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(54) SEISMIC DATA PROCESSING SYSTEM AND METHOD

(71) We, WESTERN GEOPHYSICAL COMPANY OF AMERICA, a corporation organised and existing under the laws of the State of Delaware, having an office at 360 North Crescent Drive, Beverly Hills, California 90210, 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:—

The present invention relates to seismic data telemetry processing systems and methods and particularly to reflection seismology.

In seismic exploration, an acoustic wave signal is generated at or near the surface of the earth. The acoustic wave travels downwardly and is reflected from subsurface earth layers, whence the wave returns to the earth's surface. The reflected seismic waves are detected by sensitive seismic sensors distributed in a substantially linear array at or near the surface of the earth.

Although this invention will be described with particular reference to geophysical surveying, it may be designed for use to detect objects submerged beneath the water, such as large fish, vessels and the like.

In accordance with the usual practice up to the present time, 25 to 30 seismic detectors, frequently referred to as sensors, are equally spaced along a single cable section which may be 100 to 300 feet long. The sensors are all electrically connected together to form a single elongated data channel. Fifty or more such cable sections, each constituting a channel for signal transmission, are coupled together to form a cable assembly 10,000 feet or more long. The output of each of the 50 or more channels is connected to a central signal processing device located at one end of the cable assembly. A separate pair of wires is needed for each channel. There may be, therefore, 50 or more such pairs. Because of the expense and the physical weight of such a large number of wires, the output signals from each channel can be time-division multiplexed through a single data transmission link or channel and this is employed in a preferred embodiment of the present invention.

According to one aspect of the present invention, there is provided a system for seismic data telemetry having: a central station; a plurality of seismic data

acquisition units; a common digital-data signal link coupling the central station and the acquisition units; a first and a second control-signal link coupling the central station and the data acquisition units, said two control-signal links having different signal propagation velocities; and control circuits associated with the data acquisition units and responsive to the coincidence of control signals received over the respective control-signal links for performing a desired control function in a data acquisition unit when signal coincidence is detected in the unit.

Control functions can be designed to implement time-division multiplexing and other operations in the system remotely controlled.

In accordance with a referred embodiment of the invention, the acquisition units, during operation, transmit seismic data signals from sensor units via the digital-data transmission link in a seismic cable to the central station under the use of multiplexing technology, the system including additional multiplexing means in each unit for successively sampling the output from each of a plurality of elemental seismic sensor units of a specific set of associated sensor units and electronic circuitry in each unit for applying the outputs from the specific unit to the digital-data link, so that, during operation, the outputs from each of the seismic sensor units of the specific set are sampled by a first multiplexing stage and the outputs from at least some of the units are successively applied to the central station over the digital-data transmission link by a second multiplexing stage.

Thus, it will be seen that this embodiment may be briefly defined as a two-stage multiplexing seismic data processing system. As is explained further below, the principle thus defined permits forming shorter arrays, thus achieving relatively high resolution power of the system, combined with sensitivity to relatively high acoustic signal frequencies.

As mentioned above, a seismic sensor group is often an array 100 to 300 feet long. An acoustic wave whose wavefront is substantially parallel to the plane in which the seismic sensors are disposed, will arrive at all of the sensors substantially simultaneously, thereby enhancing the output signal by summation. Under actual seismic prospecting conditions, this ideal situation rarely exists, except for the special case in which the wavefront is reflected vertically from a reflecting subterranean interface lying directly below the sensor array. In the more usual case, the acoustic wavefront sweeps across the array at an angle. Because of the angularity, the wavefront impinges on one end of the array well ahead of the time that it reaches the other end of the array. The travel time of the wavefront across the array depends upon the seismic wave-phase velocity, the wavelength of the acoustic wave, the array length and the depth of the reflecting interface, among other factors. If the array length is large compared to the wavelength of the acoustic wave, the array will attenuate the acoustic wave. Therefore, the seismic sensor array should be shorter than the wavelength of the incident seismic waves to avoid attenuation and, preferably, the array should be less than one-quarter of this wavelength for good response.

Traditionally, energy at the lower end of the seismic spectrum, involving wavelengths of many hundreds of feet, was of interest. Use of relatively long arrays was satisfactory. More recently, however, greater resolution of geologic layering, i.e. in surveying subterranean structure, is being demanded. Greater resolution requires use, and thus detection, of seismic waves having higher frequencies. But the wavelengths of the energy at the upper end of the seismic spectrum are comparable to, frequently much shorter than, the length of conventional seismic sensor arrays presently in use. It would be desirable, therefore, to substitute many shorter seismic sensor arrays for one long seismic sensor array in each cable section. Such solution to the problem has been considered to be impossible in view of the data processing complexities and the large number of conductors that would have been required, resulting in costly seismic cable assemblies of impractical size and bulk. The preferred embodiment permits one to increase resolution of large scale seismic systems, without significantly increasing the weight or bulk of the seismic cable assembly.

In accordance with the principles developed herein and explained further below, the seismic data processing system disclosed hereinafter is organized such that it features decentralization of the signal-conditioning electronics, normally mounted in a central recording vehicle, by incorporating the electronics into the individual cable sections forming the cable assembly. Seismic analog signals from individual seismic sensors are digitized and transmitted to the central station over a data transmission link by employing the above-mentioned two-stage propagation time-delay multiplexing scheme.

In accordance with an important aspect of one embodiment of this invention, a seismic cable assembly is made up of a plurality of identical seismic cable sections each of which includes a number, e.g. ten, of discrete, short, elemental seismic sensor units in place of one conventional long single array. Since each elemental seismic sensor unit operates in conjunction with a separate signal channel, the number of channels to be serviced in a complete cable assembly becomes multiplied by a factor of at least 10. Accordingly, in a preferred embodiment, the system samples and multiplexes the outputs from 500 to 1,000 data channels over a single data transmission link to the central station, within the time span of a desired sampling interval, such as 0.5 to 1.0 millisecond, referred to herein as a scan cycle.

In one embodiment of this invention, the seismic cable assembly comprises at least ten substantially identical cable sections. Included in each cable section is a number of elemental seismic sensor units. An acquisition unit, referred to hereinafter as a transceiver unit, is associated respectively with each cable section, wherein the term "transceiver unit" is used herein to describe the electronics assembly in connector modules forming part of the cable assembly and including an output circuit for transmission of digitized seismic signals onto the cable, in addition to common electronic circuits for amplifying and digitizing analog seismic data input information and switching circuitry for successively connecting the elemental seismic sensor units to the common electronic circuitry. The cable sections and connector modules with transceiver units are mechanically and electrically connected together. The signals from each of the transceiver units are successively applied to the seismic cable and thus to the central station, while the switching circuitry is connected to receive signals from the associated elemental seismic sensor units. In this fashion, digital signals from all of the sensor units are successively applied to the central station. The length of each seismic sensor unit is a predetermined fraction of the length of a seismic wavelet whose frequency corresponds to the successive application rate of the signals applied to the cable, as discussed further below.

In accordance with another aspect of one embodiment of this invention, the seismic cable assembly is composed of a number of active cable sections, each containing an interrogation (control-signal) link, a data transmission link and a number of elemental seismic sensor units, whenever the sensors are accommodated within the cable. The connector modules with the transceiver units therein connect adjacent ones of the cable sections together. Each transceiver unit has a plurality of input channels, a data repeater network and an interrogation network. The interrogation network of each transceiver unit is connected in series with the interrogation link. The elemental seismic sensor units in intermediate cable sections are coupled to corresponding input channels of the associated, specific transceiver unit located at one end of an associated cable section. The data repeater network of each transceiver unit is coupled to the data transmission link.

A further feature of one embodiment of this invention includes a multiplexer switch in each transceiver unit. The multiplexer switch is sequenced by a control network which is connected to the interrogation network. In response to interrogation pulses from the central station and transmitted over the interrogation link, the interrogation network causes the control network to sequence the multiplexer and to digitize the analog data from the seismic sensor units, and also to transmit a self-clocking digital data word to the transmission link through the data repeater network.

In accordance with another aspect of the embodiment of this invention disclosed herein, the filters, multiplexer, gain-conditioning amplifiers, digitizer and other electronics that were conventionally mounted in a recording vehicle associated with a conventional seismic data acquisition system, are removed from the central data acquisition system and are packaged in identical miniaturized connector modules to constitute the transceiver units, one of which is associated with each cable section. The plurality of identical cable sections are spaced apart and interconnected by a like plurality of identical connector modules with transceivers. Analog signals from the elemental sensor units within a cable section are fed via local data lines to the associated transceiver unit in the connector module, where they are filtered, multiplexed, sampled, gain-conditioned and digitized. All that remains in the recording vehicle in the central station having a signal receiver and recorder to record digital data words received from the data transceivers through the data transmission link and control logic to transmit control and interrogation signals to the data transceiver units through the interrogation link.

Suitably, the length of an elemental seismic sensor unit, including three or more sensors, is less than 50 feet, and preferably less than 20 feet. A sensor unit length

of 12-1/2 feet, for example, corresponds to a half-wavelength at 200 Hz, and a quarter wavelength at 100 Hz, based upon a seismic wave velocity of 5,000 feet per second. High-frequency seismic events will therefore be detected by the sensor units even in the case of very shallow reflections at remote points along the cable.

Further, the one millisecond sampling rate for the seismic signal electronics has a Nyquist frequency limit of 500 cycles per second. In the course of the sampling process, frequencies greater than the Nyquist frequency produce spurious or so-called "alias" low-frequency signals which would be indistinguishable from the desired data signal information. In the present system, the response of the one-millisecond anti-alias low-pass filters employed to exclude the high frequencies will be at least -60db (1000:1), with respect to full scale at 500 Hz. The -6db point occurs at 250 Hz. Thus, the effective upper cutoff frequency is one-half the Nyquist limit. This is, of course, well above the seismic frequencies of interest, and the system therefore provides the desired high-frequency pass band to the recorder that is desired in the high-resolution seismic data processing system described.

In accordance with another feature of one embodiment of this invention, the transceiver units have constant current power supplies and alternating current power is supplied at a frequency substantially above the highest signal sampling frequency.

In accordance with another feature of one embodiment of this invention, a trunk cable in each section of the cable assembly includes a data transmission link, an interrogation link and ancillary power and control links. The trunk cable interconnects the plurality of transceiver units in series with each other and with the central station in a recording vehicle.

Contained within each transceiver unit are preferably a plurality of pre-amplifiers/filters, each having an input and an output. The inputs are coupled to a like plurality of elemental seismic sensor units which, particularly in cases of seismic marine cables, are mounted within the associated cable section. The preamplifier/filter outputs are connected to corresponding inputs of the multiplexer, the single output of which is coupled to the common gain-conditioning amplifier, digitizer, a temporary storage and output register, code converter and the repeater network. The output of the repeater network is, in turn, connected to the data transmission link. The interrogation link is coupled to the multiplexer and to the output register through a control network. In response to an interrogation signal which is a pulse transmitted through the interrogation link to the transceivers, the multiplexer in each transceiver is sequenced by the control network to a selected, i.e. its next, channel to acquire an analog data sample. The data sample is gain-conditioned, digitized to form a digital data word and is clocked from the output register and code converter into the repeater network. Thus, as the interrogation pulse arrives at each of the respective transceiver units, a corresponding self-clocking phase-encoded data word is transmitted to the central station through the data transmission link. A second, next interrogation pulse advances the multiplexers in each of the transceiver units to a second, i.e. the next, channel for sampling and digitizing the next signal, while transmitting a phase-encoded word from the first, i.e. previously sampled channels of the transceiver units. Accordingly, over a period of one scan cycle, all of the analog input channels in all of the transceivers are sampled.

Thus, it will be realized that the preferred embodiment of the invention may be designated a two-stage time-division multiplexing system, wherein phase-encoded data words transmitted from the individual transceiver units associated with each cable section are ordered in accordance with the propagation delay time of the interrogation signal as transmitted from the central station to the different transceiver units in sequence. Phase-encoded words from corresponding channels within the transceiver units are ordered in accordance with the channel-select sequence during a scan cycle. With this arrangement, therefore, analog signals from all 500 seismic sensor units will be digitized and the digital data words will be transmitted from the cable during each one-millisecond sample interval. Thus, the signal from channel No. 1 of each of the 50 cable sections are transmitted in sequence, followed by channel No. 2 signals from each cable section, etc.

