Six channels are provided in section 94 so that six water break signals can be recorded on the tape 91. Channels 101—106 respectively serve to shape the water break pulse from amplifiers 31, 35, 40, 45, 50, and 54, respectively. Channels 101—105 have been shown in block form only. Channel 106 has been shown in more detail and includes an amplifier 107, a threshold sensing unit 108 and a shaper 109. A squelch circuit 110 serves to cut off the signal after the water break signal has been sensed. The output of the shaper is then applied by way of channel 111 to the multiplexer and converter unit 89. In a similar manner, the outputs of each of units 101—105 are applied to the multiplexer and converter unit 89. Thus, the time break signal, the timing signal, the seismic reflection signals from detectors 31—35, and water break signals from the de-

tectors 31, 35, 40, 45, 50 and 54 are stored in digital form on tape 91.

With the signals thus recorded, the tape 91 may be processed without the necessity of any individual making visual interpretation of a seismic record to determine the first break record times for computational purposes. The seismic data on the tape 91 may then be fed directly to a computer wherein the first operation is to measure the various first break times represented by the paths r1, r5, r10, r15, r20, and r24 and then compute the shot-detector distance for each of the 24 detectors. Thereafter, with the shot-detector distances known, the normal moveout computation may be completed so that the data may then be recorded in visual form, displayed or otherwise processed to reveal accurately the depths and altitudes of subsurface reflecting horizons of interest. Recording of the water break data current with the seismic reflection data eliminates the need for a human intermediary at any point in the data processing operation.

In FIGURE 2 one embodiment of the water break channel has been illustrated in detail. The input channel 95 of FIGURE 1 has been shown in FIGURE 2 as transformer coupled to a preamplifier 120. The output of the preamplifier 120 is coupled by way of a variable potentiometer 121 to the first of two class A band pass amplifier stages 122 and 123. The frequency response of this portion of the amplifier is shown in FIGURE 3. The low frequency corner occurs at about 1 kilocycle. The characteristic slope at the low end of the frequency response curve is about the same as a passive three-section RC filter network which has a slope of 18 db per octave. The high frequency corner occurs at about 15 kc and has a slope of about 30 db per octave. Thus, the amplifier has a useful pass band between 1 and 15 kc. Since the dominant seismic frequency is down about an octave from the centre of the pass band, the signal from the amplifier will be at the lower end of the band.

The class A amplifier portion 122, 123 has a maximum gain of about 70 db. The last stage 130 of the amplifier is normally biased to cut off. The signal must exceed a threshold amplitude level before the tube in stage 130 can conduct. The action of stage 130 is to act as a half wave rectifier. If the phase of the water break arrival is incorrect, only half cycle resolution can be obtained.

For preferred operation, the signal at the grid of the tube in stage 130 must be positive going at the onset of the water break to turn the stage on. One output of the stage 130 is blocked as to D.C. by a capacitor 131. The A.C. component of the signal is coupled by a transformer 132 to a galvanometer circuit 133 so that where desired, a visual wiggle-trace recording may be produced by use of a conventional recorder.

In accordance with the present invention, the signal from stage 130 is coupled to a shaper circuit 136 by way of coupling capacitor 137. The signal is applied by way of transformer 138 of the emitter-base circuit of a transistor 139. The collector of transistor 139 is connected by way of resistor 140 and battery 141 to one terminal of a gate 142. The collector of transistor 139 is also connected by way of diode 147 to the gate electrode of a silicon controlled rectifier 148. One terminal of a storage capacitor 149 is connected to battery 141. The charging circuit for capacitor 149 by battery 141 includes conductor 150 leading to one side of capacitor 149. A resistor 151 and conductor 152 lead to the other side of capacitor 149 from gate 142. The diode 147 is connected by way of resistor 154 to an output terminal 155 which is common to the cathode of silicon controlled rectifier 148. A resistor 156 is connected between terminal 155 and conductor 150. Thus, the second output terminal 157 is connected to conductor 150.

In operation, the circuit through gate 142 is closed in response to the time break to initiate charging of condenser 149 through resistor 151. When the stage 130 conducts, the signal applied to the base of transistor 139 triggers the silicon controlled rectifier 148 to discharge condenser 149. The discharge of the condenser 149 produces an output pulse having a waveform generally as shown by the solid outline in FIGURE 4.