In accordance with further features of one embodiment of this invention, the data and interrogation links comprise three parallel, redundant lines. A majority-vote circuit in each transceiver unit accepts a signal from any two of the three lines. An error-detect circuit coupled to the data and interrogation links at each transceiver unit detects a broken line within the associated cable section when the majority-vote circuit does not detect three identical inputs. The transmission link may be a broadband transmission channel having a bandwidth of at least 100 megahertz.

In accordance with another feature of one embodiment of this invention, each transceiver includes a data repeater which, in turn, includes a signal receiver, regenerator and transmitter to receive, regenerate and retransmit signals from down-link transceivers to up-link transceivers. An artificial delay line in the interrogation network may be provided and series-connected to the interrogation link in each transceiver, thereby to delay the arrival of the interrogation pulse at down-link transceivers and thereby to separate one from another the data words when transmitted from one to another, adjacent cable section.

Another feature of one embodiment of this invention is a calibration signal which is transmitted from the central station to drive each elemental seismic sensor unit. The output of each sensor unit is compared with the input signal to derive a sensor calibration factor.

In an illustrative embodiment of this invention, the cable assembly is a marine streamer cable including a terminator section. The streamer cable may contain auxiliary sensors to detect ambient water pressure and saltwater leakage inside the streamer cable.

In accordance with another aspect of one embodiment of this invention, a means is provided to measure the stretch of the active cable assembly. A shock-absorbing, elastic section is then inserted at the leading end of the cable assembly by means of a strain gauge, and a data transceiver unit is connected to the leading end of the elastic section. Output signals from the strain gauge are transmitted to an auxiliary input channel of the transceiver unit at the leading end of the elastic section.

As an additional feature of one embodiment of this invention, the trailing end of the lead-in cable is connected to the transceiver unit located at the leading end of the elastic section. The leading end of the lead-in cable is secured to a towing vehicle. The lead-in cable includes a trunk cable and a plurality of local auxiliary input channels coupled to the inputs of the transceiver unit located between the lead-in cable and the elastic section. A number of auxiliary sensors, positioned near the towing vehicle, are connected to the local auxiliary input channels.

In order to generally discuss a different aspect of the preferred embodiment of the invention, the following considerations should be taken into account.

In a conventional multichannel analog-to-digital conversion system, use is made of a multiplexer having a plurality of input terminals and a common output bus line. Each input terminal to the multiplexer is connected to receive the output signal of an analog channel and its output bus line is typically connected to an amplifier. Frequently, as in the seismic art, it is desired to eliminate the DC component of the analog signal received by each channel. Therefore, a high-pass R-C filter is typically connected between each input terminal to the multiplexer and the analog channel. Such a filter has a series capacitor and a shunt resistor, and requires that the multiplexer bus line terminate into a high-impedance load. Accordingly, in accordance with prior practice, the bus line was connected to an amplifier having a high-input impedance.

The conventional system of the foregoing character has several drawbacks, chief among which are: The capacitance value of the capacitor in each high-pass filter must be relatively large. Therefore, the capacitor is both bulky and expensive. Since each capacitor requires a separate resistor, the large number of such resistors adds considerably to the cost and bulk of the system, and also constitutes a serious impediment to miniaturization efforts. The required high-input impedance amplifier connected to the output bus line of the multiplexer seriously hampers the available design choices.

For purposes of use with the seismic data processing system of this invention, we preferably provide an improved system wherein the capacitance of each capacitor is considerably reduced, all capacitors share a common resistor connected to the output bus line of the multiplexer and the high-input impedance amplifier can be replaced by a low-input impedance operational amplifier to allow greater design flexibility. Such filter is a commutated, R-C, high-pass filter for use with a multiplexer in a multichannel analog system. Each channel receives an analog signal from a source, such as a seismic sensor. Each channel contains a capacitor connected in series with a normally open multiplexer switch which is connected to a multiplexer output bus line. A common resistor is connected to the bus line. A controller consecutively closes the switches so that the capacitor whose switch has been closed becomes connected to the common resistor to form therewith a high-pass R-C filter. In a preferred embodiment, the common resistor is the input

resistor to an operational amplifier. The cutoff frequency of the commutated filter can be varied by changing the dwell time of the switches.

In order to generally discuss a further aspect of the preferred embodiment of the invention, the following considerations should be taken into account.

In accordance with conventional systems, seismic exploration is conducted over land and water bodies, wherein in either case acoustic signals are injected into the earth and the reflected seismic signals are detected by a large number of seismic detectors, i.e. sensors, arranged into sensor arrays. For example, in marine work, the sensor arrays are housed in a streamer cable which typically is 10,000 feet long and which may contain 50 such arrays. Each array forms a single channel. Each channel is coupled to a seismic recording system through a separate pair of wires. Different sensor arrays are required for different geologic formations, for shallow or deep penetration work and, in general, different arrays are required for satisfying the different demands of geophysicists.

For deep penetration, employing low seismic frequencies, sensor arrays consist of 25 to 35 detectors distributed over 200 to 300 feet. Depending upon the desired response characteristics, the sensors may be spatially tapered within the confines of the array or the sensor outputs may be electrically weighted.

In exploring shallow earth formations, relatively high-frequency seismic energy is of interest. For this application, the required arrays are very short, i.e. 25 to 50 feet or less in length. As few as ten sensors may be used in such arrays.

In general, when seismic exploration requires different arrays for different applications, it is necessary to physically interchange the cables containing the different arrays. It would be desirable to have one single cable containing up to 500 short subarrays, i.e. sets of seismic sensors, which can be electrically reconfigured so as to become equivalent to any type of larger array required for a particular geologic condition. In a conventional system, if each subarray constitutes a single channel, 500 pairs of wires would be required. While a cable formed of 50 pairs of wires is manageable by a seismic crew, a cable formed of say 500 wire pairs for 500 channels would be nearly impossible to accommodate in field use.

Physical limitations involving the weight of the cable and other difficulties have therefore limited the number of channels which have been used in seismic systems up to the present time despite the advantages which could theoretically occur from obtaining information from additional channels. The possibility of transmitting seismic signals representing 500 channels to a central processing point presents numerous other problems. For example, the cost of the required data processing would be very high when using conventional general purpose data processing equipment, despite recent substantial cost reductions.

The matter of transmitting 500 signals to the central station could not practically be accomplished by using 500 separate pairs of wires, as noted above. Another possibility would be to provide 500 separate seismic data processing stations and multiplex the data over a lesser number of channels, so that 500 pairs of wires would not be needed. However, the provision of 500 individual, active data processing stations would be prohibitively expensive. Further, normal carrier type multiplexing would require very high-frequency, tuned circuits and associated electronics which normally is so sensitive and requires so much maintenance, as to be impractical for seismic field use. The direct transmission of digital signals also presents many problems, due to various signal degradation factors. In this connection, it may be noted that the electrical integrating characteristics of extended cables severely degrade conventional bi-level digital signals.

Because of the large number of significant electrical, mechanical, data processing, weight and cost problems as outlined above, up to the present time it has been considered to be impossible or impractical to construct usable, commercial seismic systems in which seismic signals from several hundred sensor units are separately brought back to a central station and recorded.

In accordance with an illustrative embodiment concentrating on this problem, it will be recalled that the seismic data processing system disclosed herein has a number of transceiver units disposed remotely with respect to a central station. The transceiver units are connected to the central station by the broadband data transmission link and an interrogation link. Each unit includes several input channels to each of which is connected a short seismic sensor subarray, also referred to as an elemental seismic sensor unit, consisting of three sensors, separated one from another by about 6-1/2 feet. A channel selector, which is the multiplexer mentioned above, sequentially connects the input channels to a common signal-conditioning and digitizing network including an output channel. The output channel applies digital

data signals from the elemental seismic sensor units (seismic subarrays) to the data transmission link for multiplexed transmission to the central station. In the central station, digital data words, representing seismic signals from the subarrays are weighted and composited by a formatter into new data words representative of a seismic signal that would have been obtained from a desired, much larger seismic sensor array.

In an important aspect of this feature of one embodiment, the digitized seismic signals are formatted into a self-clocking, phase-encoded, return-to-zero pulse code for transmission through the broadband transmission link, in order to reduce signal degradation, as more fully described herein. Thus, the data processing logic in each of the various transceivers preferably includes a local clock. The local clocks operate asynchronously with respect to each other although at substantially identical frequencies.

Each transceiver unit either transmits local data into the broadband transmission link or it receives data words from the farther down-link transceiver units. Data words received from down-link transceiver units are resynchronized to the local clock, regenerated and retransmitted to the next up-link transceiver unit for eventual final transmission to the central station.

For identification, the data words are separated by a short "dead space" of no-data. Furthermore, to identify the beginning of a data word, following a dead space, the first bit of each data word following a dead space, in a preferred embodiment, is characterized by a positive-going leading edge. The end of a data word is sensed when no pulse polarity reversal occurs within any two bit intervals. Suitably, the self-clocking data words are transmitted in constant-current mode.

In accordance with features of one embodiment of this invention, the central station includes a core memory and means are provided to store the digital data words, as received from the elemental seismic sensor units, i.e. subarrays, in a memory matrix in channel-sequential order. The central station also includes a formatter which extracts from the memory data words originating from selected seismic sensor units and combines these signals as new composite data words representative of desired larger arrays.

The central station may also include a coefficient read-only memory (ROM) for applying desired weighting coefficients to the data words from individual subarrays before they are combined as a composite data word.

In the central station, a means is preferably provided to measure the time interval between the application of an interrogation pulse over the interrogation link and the arrival of the respective data words from the transceiver units. The time interval is converted into an address code which is stored in an address memory, thereby to identify incoming data words as to their source in terms of the transceiver unit number and the channel number within each transceiver unit.

A controller in the central station transmits the interrogation pulses to the transceiver units over the interrogation link. In response to the interrogation signals, i.e. pulses, the electronics network in the respective transceiver units samples the analog signal present at an input channel, digitizes the sample as a self-clocking, phase-encoded digital data word and transmits the digital data word to the central station over the broadband transmission link. When the controller senses the arrival of data words from a first channel in all of the transceiver units, it sends out a second interrogation pulse to sample a second channel in all of the transceiver units, and so on, as mentioned above, until all of the input channels in all transceiver units have been sampled, the interval between successive interrogation pulses to the same channel being typically one-half to one millisecond.

In order to generally discuss a still further aspect of the preferred embodiment of the invention, the following considerations should be taken into account. This aspect relates to the problems of obtaining improved signal-to-noise ratios and increasing the capacity for discriminating closely adjacent geological formations or discontinuities and small anomalies, now to be discussed in detail.

In the well-known reflection method of making seismic surveys, a seismic impulse, such as an explosion disturbance, i.e. a shot, is initiated, and a record is made of impulses received at sensors or detectors at spaced locations along a seismic cable extending from the shot-point. The seismic sensors usually used on land are known as geophones, and those usually used in marine seismic cables are termed hydrophones. The seismic waves from the seismic impulse are reflected back to the surface from interfaces between geological layers of different properties or characteristics, to the sensors located over the area under survey. The reflected signals

received at the sensors are transmitted to recording and processing equipment in a ship or seismic vehicle.

In the course of undertaking a survey of this type for an extended geographical area or prospect, the prospect is covered by a grid of survey lines, and seismic profiles are recorded along these survey lines. In marine work, a seismic streamer cable is continuously towed through the water along one of the survey lines, and seismic impulses are initiated from the ship at regular intervals, such as every 10 or 20 seconds. On land, the seismic cable is characteristically in the form of a spread of a series of identical sections laid on the ground and connected together by plug-type electrical connectors. The line of survey through the prospect is traversed by firing a seismic shot, with the recording and data processing equipment located in a recording truck, connected onto the cable. After the shot has been fired and the seismic data have been recorded, one or more of the cable sections are disconnected from one end of the spread, moved and reconnected to the other end of the spread along the direction of travel. A multiple switch in the recording truck is advanced to a new position, thereby advancing the portion of the cable connected to the data processing equipment one or more cable-section lengths along the survey line, whereupon a new recording cycle is undertaken.