Pulse 160 has an abrupt onset and persists for an interval substantially greater than the interval between samples taken of a given trace by the multiplexer. As illustrated in FIGURE 4, the half wave rectifier alternating current signal at the output of amplifier stage 123 is very high in frequency and is such that the wave form 162 shown in FIGURE 4 might be missed by the sampling operation of the multiplexer. However, with the wave form 160 persisting for a substantial period, the multiplexing operation may be carried out without any possibility of missing the water break pulse. Using the filter illustrated in FIGURE 2, the period T in FIGURE 4 for the water break pulse would be less than 0.001 second and in general is in the frequency range of well above 1000 cycles. By producing a signal from each of the water break channels which has persistence greater than the sampling interval there will be avoided any ambiguity in the water pulse signals. In general, the sampling time of the multiplexer is about 0.002 second.

Conduction through the transistor 139 is terminated by squelching the stage 130. More particularly, the squelch circuit consists of a class A amplifier stage 163 having its input connected to the output of the stage 122. The stage 163 is thus connected in parallel with the stage 123. The amplifier stage 163 drives

a normally cut off stage 165 which is biased at the same level as stage 130. It will be noted that the bias voltage for stages 130 and 165 is developed on conductor 166 from a potentiometer in the circuit 167 which is powered by D.C. source 167a for energization of the filaments of the various amplifier tubes. The output signal from the stage 165 is coupled by way of capacitor 168 to a diode 169. The cathode of the diode 169 is connected to ground by way of resistor 170. Thus the output signal from the stage 165 is half way rectified and is applied by way of the diode 169 to the control grid of stage 130. The output of stage 165 is further filtered by the action of the condenser 171 and resistor 172, the anode of the diode 169 being coupled to the control grid of stage 130 by way of resistor 172 and conductor 173.

The action of the squelch circuit is to provide a negative D.C. bias level which is proportional to the average half cycle amplitude of the signal from the stage 165. Thus a reverse bias voltage is applied to the grid of the stage 130 through the resistor 172. The time constant of the circuit comprising resistor 172 and capacitor 171 is such that only a few cycles of the water break arrival are permitted to overcome the threshold bias of the stage 130. Stage 130 produces an exponentially decaying half cycle alternating current output at the signal arrival time. This is because the D.C. level of the squelch output exponentially decreases from ground level, at quiescence, to a maximum of about -24 volts D.C. at the arrival of the large signal. The actual squelch D.C. level varies with the input signal amplitude and the amplifier gain setting. However, when the cathode bias levels at stages 130 and 165 are properly adjusted, the squelching action is effective to overcome the amplifier for any change in signal that can overcome the threshold level at stage 130. Preferably the maximum gain setting for the amplifier as controlled by the potentiometer 121 is a function of the ambient noise level from the marine seismometer streamer 10. That is to say, the average noise level generated before the shot is detonated is used to determine the gain setting. The gain setting is such that the ambient noise level will not produce any output from stage 130. It is preferable that the gain be maintained at a level substantially below that level at which the noise will actuate stage 130 but at a sufficient gain such that the first break or the water break will drive the normally cutoff stages 130 and 165 to appreciable conduction.

The production of the output pulse 160 at terminals 155-157 makes certain that the multiplexer and converter unit 89 will not miss the first water break pulse even though an extremely high frequency component of the water break signal is employed. The persist-

ance of the pulse 160 for a time interval longer than the interval between samples of a given trace taken by multiplexer and converter unit 89 eliminates the possibility that the water break pulse will be missed.

The amplifiers and the multiplexer, and the converter units illustrated in FIGURE 1 have not been described in detail since they are known and described in patent specification No. 1,064,038. The streamer 10 may be of a construction generally conforming with streamers of the type sold by Seismic Engineering Company of Dallas, Texas and identified as Line Streamer Sections.

Water break channels will be used in number only to the extent necessary and practical. This in no way affects the operations in which the water break pulses are permanently recorded on magnetic tape. In the course of data processing, the shot-to-seismometer distances are automatically determined on the basis of the recorded arrival times of these pulses. If fewer amplifiers are used than the number of groups in the spread, the remaining distances are solved by triangulation to determine the distance from the shot to all groups.