Characteristically, in accordance with the prior art, in a 10,000-foot marine streamer cable, approximately 1,500 sensors have been employed. Groups of about 30 of these sensors have been electrically interconnected, so that seismic signals from typically 48 seismic channels are transmitted from the cable. These reflected signals are recorded and displayed in parallel traces to visually portray subsurface features of the geologic area under survey. In the absence of adjustment, the reflected signals appearing in traces which originate with hydrophone groups remote from the shot-point would be displaced with respect to those in traces originating near the shot-point, and would introduce an apparent variation in depth in the representation of a horizontal reflecting interface. In accordance with known techniques, a moveout or angularity correction is applied to adjust the adjacent traces on the display, so as to insure a faithful representation of the reflecting interfaces. The value of the moveout correction is a function of time from the shot, the average seismic-wave velocity in the earth and the distance between the shot-point and the detector groups.

In such reflection-type seismic systems which have been developed up to the present time, as noted above, it is conventional to electrically interconnect about 30 geophones or hydrophones into a single group which has a physical extent along the cable from about 100 to 300 feet; one commonly used distance is about 230 feet. With this arrangement, as noted above, at least 48 conductor pairs are employed to transmit the signals from the 48 groups of sensors to the recorder, normally located in the ship or truck used for transporting the seismic equipment.

Usually, the frequency response of such known systems is at the very low-frequency end of the spectrum, i.e. from about 5 to 40 Hz, with the peak response lying below 20 Hz. Among other factors, the lowered high-frequency response is attributable to phase differences of signals arriving at spaced-apart points along the length of the arrays of electrically connected sensors which normally extend for a distance of about 230 feet, as mentioned above. To avoid cancellation of signals which are arriving at the various sensors, the length of the electrically connected sensor units, i.e. arrays, preferably should be relatively small as compared with the wavelength of the seismic signals which are being received.

To extend the analysis on a more quantitative basis, an array, or group, of electrically connected seismic sensors disposed on the earth's surface will be considered, the array having a length s . If a seismic wave travelling horizontally along the array is incident at one end of the array, the time T required for the wave to traverse the array is

$$T = s/v \quad (A)$$

wherein v is the acoustic velocity of the propagating medium adjacent to the array. In water, the acoustic velocity is approximately 5,000 feet per second, hence the transit time T of a horizontally travelling wave in water for a 230-foot array of electrically interconnected sensors would be 0.046 of a second. For additive reinforcement along the length of the array or unit of sensors, the array length should be less than about one-quarter wavelength. The time for such a seismic wave to travel one wavelength is 0.046×4 , i.e. about 0.184 of a second, which is the period of a wave having a frequency of about 6 Hz, i.e. six cycles per second. Waves travelling along the array and having frequencies substantially greater than the 6-Hz

cutoff limit tend to be cancelled. When the length of the array is exactly one-half wavelength, the response of the array is zero, since the wave is totally cancelled.

Of course, as is well known, seismic waves may be incident upon a sensor array from many angles. For example, seismic waves reflected from deep geologic formations propagate towards the sensor array in a near-vertical direction. The wavefronts are detected nearly simultaneously by all the sensors in one array. Accordingly, in the absence of near-surface irregularities, such as weathering or elevation differences, the upper cutoff frequency is virtually infinite.

On the other hand, the travel path of seismic waves reflected from very shallow earth layers, whose depth is significantly less than the distance from the shot to the sensor array, approaches the horizontal, so that the foregoing analysis for horizontally travelling waves is applicable. Consider, for example, the relatively flat incident angle of a seismic wave reflected from a layer 1,000 feet deep with respect to a sensor array 10,000 feet away from the shot-point.

Typically, seismic reflections from shallow layers are relatively rich in the high frequencies (100 to 500 Hz) that are useful for high-resolution analysis of details of geological features. Unfortunately, presently employed seismic systems, with sensor array lengths of from 100 to 300 feet, are selectively responsive to very low frequencies, with the frequencies below 20 cycles per second predominating. The desired high-frequency waves from shallow earth layers will be cancelled by the use of long sensor arrays.

Of course, the emphasis on the lower frequencies in conventional large-area prospecting systems limits the sensitivity and the power of the system to detect and resolve closely spaced geological layers, minor discontinuities or other significant features which may not be extensive in size, particularly in the shallow part of a geological section. Further, now that many of the prospects of principal interest have been surveyed on a reconnaissance basis, it is becoming increasingly important to employ geophysical surveying techniques of high resolution for detail work.

Sensor arrays of considerable lengths have been used preferentially in reflection seismic exploration in order to discriminate between signals and unwanted noise. The general theory explaining the relation of array length to the signal-to-noise ratio may be found in the paper *The Moveout Filter* by Savit, Brustad and Sider, "Geophysics", January, 1958.

From time to time, attempts have been made to improve the high-frequency response of seismic sensor arrays by using very short arrays. Unfortunately, the most common result was a considerable degradation of data quality, owing to the inevitable decrease in signal-to-noise ratio.

Some exploration seismologists gave preliminary consideration to the possibility that the final signal-to-noise ratio could be restored to a value comparable to that of arrays in common use by greatly increasing the number of arrays, in effect retaining the number of individual sensors in common use but subdividing them into many more, but shorter, arrays. However, the combination of two principal factors rendered this procedure impractical. The first had to do with processing procedures. In order to determine the normal moveout corrections to be used in assembling the data, as received, correlation (or equivalent) processes have to be used among sets of individual seismic traces (data from individual arrays). With data from short arrays, the poor signal-to-noise ratios reduced the effectiveness of this process. Furthermore, the vastly increased number of individual data recordings increased data reduction (processing) costs to levels unacceptable for commercial prospects. Moreover, many other problems and complexities made the implementing of such a system appear to be a project presenting insurmountable difficulties.

More specifically, another difficulty resulting from the use of shorter arrays of sensors is that, for example, if a full length two-mile seismic cable is to be employed, and if the sensor density is to remain unchanged, the number of signal channels which must be connected to the recorder is increased by an order of magnitude as the array length is reduced. This would mean that about ten times as many conductor pairs would have to be added, if the array lengths were to be significantly reduced. This, of course, would greatly increase the number of contacts required in connector plugs used to couple cable sections made according to previously proposed techniques. Further, the large number of conductors would greatly increase the weight and the bulk of the cables and decrease their flexibility to unacceptable levels.

Typical prior art systems which are useful in reviewing the background of the presently discussed aspect include United States Patent No. 3,133,262 of Booth B.

Strange, "Dual Seismic Surveying System", granted May 12, 1964, which discloses two overlapping hydrophone spreads in a single marine cable; United States Reissue Patent No. Re 25,204 of Carl H. Becker, "Method of Geophysical Exploration"; C. H. Savit, et al., United States Patent No. 3,096,846, granted July 9, 1963, entitled "Method and Apparatus for Seismographic Exploration", which discloses fixed tapering and weighting of seismic signals from different seismic sensors to provide directivity; J. P. Woods, et al., United States Patent No. 3,346,068, which discloses directionally sensitive seismic transmitting and receiving arrangements; C. E. Welles, United States Patent No. 3,689,873, which discloses some delay and weighting circuits for seismic signals; and R. G. Quay, United States Patent No. 3,613,071, which shows the use of two arrays of geophones, having different spacing and different sampling rates.

In order to solve these problems, we have developed a seismic system for the systematic surveying of extensive prospects which is responsive to significantly higher frequencies than such systems which have been employed heretofore. More specifically, it is contemplated that relatively short elemental sensor, such as hydrophone, units shall be employed throughout the full length of a normal size seismic cable. In a specific illustrative embodiment of the cable, only three sensors are employed in one elemental sensor unit, and these are spaced 6.25 feet apart to provide an elemental sensor unit length of approximately 12.5 feet. From equation (A), and if water is assumed to be the medium, the criterion that 12.5 feet is one-quarter of a full wavelength of 500 feet, it follows that the period of the wave is 0.010 of a second, corresponding to a limiting frequency of 100 Hz. In the case of a reasonable angle of incidence for shallow reflections of about 60°, the upper frequency limit is 200 Hz. Horizontally travelling noise having a frequency substantially above 100 Hz is attenuated, which is desirable to improve signal-to-noise ratios. Thus, by use of short elemental sensor arrays, the upper frequency cutoff point has been raised from 6 to 100 Hz for seismic waves propagating nearly horizontally. Of course, with an even shorter sensor unit length, an even higher frequency response would be obtained. A 6.5-foot sensor unit length raises the response for horizontal propagation to about 200 Hz. With a somewhat greater elemental sensor unit length, such as 25 feet, the response would be reduced to 50 Hz, which is, of course, still a great improvement over presently used commercial prospecting systems.

It was found that the longer array lengths necessary to achieve high signal-to-noise ratios for each of the larger number of individual traces making up the cross section are attained by adding the signals from the required number of elemental sensor units with such time delays as are needed to insure that all the reflection signals which are to be combined into one trace are summed substantially in phase, and these delays are changed during the course of a shot to steer the arrays producing the traces. In effect, the delays render the arriving wavefront parallel to the array, so that the phase velocity of the signal along each array is effectively infinite.

Since the dip of subterranean reflecting geological interfaces is generally unknown to the seismic surveyor prior to conducting the survey. It will normally be necessary to assume a priori that all these reflectors are horizontal and to apply time delays to correspond to those which would apply to a horizontal reflector giving rise to the signal received at each moment in time and at each distance from the shot-point. To the extent that such programmed time delays do not correspond to the real signal delays, the signals will be summed out of phase. The phase error will, however, normally be much smaller than the phase error resulting from the simple, simultaneous summations produced by the fixed arrays of the prior art. Accordingly, the upper limit of the frequency response will be substantially higher.

As will be described further below, the individual recordings of data from separate sets of sensors forming arrays are preserved, so that after a first-cut processing as described above, the array-forming time delays may be reprogrammed and reapplied, to more precisely and effectively align the wavefront to be parallel to the horizontal (i.e. parallelism with the array) and thereby achieve a more nearly in-phase sum, which will have a substantially higher high-frequency cutoff point.

The use of shorter lengths of sensor units with the full length cable, as required for expeditious prospecting work, raises the problem of transmitting the resultant great number of signals to the recorder, without requiring an unduly bulky, heavy and expensive cable. This difficulty has been overcome by the feature that the electronics are included within the cable to sample and multiplex the signals from each of the relatively short elemental seismic sensor units and to send the signals over a single data transmission link, i.e. channel, or over a greatly reduced number of such channels, to the recording and processing equipment located at one end of

the cable. Preferably, the sampling rate for the multiplexed signals will be more than twice the highest frequency to be transmitted. Accordingly, in one embodiment of the presently discussed system, a sampling rate in the order of at least 500, and preferably 1,000 or more, samples per second is employed.

In systems, such as the present system, where higher frequency seismic signals are employed, i.e. put to use, certain problems arise which are not encountered, or at least not to the same extent, at lower frequencies. More specifically, for example, when a geological formation making a substantial dip angle with the horizontal is encountered in a geophysical survey, high-frequency signals of 100 or 200 Hz may be greatly attenuated by the prior art long arrays. Further, a significant difference in amplitude and in frequency content may appear in the received signals from a layer having a substantial dip angle, depending on the direction of deployment of the seismic sensors with respect to the direction of dip, or the orientation of the seismic array or cable relative to the shot-point.

This problem is proposed to be solved by arrangements which perform the function of continuously steering each of a number of arrays, established along the length of a seismic cable, into the expected direction from which reflected seismic waves will travel during successive intervals of time. In particular, the higher-frequency energy, which is more emphasized by smaller geological discontinuities and formations, will be detected more readily by the directional arrays, and the system will not give disparate results, depending on the direction of traverse along a survey line in an extended survey.