The following example will illustrate the procedure more clearly. Assume a streamer of length L with 24 evenly spaced groups and a water break amplifier for groups 1, 5, 10, 15, 20, and 24 as in FIGURE 1. The shooting procedure is that for a split profile with the shot offset broadside from the cable. Calculation of distances to groups intermediate to two adjacent water break groups i and j will be in accordance with the following expressions:

$$x = \frac{r_i^2 - r_j^2 + c^2}{2c} \quad (1)$$

$$h = \sqrt{r_i^2 - x^2} \quad (2)$$

where:

x and h are the distances shown in FIGURE 1;

r_i and r_j are distances to the two adjacent water break groups;

$r_i \geq r_j$; and

$$c = \frac{|i-j|}{23} L.$$

If $i < j$

$$r_{i-k} = \sqrt{h^2 + |x - k\Delta c|^2} \quad (3)$$

If $i > j$

$$r_{i+k} = \sqrt{h^2 + |x - c + k\Delta c|^2} \quad (4)$$

where:

$k=1, 2, \dots (|i-j|-1)$ and

$$\Delta c = \frac{1}{23} L.$$

As shown in FIGURE 5, the tape 91 is applied to a playback unit 200 which feeds

a computer 201 where the foregoing computations are carried out in connection with normal moveout corrections. Computer 201 may be of the type described in patent specification 946,457. Computer 201 is programmed to include the operations represented by Equations 1-4.

WHAT WE CLAIM IS:—

1. In a marine seismic exploration system wherein detectors spaced along a towed member move along a traverse at a predetermined depth, the method which comprises:

- (a) producing a seismic disturbance at a marine shot location,
- (b) detecting acoustic energy generated by said seismic disturbance at a set of spaced points in the vicinity of said location to produce a corresponding set of electrical signals,
- (c) sequentially sampling the amplitudes of said signals,
- (d) converting the sampled electrical amplitudes into digital signals,
- (e) magnetically recording said digital signals on a real time base referenced to the time occurrence of said seismic disturbance,
- (f) converting the first break energy in each of the signals is associated with a sub set of said detectors into a waveform persisting over a period greater than the digital sampling interval, and
- (g) recording the waveforms on said time base.

2. A method according to claim 1 wherein the onsets of the persistent waveforms are converted into digital signals.

3. A method according to claim 1 or 2, further comprising the steps of:

- (a) reproducing the recorded digital signals,
- (b) from the reproduced signals representative of said first break signals, computing the distance from said seismic disturbance to the detectors of said sub set, and,
- (c) based on said distances, correcting the remaining reproduced signals for normal moveout.

4. In a marine seismic exploration system wherein a disturbance is created in water for generating seismic signals and detectors are spaced along a towing member adapted to move along a traverse at a predetermined depth, the system comprising:

- (a) analog-to-digital conversion means responsive to the output signals from each of said detectors concurrently to produce digital functions representative of the signals from said detectors, said output signals being electrical analogs of the seismic disturbance,
- (b) a recorder responsive to the output of



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ance of the pulse 160 for a time interval longer than the interval between samples of a given trace taken by multiplexer and converter unit 89 eliminates the possibility that the water break pulse will be missed.

The amplifiers and the multiplexer, and the converter units illustrated in FIGURE 1 have not been described in detail since they are known and described in patent specification No. 1,064,038. The streamer 10 may be of a construction generally conforming with streamers of the type sold by Seismic Engineering Company of Dallas, Texas and identified as Line Streamer Sections.

Water break channels will be used in number only to the extent necessary and practical. This in no way affects the operations in which the water break pulses are permanently recorded on magnetic tape. In the course of data processing, the shot-to-seismometer distances are automatically determined on the basis of the recorded arrival times of these pulses. If fewer amplifiers are used than the number of groups in the spread, the remaining distances are solved by triangulation to determine the distance from the shot to all groups.

The following example will illustrate the procedure more clearly. Assume a streamer of length L with 24 evenly spaced groups and a water break amplifier for groups 1, 5, 10, 15, 20, and 24 as in FIGURE 1. The shooting procedure is that for a split profile with the shot offset broadside from the cable. Calculation of distances to groups intermediate to two adjacent water break groups i and j will be in accordance with the following expressions:

$$x = \frac{r_i^2 - r_j^2 + c^2}{2c} \quad (1)$$

$$h = \sqrt{r_i^2 - x^2} \quad (2)$$

where:

x and h are the distances shown in FIGURE 1;

r_i and r_j are distances to the two adjacent water break groups;

$r_i \geq r_j$; and

$$c = \frac{|i-j|}{23} L.$$

If $i < j$

$$r_{i+k} = \sqrt{h^2 + |x - k\Delta c|^2} \quad (3)$$

If $i > j$

$$r_{i+k} = \sqrt{h^2 + |x - c + k\Delta c|^2} \quad (4)$$

where:

$k = 1, 2, \dots, (|i-j|-1)$ and

$$\Delta c = \frac{1}{23} L.$$

As shown in FIGURE 5, the tape 91 is applied to a playback unit 200 which feeds

a computer 201 where the foregoing computations are carried out in connection with normal moveout corrections. Computer 201 may be of the type described in patent specification 946,457. Computer 201 is programmed to include the operations represented by Equations 1—4.