In light of the foregoing background, this aspect of one embodiment of the present invention involves a geophysical exploration method in which at least two arrays of sensor units (hydrophones or geophones) are established in a single seismic cable, and a geophysical survey is undertaken by individually varying the directivity of each of these arrays to selectively receive signals from a seismic disturbance as reflected from one after the other of progressively deeper strata. The array outputs are subsequently processed to produce geophysical cross sections.

Thus, there is provided a reflection seismographic exploration method, comprising the steps of initiating a seismic disturbance, establishing at least two direction-sensitive seismometer arrays in a cable, and forming a geophysical survey by individually varying the directivity of each of the arrays during the course of recording reflections of the seismic disturbance, thereby to obtain array signals.

As explained above, the seismic cable of the preferred embodiment of the invention is provided with a large number of generally uniformly spaced elemental seismic sensor units, and signals from each of these units are transmitted from the cable to seismic data processing apparatus, instead of being electrically combined within the cable. As noted above, in known marine cables, about 10,000 feet in length, approximately 1,500 hydrophones are employed and the signals from groups, i.e. arrays, of about 30 of these hydrophones would be combined to form a single channel so that seismic signals from 48 channels would be transmitted from the cable. By way of contrast, the present invention might involve the use of approximately the same total number of seismic sensors, but would combine the outputs from only a few sensors to form an elemental sensor unit signal, and transmit seismic signals representing several hundred of these elemental sensor units from the cable. These seismic signals are combined to produce a lesser number of directional array signals representing adjacent paths through the geological structure toward which the individual arrays are directed by continuously changing the momentaneous direction. These array signals are subsequently combined to produce a geophysical representation of a cross section of the earth.

Thus, a seismic cable assembly is provided which has a great number of short elemental sensor units and, as stated above and explained in detail below, signals from each sensor unit are sampled and multiplexed into a single data transmission channel connected to a recording and storage device. An array former assembles the stored data to synthesize the response of an array having any desired characteristics.

The central station of which the array former is one component suitably includes a high-capacity recorder of the video-recorder type to store the digital signals representing seismic signals from all of the multiplicity of elemental sensor units in each of the many sets of such units within the seismic cable. The recorded digital signals are then processed by a second array former by synthesizing a plurality of direction-sensitive sensor array signals along the line of survey, forming a series of geophysical traces by individually directing the arrays toward expected reflection points, which change as a function of reflection travel time, after a

shot. This technique makes it possible to record more selectively the energy reflected at varying angles from adjacent paths through the geophysical structure being surveyed, to the respective adjacent arrays along the length of the cable. Subsequently, the traces formed from adjacent arrays are combined by means well known in the art to produce a complete geophysical cross section.

It was found to be useful when it is possible that the initial signals received by the first portion, or portions, of the seismic cable closest to the shot-point may be sampled at a higher rate. At a later stage in the recording cycle from the same shot, when the reflections reach the more distant parts of the cable, the sampling rate for each elemental sensor unit along the entire cable will be reduced. More specifically, during the initial period, when reflected seismic signals are reaching only sensors in the first half of the cable, each of the sensor units in this portion of the cable can be sampled at twice the normal rate, and the sensor units in the second half of the cable will not be sampled at all. With this arrangement, the recorder will, of course be recording the same number of total samples during the entire recording, i.e. scan, cycle, because during the first portion of the cycle the sensor units on the first half of the cable will be sampled twice during the normal scan cycle, also called sampling interval, whereas in the later portion of the scan cycle, all of the units will be sampled once during the normal sampling interval. After a time interval less than that required for reflected signals to reach the second half of the cable, the system will shift to the second mode in which all of the sensor units will be sampled at a somewhat slower rate. By way of specific example, if the normal sampling rate for the entire cable is one sample per millisecond, then, during the initial interval, the sensor units in the first half of the cable could be sampled at a rate of two samples per millisecond, while no sampling from the second, more remote, portion of the seismic cable will take place. During both portions of the cycle, the recorder will be receiving samples at a rate equal to the product of 1,000 samples per second times the total number of sensor units in the cable. It is noted in passing that the initial signals received by the near portion of the seismic cable will include higher frequency components because of the relatively short travel paths traversed by the seismic waves, and these higher frequencies may be faithfully recorded at the higher sampling rate. Thus, with samples from the nearer portion of the cable being taken at a rate of 2,000 samples per second, instead of 1,000 samples per second, the maximum information which can be transmitted approaches that occurring at 1,000 cycles per second instead of 500 cycles per second, which is one-half of the lower sampling rate. Accordingly, the higher sampling rate permits even higher definition, i.e. resolution, for selected portions of the geologic section being surveyed.

A particular feature of one embodiment of the invention involves the use of ten or more arrays, i.e. sets of sensor units, spaced along a cable, with each such set including a plurality of elemental sensor units, and combining the signals from the sensor units thus making up each array with selected delays between the combined signals, precisely sufficient to direct the array toward adjacent subsurface points in the area under survey, with the delay between units being different for different signal arrays, and also varying with time, thereby to direct the arrays to receive signals from successively deeper strata. The resultant trace signals may then be combined, employing the usual moveout-correction and display techniques, to produce the complete seismic section.

These features are rendered useful from a practical point of view by the use of specific cable electronics circuitry, with its alternating current power supply operating at a high frequency above the seismic signal band of interest, special amplification, digitizing, and test circuits, and the array former special data processing circuits, including, for example, the matrix storage arrangements for holding a "time-window" matrix of seismic signal samples, and high-speed arrangements for making a weighted combination of selected samples to form the seismic trace signals from which the survey cross section is prepared.

Now that many of the individual features of a specific embodiment of the invention have been noted, it is useful to return to certain of the basic design aspects and to note how the various features contribute toward the achieving of the final result. As noted initially, improvement of the signal-to-noise ratio and increased sensitivity and discrimination of large-scale seismic prospects are among the problems to be solved. These objects are achieved in general by increasing the high-frequency response of the seismic system. Factors which contribute to the increased high-frequency response include (1) the close spacing of the elemental sensor units, (2) the generation and transmission of a large number (in the order of several hundred)

seismic signals from a seismic cable of a given length, (3) the combining of elemental seismic sensor unit signals on a continuously variable delay basis to provide directional array signals always pointing to the depth from which the reflected signals are expected to arrive, and (4) providing in-cable electronics to amplify, digitize, multiplex in two stages, correct, test and otherwise process the high-frequency seismic signals and bring them out of the cable. It is emphasized that all of the foregoing factors, and many others enumerated in the present introduction and specification, all play a part in, and contribute significantly to, the complete system disclosed in the present specification.

It is believed that the disclosed seismic data processing system has approximately doubled the resolution of large-scale seismic prospecting systems, by raising the upper limit of the pass band of the seismic system by at least one octave. More specifically, the upper 6 db-down point encountered in large-scale seismic systems up to the present has been about 40 Hz, as compared with at least 80 Hz for the system and method disclosed in this specification.

In order to generally discuss a still further aspect of the preferred embodiment of the invention, the following considerations should be taken into account.

As this embodiment relates in general to seismic analog signal data acquisition systems wherein the outputs from a plurality of signal-receiving channels are multiplexed and the amplitudes of the sampled signals converted into digital words, it is believed to be helpful to recall that, in a conventional, multichannel, analog-to-digital conversion system, use is made of a multiplexer having a plurality of input terminals and a common output bus line. Each input terminal to the multiplexer is connected to receive the output signal from an analog device, such as a seismic sensor. Frequently, as in the seismic art, it is desired to eliminate the DC component of the analog signals received by each multiplexer channel. Therefore, a DC blocking capacitor is typically connected between each input terminal to the multiplexer and the analog device. The multiplexer bus line is connected to a signal-conditioner-and-amplifier network, referred to herein as a SCAN. Thus, a SCAN samples the signals and conditions and amplifies the sampled signals.

For reasons which are well known to those skilled in the art, spurious voltages are developed across the DC blocking capacitors and the SCAN. The spurious voltages can be attributed to thermoelectric effects, Peltier effects, offset drifts in the amplifier stages, field-effect transistor (FET) switches having feedthrough capacitors and leakage resistors between their control and switching elements, etc. The spurious voltage problem is particularly acute in the seismic art because the incoming analog signals have an extremely wide dynamic range, say up to 1200 db (1:1,000,000). Quite frequently, the spurious voltage is of a magnitude comparable to that of the detected seismic signals.

In a typical prior art multichannel, seismic system, each channel has a DC blocking capacitor connected to one terminal of a normally open multiplexer switch, while the other terminal of the switch is connected to the multiplexer output bus line. The bus line is connected to the signal-conditioner-and-amplifier network (SCAN) which includes control means for consecutively closing the multiplexer switches. The capacitor whose switch has been closed will transmit the spurious voltage thereacross through the SCAN to a utilization device, typically an analog-to-digital converter.

In accordance with the presently discussed feature of one embodiment of this invention, the blocking capacitor of one of the input channels to the multiplexer is grounded, thus making this channel a test channel. The spurious voltage developed across the capacitor in the test channel will be substantially the same as each one of the spurious voltages developed across the capacitors in the signal-receiving multiplexer channels, because all of the capacitors and switches are substantially identical. A sample-and-hold (S/H) network, i.e. circuit, consisting of a series capacitor and a normally ungrounded shunt switch is connected between the output of the SCAN and the input to the analog-to-digital converter, constituting the utilization device. Periodically, namely during each scan cycle of the multiplexer, the charge in the blocking capacitor in the test channel will be transferred to the series capacitor in the S/H circuit but with opposite polarity and preferably of equal amplitude as a sample voltage. Each spurious voltage from each signal-receiving channel will be added successively and algebraically to the sample voltage and, therefore, substantially cancelled by the sample voltage.

Thus, preferably, each transceiver unit comprises a plurality of signal-receiving input channels of which one receives no signals and is grounded, a multiplexer having a plurality of inputs and a common output bus line, there being a capacitor

connected between each of the input channels and one of the multiplexer inputs, each capacitor having a spurious voltage developed thereacross, during operation, combined with circuit means including an amplifier for connecting the multiplexer bus line to a utilization device and a sample-and-hold circuit connected between the circuit means and the utilization device, the sample-and-hold circuit means comprising a shunt switch and a series capacitor for developing a sample voltage thereacross equal and of opposite polarity to the spurious voltage each time that the grounded input channel is scanned by the multiplexer and the shunt switch is closed whereby, during use, the sample voltage will successively cancel out the spurious voltages from the signal-receiving channels, as the multiplexer scans the signal-receiving channels.

In order to generally discuss a different aspect of the preferred embodiment of the invention, the following considerations should be taken into account.

In the multichannel analog/digital seismic data processing system described herein, the signals are first multiplexed, i.e. sampled, and then converted into digital numbers corresponding to the sampled signal amplitudes. When these amplitudes have a very wide dynamic range, say between 0 and 90 db, it is desirable to first pass the sampled analog signals through a binary gain-ranging amplifier system prior to converting them into digital numbers. In this fashion, the amplified output signals will fall within a limited range thus enhancing the signal-to-noise ratio.

A widely employed, known binary gain-ranging system includes a plurality of fixed-gain amplifiers whose outputs can be selectively connected to a common bus line by a system controller. A comparator makes a comparison between the amplitude of the output signal from the common bus line and a single reference voltage. If the output signal is smaller than the reference voltage then the comparator will cause the controller to insert into the system an additional amplifier. The process is repeated until the output signal from the common bus line becomes greater than the single reference voltage. The gain of a number of cascaded amplifiers can be expressed in exponential form to any particular base, typically 2. For example, if the gain is to range in incremental gain steps having a ratio of 2:1 from 2^0 to 2^{16} , sixteen gain decisions and fifteen amplifiers are required. The drawbacks of such a binary gain-ranging system stem primarily from the relatively large number of required fixed-gain amplifiers. Also, the comparator must be adapted to make sixteen decisions based on sixteen comparisons and the controller must be adapted to execute these sixteen decisions.

In such a system, the total time required to select the proper gain in order to amplify each sampled analog signal, including the time required by the amplifiers to settle to their steady states is relatively long, so that the system is wasteful of expensive data processing time. Additionally, the large number of required amplifiers and associated hardware would require a larger volume than is generally available in miniaturized systems. Furthermore, since signals having different amplitudes must pass through different numbers of amplifiers, differences in amplifier characteristics of the various amplifiers adversely affect the output signals.

Accordingly, it is desirable to reduce the number of required amplifiers and to reduce the size of conventional gain-ranging amplifier systems for purposes of this invention, which solves this problem, also by providing a new and improved binary gain-ranging system which is especially adapted for use in confined areas, for example within the seismic streamer cable used in the seismic data processing system of one embodiment of the invention, the cable having an outside diameter of only a few inches.

The gain-ranging amplifier system developed for this embodiment comprises at least two, preferably four, bi-gain amplifiers connected in cascade between an input terminal and an output terminal. Each amplifier normally has a low-gain state and can be switched by a controller to a high-gain state. Voltage reference means selectively provide a discrete reference voltage to correspond with each amplifier. A comparator makes a comparison between the system's output voltage and the selected reference voltage. If the comparison shows that the reference voltage is greater than the output voltage, the controller adjusts the first amplifier to its high-gain state. Thereafter, the comparator makes a second comparison between the system's output voltage and the reference voltage which corresponds to the second amplifier. Again, if the comparison indicates that the reference voltage is greater than the output voltage, the controller will adjust the second amplifier to its high-gain state. This process will be repeated until the comparison indicates that the system's output voltage is greater than the reference voltage corresponding to that of at least one of a particular amplifier, or until all of the amplifiers have been

adjusted to their high-gain states. Thus, the overall gain of the system is adjustable in incremental steps from a low-gain value, preferably unity, for large-amplitude incoming signals, to a high-gain value for small-amplitude incoming signals. By this means, no amplifier is in danger of being overdriven.

In accordance with a feature of one embodiment of the invention, arrangements are provided for automatically cancelling DC or very low-frequency noise signals that may be present at the input terminals to each amplifier as a result of the individual amplifier characteristics. The noise-cancelling circuit includes a capacitor and a switch connected between the input-output circuit of each amplifier for periodically isolating the amplifier and charging the capacitor with the self-generated amplifier noise. The charge on the capacitor will have an amplitude and polarity equal and opposite to the self-generated noise, such that it substantially cancels the DC noise signals appearing on the input terminals to each amplifier.

A distinct advantage of the disclosed system stems from the fact that all four amplifiers are always connected in the circuit. The above fact being true, there is no danger of differential distortion at different signal levels as was true of the prior art.

Thus, in broad terms, the telemetry system comprises a gain-ranging amplifier system comprising a number of cascaded amplifier stages each having an input and an output, and each having n gain states, there being provided a switching system for controlling the gain state of the amplifier stages in response to the output from the amplifier system, wherein the gain states are so chosen and the switching system is so configured that the overall gain of the cascaded amplifier stages may be made to equal the consecutive powers of n from the zeroth to the 2^m-1 th.

Returning now to the main aspect of the invention, it will be apparent that the preferred embodiment can be designed to provide equipment for initiating a desired switching sequence in at least one of a plurality of data acquisition units, in practice the transceiver units mentioned above. The acquisition units are positioned in a desired pattern at locations remote from a central signal processor at the central station which includes a control-signal transmitter. The acquisition units are substantially equally spaced from one another along one or more transmission links, also referred to as transmission channels. The acquisition units are connected to the control signal transmitter by two signal transmission links. The travel velocity of a signal through the first link is less than that through the second link. During operation, a first signal is transmitted through the first link to the plurality of data acquisition units. A second signal is transmitted through the second link after a preselected time delay following transmission of the first signal. The signal travelling through the second link overtakes the signal travelling through the first link at the specific data acquisition unit thus selected for some switching action. When the simultaneous presence of both signals is detected at the selected data acquisition unit, the desired switching sequence is initiated.

One may also initialize a desired switching sequence pertaining to one scan cycle in all of the acquisition units. The first signal may be characterized by one of a plurality of properties or states. When the state of the first signal is identified, a desired switching action is initiated in all of a data acquisition units in turn, in response to the particular state of the first signal.

Thus, this aspect forms part of a system for transmission and selective control of sub-multiplexed seismic data over a signal transmission link to a common central station including the signal processor. A plurality of data acquisition units are connected to the central signal processor through the signal transmission link. The data acquisition units are evenly spaced apart from one another in an array at increasingly greater distances along the transmission link from the central station and processor. The signal transmission link includes the interrogation channel, control channel and the data channel. The signal propagation velocity through the interrogation channel is different from the propagation velocity through the control channel.

Associated with each data acquisition unit are the plurality of analog data input channels, the multiplexer operable as the channel-selector, the analog-to-digital converter and the output signal storage register, as mentioned above and described in detail below. The input signals from the input channels are multiplexed, converted to digital form and temporarily stored in the output signal storage register.

The output signal storage register of each data acquisition unit, i.e. transceiver unit, is connected to recording apparatus in the central processor of the central station through the data channel of the signal transmission link. The data acquisition

units further are provided with an interrogation-signal-property identifier and first and second signal coincidence detectors.

At selected sample intervals, the controller transmits an interrogation signal through the interrogation channel to each data acquisition unit in sequence. The interrogation signal is characterized by one of a plurality of properties. When the signal-property identifier responds to an interrogation signal having a first property, it resets the multiplexer. When the signal-property identifier detects a signal having a second property, it advances the multiplexer and outputs data from the output signal storage register into the data channel for transmission to the recording apparatus. Additionally, any given data acquisition, i.e. transceiver, unit receives, regenerates and retransmits data arriving from more remote such units.

At a preselected time, different from the time of transmission of the interrogation signal, a control signal may be transmitted through the control line by the control means. The preselected time difference is $(n-1)R$, wherein n is an integer representing the rank of the n th data acquisition unit and R is the signal travel time difference of the signal through the interrogation and control channels between any two data acquisition units.

The interrogation signal is preferably a pulse of preselected duration, i.e. width. The property or state of an interrogation signal which is employed as a control parameter in the embodiment disclosed herein is then the width of the pulse. A wider pulse is defined as having a first property, while a narrower pulse is defined as having a second property or state. The width of a narrower pulse is preferably about one half of the width of a wider pulse. The width of a wider pulse is preferably less than one-half of the preselected sample interval.

In accordance with an important aspect of this embodiment of the invention, a desired switching sequence is initiated in the members of a desired subset of consecutive data acquisition units, the subset being selected from the plurality of data acquisition units. The subset includes a first selected unit and a last selected unit. An interrogation pulse in the first state is transmitted from the central processor through the interrogation channel. After a selected time delay, a long control pulse is transmitted through the control channel. The leading edge of the long control pulse overtakes and intercepts the interrogation pulse in the first state at the first selected unit. The trailing edge of the long control pulse overtakes the interrogation pulse and then passes ahead of the interrogation pulse at all units beyond the last selected unit. The length of the long control pulse is equal to a first integral multiple of the signal travel time difference through the two channels between any two data acquisition units. The desired switching sequence will occur only in those units where the interrogation and control pulses are substantially simultaneously present. The first integral multiple is equal to the number of members, less one, included in the subset. The selected time delay is a second integral multiple of the signal travel time difference between any two data acquisition units, the second multiple being equal to the number of units intervening between the first selected unit and the central processor.

In accordance with a further feature of this embodiment of the invention, three parallel control channels are provided. A majority-vote circuit at each data acquisition unit is coupled to the three control channels. A delayed long control pulse is transmitted through the three control channels in parallel. Simultaneous reception at a data acquisition unit of an interrogation pulse in the first state through the interrogation channel and a long control pulse through at least any two of the three control channels initiates a first desired switching sequence.

In accordance with another feature of this embodiment of the invention, a delayed short control pulse is transmitted through the first one of the three control lines. Simultaneous arrival at a selected data acquisition unit of an interrogation pulse in the first state and a delayed short control pulse through the first control channel initiates a second desired switching action.

In accordance with yet another feature of this embodiment of the invention, a third desired switching action in a selected data acquisition unit is initiated by the simultaneous arrival of an interrogation pulse in the first state through the interrogation channel and a delayed short control pulse through the second one of the three control lines.

In addition, a fourth desired switching action in a selected data acquisition unit may be initiated by the simultaneous arrival of an interrogation pulse in the first state through the interrogation channel and a delayed short control pulse through the third one of the three control lines.

In another embodiment of this aspect of the invention, interrogation and control pulses are repeatedly transmitted to the data acquisition units at short sample intervals, which may be less than one millisecond. The width of the control pulse is adjusted to enable the desired switching sequence in at least some of the data acquisition units. For example, half of the units closest to the central station including the processing unit may be activated. The number of pulse transmissions may be in the order of 500 to 1,000 such transmissions, extending over a time period of one-half to one second. Thereafter, the width of the control pulse is adjusted so as to enable the desired switching sequence in all of the data acquisition units. At the same time, the pulse-transmission repetition interval is increased to one or two or more milliseconds. Additional pulse transmissions may then number from 1,000 to 6,000 or more such transmissions, to complete a recording cycle.

In accordance with a still further embodiment of this aspect of the invention, interrogation and control pulses are repeatedly transmitted to the data acquisition units at preselected sample intervals after a first recording cycle is initiated. The width and time of transmission of the control pulse are adjusted to enable a desired switching sequence in a first subset of data acquisition units containing a preselected number of member units. After the first recording cycle has been completed, a second recording cycle is initiated and the width and time of transmission of the control pulse are adjusted to enable a desired switching sequence in a second subset of data acquisition units. The above steps may be repeated a plurality of times to provide a means for enabling a desired switching sequence in successive subsets of consecutive data acquisition units.

In accordance with yet another feature of this aspect of the invention, the width of the control pulse remains constant for each recording cycle. For each recording cycle, the time of transmission of the control pulse is delayed with respect to the transmission time of the interrogation pulse by a different integral multiple of the signal travel-time difference, i.e. delay, between any two units. For example, by increasing the delay by one unit multiple after each recording cycle, successive subsets of data acquisition units will be enabled consecutively, thereby providing the desired roll-along capability as described above.

By the use of a single, time-delay two-stage-multiplexed telemeter link, it now becomes economical and practical to initially deploy an indefinite number of seismic sensor units. Use of a single telemeter link reduces the bulk of the seismic cables such that the desideratum of providing 500 to 1,000 separate data channels may now be achieved.

Thus, in accordance with another aspect of the invention, there is provided a method for signalling members of a subset of seismic data acquisition units in a system according to the first aspect, the method comprising the steps of transmitting a first signal to the seismic data acquisition units; transmitting a more rapidly travelling second signal to the seismic data acquisition units; and delaying transmission of the second signal with respect to the first signal, so that the first and second signals are present substantially simultaneously at the members of the selected subset of seismic data acquisition units.

According to another aspect of the invention, there is provided a method of seismographic signalling comprising the steps of: providing a central station; disposing a plurality of substantially-identical, multiple-input-channel, data acquisition units in spaced-apart relationship, remotely with respect to said central station; connecting seismic sensors to the input channels of the units; interconnecting said data acquisition units with said central station by a digital data-signal transmission channel and by two control-signal transmission channels; initiating a seismic disturbance; transmitting from said central station a first control signal having a desired duration through one control signal channel; transmitting from said central station a second control signal having a first characteristic through the other control channel and retarding propagation of said second signal by a known time increment per data acquisition unit; delaying the transmission of said first control signal with respect to said second control signal by an integral multiple of said known time increment, so that said first and second signals are coincident at the members of a desired subset; and sensing, in each data acquisition unit, the coincident presence of said two signals as a data-acquisition-unit selection signal.