WHAT WE CLAIM IS:—

1. In a marine seismic exploration system wherein detectors spaced along a towed member move along a traverse at a predetermined depth, the method which comprises:

- (a) producing a seismic disturbance at a marine shot location,
- (b) detecting acoustic energy generated by said seismic disturbance at a set of spaced points in the vicinity of said location to produce a corresponding set of electrical signals,
- (c) sequentially sampling the amplitudes of said signals,
- (d) converting the sampled electrical amplitudes into digital signals,
- (e) magnetically recording said digital signals on a real time base referenced to the time occurrence of said seismic disturbance,
- (f) converting the first break energy in each of the signals is associated with a sub set of said detectors into a waveform persisting over a period greater than the digital sampling interval, and
- (g) recording the waveforms on said time base.

2. A method according to claim 1 wherein the onsets of the persistent waveforms are converted into digital signals.

3. A method according to claim 1 or 2, further comprising the steps of:

- (a) reproducing the recorded digital signals,
- (b) from the reproduced signals representative of said first break signals, computing the distance from said seismic disturbance to the detectors of said sub set, and,
- (c) based on said distances, correcting the remaining reproduced signals for normal moveout.

4. In a marine seismic exploration system wherein a disturbance is created in water for generating seismic signals and detectors are spaced along a towing member adapted to move along a traverse at a predetermined depth, the system comprising:

- (a) analog-to-digital conversion means responsive to the output signals from each of said detectors concurrently to produce digital functions representative of the signals from said detectors, said output signals being electrical analogs of the seismic disturbance,
- (b) a recorder responsive to the output of

- said conversion means to produce reproducible recordings of said functions,
- 5 (c) signal channels individually connected to a selected subgroup of said detectors and having means for producing persistent output signals beginning in response to the respective first breaks in the signals from said subgroup, and,
- 10 (d) circuit means for applying said persistent output signals from said signal channels to said conversion means concurrently to record in reproducible form the time occurrences of said first break energy.
- 15 5. A combination according to claim 4, wherein said analog-to-digital conversion means produces digital functions representative of the amplitudes of each of the signals
- 20 from said detectors at time-spaced sampling intervals, and the means in the signal channels produces output signals which each persist for a period in excess of said sampling interval.
- 25 6. A combination according to claims 4 or 5, including a multiplexer for serially combining the output signals from each of said detectors, a recorder responsive to the output of said multiplexer to produce reproducible recordings of said functions, and
- 30 a circuit means for applying the output signals from said signal channels through said conversion means and said multiplexer to said recorder concurrently to record in reproducible form the time occurrences of said first break energy.
- 35 7. In a marine seismic exploration system wherein a disturbance is created in water for generating seismic signals and detectors are spaced along a towing member adapted to move along a traverse at a predetermined depth, the system comprising:—
- 40 (a) analog-to-digital conversion means responsive to the output signals from each of said detectors concurrently to
- produce digital functions representative of the signals from said detectors, said output signals being electrical analogs of the seismic disturbance,
- (b) a recorder responsive to the output of said conversion means to produce reproducible recordings of said functions,
- (c) first break signal channels individually connected to a selected subgroup of said detectors and having a band pass filter whose low frequency cutoff is an octave above the dominant frequency of said detector output signals,
- (d) shaping means responsive to the outputs of said channels for producing persistent output signals, beginning in response to the first breaks in the signals from said subgroups, and,
- (e) circuit means for applying said output signals from said shaping means to said conversion means concurrently to record in reproducible form representations of the time occurrences of said first break energy.
8. In a marine seismic exploration system wherein detectors spaced along a towed member move along a traverse at a predetermined depth, the method substantially as hereinbefore described with reference to the accompanying drawings.
9. In a marine seismic exploration system wherein detectors are spaced along a towing member adapted to move along a traverse at a predetermined depth, the apparatus combination substantially as hereinbefore described with reference to the accompanying drawings.
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