For a better understanding of the invention and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings, wherein:

Figure 1 is an overall, schematic view of an illustrative embodiment of a seismic data processing system deployed in water;

Figures 2a to 2d are cross-sectional views of a section of a seismic cable of Figure 1;

Figures 3a to 3d are cross-sectional views of a connector module with transceiver unit forming part of the seismic cable of Figure 1;

Figure 4 is a circuit diagram of the power-supply connections for the transceiver units;

Figure 5 is a schematic circuit diagram of a transceiver unit;

Figure 6 is a schematic diagram of majority-vote and error detect circuits;

Figure 7a is a schematic illustration of a pressure transducer;

Figure 7b shows the electrical connections of the auxiliary channels;

Figure 8a is a cross-sectional view of a terminator section;

Figure 8b is a schematic illustration of the electrical connections in the terminator section;

Figure 9 is a cross-sectional view of the lead-in cable section;

Figure 10 is a timing diagram showing one type of a self-clocking code for transmitting data words;

Figure 11 is a timing diagram of a scan cycle;

Figure 12 is a timing diagram showing the sequence of interrogation signal and data signal transmission with respect to two cable sections;

Figure 13 is a timing diagram illustrating a method for activating three consecutive transceiver units but no others;

Figure 14 is a schematic block diagram representation of a typical filter circuit for a seismic analog-to-digital signal processing system;

Figure 15 is a diagrammatic representation of a commutated high-pass filter;

Figure 16 is a schematic representation of an analog-to-digital conversion system utilizing the commutated filter of Figure 15;

Figure 17 is a schematic block diagram representation of the seismic data processing system of this invention;

Figure 18 is a schematic representation of the electronics contained in a transceiver unit;

Figure 19 is a detailed schematic representation of the repeater network in the transceiver unit of Figure 18;

Figure 20 shows timing diagrams useful in explaining the operation of the system of Figure 17;

Figure 21 is a schematic representation of an array former as contained in the central station of one embodiment of a system in accordance with the invention;

Figure 22 illustrates modifications in the form of different pulse codes, as used by the equipment of this embodiment of the invention;

Figure 23 is a diagram of a marine seismic exploration system;

Figures 24 and 25 are diagrams of the response of an unsteered seismic cable array at various frequencies as a function of the dip or tilt of the strata from which signals are reflected;

Figure 26 is a diagram indicating the configuration of a typical known unsteered seismic array;

Figure 27 is a diagram illustrating a tapered array;

Figure 28 is a plot of an illustrative example of the root mean square (RMS) velocity of seismic waves as a function of the reflection time from the initial "shot" until seismic reflection reaches a sensor;

Figure 29 is a simplified diagram employed in calculating the delay at adjacent sensor units making up a multi-unit seismic array;

Figure 30 shows the response of a steerable seismic array as a function of dip angle;

Figure 31 is a block diagram of an illustrative embodiment of a seismic data processing system;

Figure 32 is a block diagram of the cable electronics and the seismic sensor units which are employed in an illustrative embodiment of the invention;

Figure 33 is a detailed block diagram of an array former which forms part of the circuit of Figure 31;

Figure 34 is an overall block diagram of the special purpose data processing equipment employed in the implementation of the beam steering array former;

Figure 35 is a diagram illustrating the formation of arrays in the beam steerer of Figures 31 and 34;

Figure 36 is a simplified schematic block diagram representation of a typical digital-to-analog conversion system;

Figure 37 is a simplified schematic block diagram representation of such system as modified to provide DC-offset removal;

Figure 38 is a diagram of a modified circuit corresponding to that of Figure 37, but having the filter of Figure 15 substituted into the input channels;

Figure 39 is a block diagram representation of a binary gain-ranging amplification system as used in the illustrated embodiment of the invention;

Figure 40 is a schematic diagram of an amplifier stage of the system of Figure 39 with noise-cancelling means;

Figures 41 and 42 are schematic representation of the noise-cancelling principle implemented in the circuit of Figure 40;

Figure 43 is a greatly simplified, schematic representation of a multichannel seismic data processing system showing the data acquisition units which are the transceivers, interconnected through a multichannel telemetry link to the central signal processor, which is the common central station, this representation being used in explaining a specific modification of the illustrated embodiment;

Figure 44 is a block diagram of the signal-conditioning logic contained in each transceiver unit;

Figure 45 is a diagram of the signal-property identifier and of the first and second signal coincidence detectors in a transceiver unit;

Figure 46 illustrates a circuit arrangement for delaying transmission of a control signal following transmission of an interrogation signal and for applying a time shift to the control signal;

Figure 47 is an expansion of the illustration of Figure 43, showing seven data acquisition units of which three consecutive units are to be activated and a timing diagram showing the time relationships of the control and interrogation pulses with respect to the transceiver units; and

Figure 48 illustrates an alternate embodiment of the control and interrogation circuits of Figure 45.

Referring to Figure 1 a vessel 10 tows a seismic sensor cable assembly 12 through a body of water 14. Seismic sensor cable assembly 12 is connected to a shock-absorbing elastic section 16 and to a lead-in section 17. The trailing end of cable assembly 12 is connected to a short terminator section 18. Cable assembly 12 is divided into individual active cable sections 20, each being typically 196.8 feet (60 meters) long. Each of a number of connector modules 13, containing an electronics package, referred to herein as a transceiver unit, connects active cable sections 20 together, electrically and mechanically. A typical seismic sensor cable assembly 12 consists of 50 or more active sections 20, and may have a total length of 10,000 feet or more. Each cable section may contain ten elemental sensor units 21, each one of which constitutes a single channel. The entire cable assembly 12 therefore produces output signals from 500 individual channels. The sensors may be hydrophones, as the illustrated embodiment is a marine seismic cable.

Signal outputs from elemental sensor units 21 are coupled to one of the transceiver units which transmits the signals to a central station 2 on vessel 10. The central station includes control circuitry 4 to transmit interrogation, command, power and test signals and an apparatus 6 to receive and record digital data words from a data transmission link in the cable.

At intervals, as the vessel tows cable assembly 12 through the water, a seismic sound source 19, such as an air gun or a gas exploder, generates acoustic waves in the water. The acoustic waves propagate downwardly through water 14 along ray path 15, for example, impinging upon water bottom 22, where they become refracted along path 23 due to the difference in velocity between water 14 and earth formation 24. Penetrating the earth, the acoustic waves continue along refracted ray path 23 and become reflected from a subsurface earth layer 26. The reflected acoustic waves return along ray path 28 to water bottom 22 and thence continue upwardly along ray path 30. The reflected waves are detected by sensor units 21 which convert the reflected acoustic waves into electrical signals. The acoustic waves also take other ray paths, such as 31—32—34—36, where they are detected by sensor units, such as 21', more remote from vessel 10 than sensor unit 21. Although similar ray paths may be traced between sound source 19 and each of the 500 elemental seismic sensor units in seismic cable assembly 12, only two such paths have been drawn for simplicity.

Figure 2a is a schematic longitudinal cross-sectional showing of the leading end of an active seismic cable section 20. For convenience in representation, the longitudinal dimensions have been significantly reduced. The section consists of an outer plastic skin 40, three steel stress members 42, 43 (the third stress member not

shown), a plurality of bulkhead spacers 44 and a terminal bulkhead 46, one at each end of the section. Plastic skin 40 has an internal diameter of 2.75 inches with a 0.187 of an inch wall thickness. Spacer bulkheads 44 are placed at two-foot intervals inside plastic skin 40 for internal support. Each bulkhead 44 has three holes 48, 48', 48'' (Figure 2b) for the passage of the stress members and a central hole 50 for the passage of trunk cable bundle 52. The skin is fastened to terminal bulkhead 46 by steel bands 54, 56. The entire skin is filled with a light kerosene to give it neutral buoyancy in water.

A plurality of sensors 23, such as hydrophones, are mounted at 6.56-foot (two meter) intervals inside cable section 20. Each sensor is supported between a pair of closely spaced bulkheads 44 by flexible ties of any convenient type. Each cable section preferably contains at least thirty seismic sensors 23. In a preferred configuration, three sensors 23 are connected in parallel to perform like a single instrument by local data lines 58, 60, thereby to form an elemental seismic sensor unit 21. Since the sensors are 6.56 feet apart, the length of the elemental sensor unit is 13.12 feet (four meters) and the separation between group centers is 19.68 feet (six meters). Local data lines 58, 60 joint cable bundle 52 and conduct the sensor unit signals to appropriate pins of a multiconductor connecting plug 62. In this arrangement, each elemental seismic sensor unit of three sensors supplies signals to a single, common data channel. The parallel connection causes the electrical outputs of the individual sensors 23 to be algebraically summed.

Summation of the signals tends to reinforce desired, systematic reflected signals and to suppress undesired, random noise signals, provided the seismic wavefront is substantially parallel to the plane of the array. In this ideal circumstance, all of the sensors 23 in elemental sensor units 21 or 21' (Figure 1) will "see" the wavefront, and receive the seismic waves, in phase. The angle becomes greater with increasing distance from the source. Additionally, the ray path angle will depend upon the slope of water bottom 22, reflecting interface 26 and many other factors.

By definition, a wavefront, such as 35, which may be a wavelet crest, propagates such that its extension remains perpendicular to the ray paths 30, 36. As wavelet crest 35 sweeps across cable assembly 12, it will be first seen by sensor unit 21, and some time later, by sensor unit 21'. At the instant that wavelet crest 35 impinges upon sensor unit 21, it is possible that the wavelet trough of a preceding wavelet is still being sensed by a sensor unit 21'. If all of the sensors between 21 and 21' were connected together in one long array, signals from the sensor outputs would tend to attenuate, rather than reinforce, one another. It is desirable therefore that the length of an individual elemental sensor unit be short with respect to the wavelength of the highest-frequency seismic signal of interest.

The wavelength of a seismic wave as seen by a group of seismic sensors electrically connected together depends in a complex way on the angle of dip and the depth of subsurface earth layers, the seismic wave velocity, the distance between the acoustic source and the sensors, and many other factors. Consideration will now be given to a group of electrically connected seismic sensors disposed at or near the surface of a body of water, for example. The group has a length X. If a horizontally travelling wavelet (angle of incidence = 90°) is incident at one end of the group, the time T required for the wavelet to traverse the group is

$$T = X/V \quad (B)$$

wherein V is the acoustic velocity in the propagation medium. Using water velocity of 5,000 feet per second and the 230-foot group length of the prior art, the transit time for the wavelet is 0.046 of a second. For additive response along the length of the sensor group, the group length should be less than one-quarter wavelength. The time to travel one wavelength is therefore 0.046×4 or about 0.184 of a second. This period corresponds to a limiting frequency of about 6 Hz. Waves incident on the end of the group having frequencies substantially greater than the 6-Hz cutoff limit will tend to be greatly attenuated.

In the illustrative system, the length of an elemental sensor unit is 13.12 feet. The travel time for a wavelet will be 0.026 of a second. The frequency corresponding to a quarter wavelength will be

$$f = 1/(0.0026 \times 4) = 96.1 \text{ Hz.}$$

Thus, by use of a short elemental seismic sensor unit or group, the upper cutoff frequency has been substantially extended. Assuming an angle of incidence of 30°

for a wide-angle shallow reflection signal received toward the end of the cable assembly, the upper cutoff frequency is raised to

$$f=96.1/\sin 30^\circ=192.2 \text{ Hz.}$$

Returning now to Figure 2a, in addition to the seismic sensors 23, auxiliary sensors, such as a pressure transducer 64 leakage detector wires 66, 68 and water break detector 72 are mounted in cable section 20 near the leading end. Electrical connections from the auxiliary sensors joint cable bundle 52 and transmit sensor output signals to appropriate pins of connecting plug 62. In a typical cable section 20, there may be ten data channels and three auxiliary channels.

Figure 2c is a cross-sectional view of the cable section along line 2c—c, showing the configuration of the seismic and auxiliary sensors inside the skin 40. Part numbers in Figure 2c correspond to like numbers in Figure 2a. Figure 2d is a cross section of bulkhead 44 along line 2d—d, Figure 2b, showing holes 48 for stress member 42 and orifice 50 for cable bundle 52.

Two cable sections are joined as shown in Figure 3a. In this illustration, the ends of adjacent cable sections are symmetrical, hence only one end will be described in detail. Stress members 42 and 43 protrude through terminal bulkhead 46 and are terminated by standard aircraft-type clevises 45, 47. Cable bundle 52, which extends through a central hole in terminal bulkhead 46, is terminated at connecting plug 62.

A connector module 13 is provided between adjacent sections 20. Each connector module 13 contains a transceiver unit, the purpose of which is to accept analog signals from seismic sensor units and auxiliary sensors, to digitize the signals and to transmit the digital data to vessel 10 through a data transmission link in cable bundle 52. Connector module 13 has a bulkhead connector 76 at each end to mate with a connecting plug 62. The mating connecting plugs permit coupling the sensor units to the internal transceiver unit, and provide means to couple the transceiver units in series with the transmission link, interrogation link, power and test signal channels in trunk cable bundle 52. Short stress members 78, 80 (a third member not shown), terminated by aircraft-type clevises 82, 84, which are matable with clevises 45, 47, are secured to connector module 13 by steel clips 86, 88. The housing 75 of connector module 13 and the bulkhead connectors 76 are designed to withstand an ambient pressure of up to 2,000 psi. The outer dimensions are 2.5 inches×14 inches.

When two cable sections 20, 20' are to be joined, clevises 45 and 47 of stress members 42, 43 are fastened to the mating clevises 82, 84 of short stress members 78, 80 by pins 90, 92. A connecting plug 62 is mated with bulkhead connector 76 at each end of connector module 13. A plastic boot 94, having an internal diameter slightly larger than the outer diameter of skin 40, is slipped over terminal bulkheads 46. Boot 94 is fastened to terminal bulkheads 46 by steel bands 96, 98. The interior of boot 94 may be filled with a light kerosene for buoyancy. Better flotation capability in a marine environment can be obtained by use of syntactic foam, such as is made by Dow Chemical Corp. and supplied by Universal Urethanes Inc. of Houston, Texas.

Connector module 13 is shown in partial cross section in Figure 3b. Each end of the cylindrical housing 75 of connector module 13, Figure 3b, is closed by bulkhead connector 76 that slides into a recess 100 machined into the end of housing 75. O-rings 102, 104 form a fluid-tight seal around the connector. Bulkhead connector 76 is held in place by snap-ring 106.

Connector module 13 is shown in cross section along line 3c—c in Figure 3c, and along line 3d—d in Figure 3d. The transceiver unit electronics contained within connector module 13, described in detail below, are mounted on three printed circuit boards 108, 110, 112, Figures 3c and 3d. The three boards, comprising the transceiver unit 111, are packaged in the shape of a triangular prism. They are designed to be inserted inside housing 75. Prior to insertion, the interior of housing 75 is lined with a thin fiberglass sheet (not shown) to insulate the electronics from the steel wall. After connector module 13 has been assembled, it is filled with mineral oil of any well-known type that is harmless to the electronics components. This provides good thermal conduction and prevents water invasion.

At sea, in rough weather, towing vessel 10 (Figure 1) is subject to unpredictable accelerations around the pitch, roll and yaw axes. To prevent such accelerations from being transmitted to seismic sensor cable assembly 12, one or more elastic cable sections 16 are connected between lead-in section 17 and cable 12. The

elastic cable sections are similar in construction to an active cable section, except that there are no seismic or auxiliary sensors contained therein. In place of steel stress members, nylon or other elastic ropes are used. A cable bundle, equivalent to cable bundle 52 of Figure 2a, is threaded through the center holes 50 of the bulkheads 44. Sufficient slack in cable bundle 52 is provided to permit the section to stretch up to 50% of its relaxed length. In a preferred design, two such stretch sections are used. A connector module is connected between the leading end of the first active section and the trailing end of the second, trailing elastic section. A second connector module 13' is inserted between the trailing end of the lead-in cable section 17 and the leading end of the leading stretch section.

Cable bundle 52 in each cable section 20 contains two sets of conductors. One set of local data line conductors, such as 58, 60, transmits analog signals from the elemental seismic sensor units 21 and the auxiliary sensors within each cable section to the transceiver unit inside an adjacent connector module 13. The local conductors are preferably coaxial cables, such as RG-174. The other set of cables are feed-through trunk lines for transmitting interrogate, command and control signals from vessel 10 to each transceiver 111 in a connector module 13 and for transmitting data signals from each transceiver unit 111 back to vessel 10. The trunk lines include a data transmission link, an interrogation link, two command links, two test lines and a power transmission line. By means of the plug connections at connector module 13 and described above, the trunk lines extend over the entire length of cable assembly 12.

In a preferred embodiment, the wideband data transmission link consists of three RG-58/CU coaxial cables. Coaxial cables are required in order to accommodate the 20-Megabit per second transmission rate (40 Mhz, for a word consisting of all ONE's, as described hereinbelow). Three cables are used rather than one for redundancy. If one cable should break, two more are available for use.

The interrogation link consists of three redundant transmission lines of twisted wire pairs. Twisted wire pairs are permissible for this and all remaining signal transmission lines, because the transmission rate of interrogation pulses is relatively low, actually in the KHz range.

The two twisted wire pair command links transmit the control signals. The test and test-control lines are twisted wire pairs through which are transmitted a test signal and a test-control pulse.

The power transmission line consists of two twisted pairs of #14 AWG wire, connected in parallel. Through this line is transmitted AC power to energize the transceiver unit power supplies contained in each of the connector modules 13.

A block diagram of a transceiver unit 111 mounted on printed circuit boards 108, 110, 112 (Figure 3b) of a connector module 13 is shown in Figure 5. Principal components are a repeater unit 114, an interrogation network 116, a command network 118, preamplifiers 120, a multiplexer 122, gain-conditioning amplifiers 124, an analog-to-digital converter (digitizer) 126, an output register and code converter 128, an error detector 130, a control network 132, a power supply 134, a test driver 136 and a test control relay 138. The transceiver circuit elements are described in detail further below, but the functions of the transceiver unit 111 are outlined in block form in Figure 5 for a better understanding of the operation thereof.

Repeater network 114 transmits a local self-clocking phase-encoded data word to central station 2 (Figure 1) via data transmission link D1, D2, D3, and thereafter receives, regenerates and retransmits self-clocking phase-encoded data words from down-link transceiver units. These functions are initiated in response to a first interrogation pulse and are completed before the arrival of a second interrogation pulse. Upon command, or in the event of a power failure in a transceiver unit, the data receiver may be bypassed, as explained further below.

Interrogation network 116 receives, buffers and retransmits interrogation pulses through the triple-redundant interrogation link IP1, IP2, IP3. In this unit, the interrogation pulse is identified by a pulse width identification circuit, as it is either a wide S1 or a narrow S2 pulse. The S1 pulse is 1,500 nanoseconds wide; the S2 pulse is 600 nanoseconds wide, where one nanosecond is a billionth of a second. Interrogation network 116 includes an artificial delay line in series with the interrogation link. The preferred delay is 600 nanoseconds. The artificial delay line is tapped so that small adjustments may be made to compensate for slight differences in signal propagation times through the interrogation link.

Command network 118 receives, buffers and retransmits to down-link transceivers the two command signals DATEN (data enable) and DATA BYPASS. Simultaneous

arrival of an S1 interrogation pulse and a DATA BYPASS pulse at a selected transceiver unit will cause phase-encoded words to be bypassed around the corresponding repeater network 114 through a bypass circuit, as described further below. DATEN is a pulse whose width may be adjusted by multiples of the artificial delay time set into the interrogation network 116. The transceiver units in one or more selected, contiguous cable sections are activated only by the coincidental presence of a DATEN pulse and an S1 interrogation pulse, which both are of the nature of signal pulses.

The interrogation network 116, command network 118 and repeater network 114 are provided with power failure bypass lines actuated by relays, as described further below. In event of a power failure, the relays are deactivated to divert incoming phase-encoded words and interrogation and command pulses around the defective transceiver.

Analog data are transmitted from elemental seismic sensor units 21 via local coaxial cables 58, 60 through preamplifiers 120 and filters to the inputs of multiplexer 122. In response to an S1 pulse, when received and detected by interrogation network 116, control network 132 resets multiplexer 122 to channel #0. In response to the leading edges of a series of S2 pulses, the multiplexer is sequenced through a normal scan cycle to sample the input channels, one after another. In the preferred embodiment, there are fourteen input channels. Channel #0 is a dummy or pseudo channel. Analog seismic data signals are handled through channels #1-10. Analog signals from auxiliary sensors are transmitted through channels #11-13.

When multiplexer 122 is reset to channel #0, certain so-called "housekeeping" and test functions are performed: The gain-conditioning amplifiers 124 are set to unity gain while DC offset is automatically removed from the multiplexer and amplifier inputs. At this time also, an error-detect circuit, described below, provides a warning if one or more of the three redundant data transmission lines is defective.

As each of channels #1-13 is sampled, the sampled analog data signal is gain-conditioned in gain-conditioning amplifier 124. As is well known, seismic signals have a wide dynamic range of as much as 120 db (1,000,000:1). Signal gain-conditioning includes the step of compressing the dynamic range of the seismic signals to hold the range within limits of the analog-to-digital converter. The gain-conditioned signal is converted by analog-to-digital converter 126 into a binary number which forms the sign and mantissa part of a floating point number. The gain states of the gain-conditioning amplifier 124 are encoded as a four-bit code. The four-bit code is combined with the mantissa in output register 128 to form a floating point number of 10 to 16 bits resolution. The floating point number is representative of the amplitude level of the seismic data signal at the time of sampling. Four additional bits including a parity bit may be added to the data word as a preamble to allow proper identification of the start of phase-encoded words.

The twenty bits comprising the data word are encoded in any convenient self-clocking code and are transmitted in return-to-zero mode (RZ) over a wideband telemeter link in direct digital data transmission mode. In a preferred embodiment, a self-clocking code, such as di-phase M, is used. An example of a coded data word is illustrated in Figure 10. Self-clocking codes, such as that illustrated herein, are described on pages 4 through 18 of "The Interface Handbook" by Kenneth M. True, published by Fairchild Instrument Co., 464 Ellis Street, Mountain View, California 94042. Circuits implementing such codes are discussed in the same publication. The absence of data is represented by a logic level of zero. Fifty nanoseconds before the first data bit, the logic level drops to -5V so that the first data bit must be a positive-going pulse. Each data bit occupies a cell time of 50 nanoseconds. A binary "1" is represented by one polarity reversal at the middle of one 50-nanosecond cell time, while a binary "0" is represented by no polarity reversal. Consecutive binary zeros are represented by successive 50-nanosecond polarity reversals at the cell-time boundaries. Since there are 20 data bits, a phase-encoded word occupies a time slot of 1,000 nanoseconds, i.e. one microsecond (millionth of a second). At the end of a phase-encoded word, the logic level drops to -5V for 75 nanoseconds and then goes to zero. The logic circuitry in repeater network 114 always seeks a positive-going pulse within an interval of any two cell times. When no such pulse is found, the logic senses the end of a data word.

The maximum phase change frequency of the phase-encoded words is 40 megahertz, MHz (for all ONE's). But, because of the fast rise time at the leading edge of the pulses, the bandwidth of the data transmission link must be at least 100 MHz.

The inputs to multiplexer 122 are AC-coupled by capacitors 123. The multiplexer output is coupled to gain-conditioning amplifier 124 through series resistor 140 and unity gain buffer amplifier 142. Capacitors 123 and series resistor 140 taken in combination with multiplexer switch 122, form a high-pass commutated RC filter. The cutoff frequency of the filter is

$$f = [1/(2RC)](D/T)$$

wherein D is the channel-on time and T is the channel-off time. The filter is described below in detail in conjunction with Figures 15 and 16.

The operation of the preferred gain-conditioning amplifier 124, in combination with analog-to-digital converter 126 and output register 128 to form a floating point data word is described further below in conjunction with Figures 39 through 42.

In a typical operating cycle, all fourteen analog channels of each transceiver 111 are sampled within one scan cycle. A new scan cycle is initiated at a desired sample rate, such as once every one-half or one millisecond. Thus, at a one-millisecond sample rate, the 14 channels of every transceiver are sampled at 71.4-microsecond intervals. Completion of one scan cycle requires that the interrogation means in controller 4 of the common central station 2 in vessel 10 transmits one S1 pulse and thirteen S2 pulses every millisecond.

Figure 11 illustrates the timing of the interrogation signals, namely S1 and S2 pulses, within a one-millisecond scan cycle. As an S1 interrogation pulse propagates along interrogation link IP1, IP2, IP3 in cable assembly 12 to the transceiver units 111, Figure 5, a corresponding multiplexers are reset to channel #0. In turn, a data word is clocked by controller network 132, from output register and code converter 128, through the repeater network 114 into the data transmission link D1, D2, D3. The phase-encoded words are time-delay multiplexed into the data link by reason of the inherent delay time of the interrogation pulse between adjacent transceiver units and the artificial delay time set into the interrogation network. After 71.4 microseconds, the first S2 pulse is transmitted. The multiplexers in the transceiver units 111 are successively advanced to channel #1 as the S2 pulse reaches each transceiver unit, and phase-encoded words are again clocked into the data link from each transceiver unit in sequence. Additional S2 pulses are transmitted until all channels in all transceiver units have been sampled.

The above-described sequence is illustrated in the timing diagram of Figure 12. Interrogation (IP) pulses flow outward, i.e. down-link, from right to left (the time base increases to the right), from the central station 2 to transceiver units in the 50 connector modules 13A, 13B, 13C, etc., in that sequence. In the upper three plots of Figure 12, therefore, time increases from left to right. An S2 pulse, for example, arrives at connector module 13A, to advance the multiplexer 122 of the transceiver unit to channel #1. After passing through the artificial delay line, the S2 pulse leaves connector module 13A, 600 nanoseconds later. The distance between the transceiver unit in connector module 13A and the transceiver unit in connector module 13B is 196.8 feet. Assuming a propagation velocity of 1.305 nanoseconds per foot in the twisted-pair interrogation link IP1, IP2, IP3, the S2 pulse will arrive at connector module 13B, 256.8 nanoseconds later. The total delay between modules 13A and 13B is therefore 856.8 nanoseconds.

As soon as the leading edge of the S2 pulse for channel #1 is recognized by the transceiver unit in connector module 13A, a phase-encoded word is clocked out from the register 128 into the data transmission link D1, D2, D3. The data flow is from left to right (the time base increases to the left), up-link towards the central station. When the S2 pulse arrives at connector module 13B, 856.8 nanoseconds later, the data word for connector module 13B is similarly clocked out. The signal propagation velocity in the coaxial cable forming the data transmission link is 1.542 nanoseconds per foot. Therefore, the leading edge of the phase-encoded word from connector module 13B will arrive at the repeater network 114 in connector module 13A, 1160.3 nanoseconds after the leading edge of the phase-encoded word from connector module 13A left repeater network 114. A phase-encoded word separation of 160.3 nanoseconds is therefore provided.

A two-stage, delay-time sequential/channel-sequential multiplexing system is thus disclosed herein. The phase-encoded word transmitted from successive ones of the fifty transceiver units in the connector modules are ordered in accordance with the propagation delay time of the interrogation pulse between the central station and the respective transceiver units. Phase-encoded words from the fourteen channels

within each of the respective transceiver units are ordered in accordance with the channel-select sequence during a scan cycle.

The DATEN input from the central station to command network 118 in Figure 5 enables the operation of the system as outlined above. The timing of the application of a DATEN pulse permits either all of the sections of the seismic cable assembly to be employed, or only some portion thereof, such as the forward half of the cable sections. As mentioned above, it may be desirable to sample the elemental seismic sensor units in the proximate half of the cable at one sampling rate immediately following generation of a seismic impulse, i.e. shot, and subsequently to sample signals from the entire cable at a different rate. The use of DATEN pulses of suitable length and timing may be employed to accomplish these functions. In the following description, the necessary timing and length of the DATEN pulses will be described on a general basis, so that any number of the transceiver units may be selectively enabled.

Before considering the timing diagrams in detail, it is useful to review the overall data acquisition scheme, and the time frame in which the data originating with each of the 500 elemental seismic sensor units is transmitted from the cable. First, it should be noted that each of the 50 cable sections has ten elemental seismic sensor units along its length and an associated transceiver unit which processes the data from these ten sensor units. Upon command from the ship-board control unit 4 in central station 2 of Figure 1 by the transmission of a wide S1 pulse, phase-encoded words from the last channel of each of the 50 cable sections are sent from the cable in sequence, over the single data link D1, D2, D3 (made up of three redundant coaxial cables). Subsequently, upon receipt of a narrow S2 pulse, the transceiver unit 111 associated with each of the 50 cable sections will transmit channel #1 information from each cable section in sequence. Then, following receipt of another S2 pulse, channel #2 information is sent from each of the 50 cable sections and so forth.

Concerning timing, each cycle of sampling the signal present at all 500 channels occurs during one millisecond, i.e. one one-thousandth of a second. This cycle is defined as a scan cycle and is the time between successive S1 pulses, each S1 pulse being followed by thirteen S2 pulses before the next S1 pulse is generated. Transmission of an individual binary bit of a phase-encoded word only occupies 50 nanoseconds. With each phase-encoded word being represented by twenty bits, each phase-encoded word is transmitted in about 1,000 nanoseconds, i.e. in one microsecond (millionth of a second). Of course, there are 1,000 microseconds in each one-millisecond sampling interval, so that there is ample time to transmit data signals from the 500 seismic channels through the cable during each sampling interval, i.e. scan cycle, in a systematic manner as described below.

Activation of one or more transceiver units requires the simultaneous presence of an S1 pulse and a DATEN (data enable) pulse, as will now be explained with reference to Figure 13. A plurality of cable sections are disposed remotely with respect to the central station. At the leading ends of each section are located connector modules 13A—G, each containing a separate transceiver unit. Assume for example that it is desired to enable only the three consecutive transceiver units in connector modules 13C, 13D and 13E, but no others. Circuitry for performing this function is described in detail below in connection with Figures 43 through 48, but is briefly described here for a better understanding of this feature of the illustrated embodiment of the invention.

An S1 pulse is transmitted from central station 2 through the interrogation link to each connector module 13 in sequence. The instant of arrival of signal pulse S1 at module 13A is $t=0$, the arrival time at module 13B will be $t=856.8$ nanoseconds, the arrival time of signal pulse S1 at module 13C will be $t=1713.6$ nanoseconds, etc. The six timing lines in Figure 13, labelled IPA—IPF, represent the locations of the same S1 pulse with respect to connector modules 13A—F each containing separate transceivers, at the end of each 856.8-nanosecond interrogation pulse travel-time interval. Some time after an S1 pulse is transmitted, a DATEN pulse is transmitted through the command link (Figure 5). The signal propagation velocities in the twisted wire pairs comprising the interrogation and command links are the same. However, because of the 600-nanosecond delay line in each transceiver unit that is included in interrogation network 116, the effective S1 pulse velocity is lower than the command pulse velocity because there are no delay lines in the command link. Accordingly, a DATEN pulse, delayed 1,200 nanoseconds with respect to a corresponding IP pulse, will intercept the S1 pulse at the third transceiver unit in connector module 13C. The six timing lines labelled DATEN-A—F show the

position of a DATEN pulse with respect to the S1 pulse at the end of each 856.8-nanosecond interrogation pulse travel time interval.

Referring still to Figure 13, when an S1 pulse arrives at the transceiver unit in connector module 13A, no action will occur at module 13A because the DATEN pulse is lagging 1,200 nanoseconds behind. At the transceiver unit in connector module 13B, the DATEN pulse is 600 nanoseconds behind, so that no action will take place at module 13B. The DATEN pulse intercepts the S1 pulse at the transceiver unit in connector module 13C, so that the transceiver unit in connector module 13C is activated. At module 13D, the leading end of the DATEN pulse is ahead of the S1 pulse by 600 nanoseconds, but because of the width of the DATEN pulse, it is still available to activate the transceiver unit in connector module 13D. At module 13E, although the leading edge of DATEN is 1,200 nanoseconds in advance of pulse S1, its trailing edge has not yet passed the IP pulse S1. Hence, the transceiver unit in connector module 13E is activated. Finally, by the time the S1 pulse arrives at the unit in connector module 13F, the trailing edge of the DATEN pulse is well ahead of the S1 pulse. Therefore, the transceiver unit in connector module 13F and all subsequent transceiver units will not be activated. All transceiver units that are activated by coincident S1 and DATEN pulses will remain active for one entire scan cycle, so that they will be responsive to all following, incoming S2 pulses. The width W of a DATEN pulse is equal to

$$W = [(L-1) \times DLY] + dt$$

wherein

L=number of transceiver units to be activated,

DLY=artificial delay line time,

dt=a small time increment of arbitrary length to allow for slight propagation time differences.

In the example of Figure 13, the width of the DATEN pulse is

$$[(3-1) \times 600] + 300 = 1,500 \text{ nanoseconds.}$$

The initial delay time ID, to be applied to the DATEN pulse is

$$ID = M \times DLY,$$

wherein M is the number of transceiver units to be skipped between the central control station and the first active transceiver unit.

As discussed above, a DATA BYPASS pulse coincident with an S1 pulse is used to bypass data around a defective transceiver unit. The delay BD to be applied to the DATA BYPASS pulse relative to an associated S1 pulse is

$$BD = K \times DLY,$$

wherein K is the number of transceiver units intervening between the central station and the defective transceiver unit.

Returning now to Figure 5, the data and interrogation links forming part of cable bundle 52 consist each of three lines in parallel. In case one of the lines is broken, the other two remain available. Any two good lines are selected by majority vote. A majority-vote circuit 131 is coupled to the input lines of repeater network 114 and another such circuit (not shown) is associated with interrogation network 116. The circuit 131 of Figure 5 is shown in detail in Figure 6 and consists of AND gates 136, 138, 140 and an OR gate 142. A logic-1 present simultaneously on any two of the three data lines will produce a logic-1 at the output of OR gate 142.

Error-detect circuit 130 is coupled to the majority-vote circuit in repeater network 114 and provides a signal in the event that at least one of the data lines D1, D2 or D3 becomes broken. The circuit (Figure 6) consists of NAND gate 144, diode 146, storage capacitor 148 and bias resistor 150. A negative voltage is applied to error-detect line 152 to hold it slightly negative when there is no output from gate 144. If any one of lines D1, D2, D3 becomes disabled, the output of NAND gate 144 opens. During a normal scan cycle, phase encoded signals flow at a 40 MHz rate, through the majority-vote circuit and to NAND gate 144 connected to the inputs of repeater network 114. So long as all three lines are good, there will be no output from NAND gate 144. If, however, one line is defective, a 40 MHz signal will be present at the output of NAND gate 144. The signal is rectified by diode 146. The

resulting rectified voltage becomes stored in capacitor 148, creating a positive-error voltage on error-detect line 152. During the period that multiplexer 122 is reset to channel #0, switch arm 154, which is located between gain-conditioner amplifier 124 and analog-to-digital converter 126, see Figure 5, is moved from contact 156 to contact 160, permitting analog-to-digital converter 126 to sample the voltage level existing on error-detect line 152. A mechanical switch 154 is shown in Figure 5 for simplicity, but it should be understood that a high-speed Schottky FET (field-effect transistor) switch is used in practice.

Marine streamer cables of the type described tend to stretch as much as one percent (1%) when under tow. For a 10,000-foot cable, the total stretch will be in the order of 100 feet. The seismic sensor units are spaced on 19.68-foot (six meter) group centers within each cable section. With a 100-foot stretch, the sensor units in the leading end of cable assembly 12 will be displaced nearly five-group intervals with respect to the sensor units in the trailing end of the cable assembly. In synthesizing a larger array from a number of elemental sensor units, it is necessary to know the exact sensor unit spacing. If the spacing is not known accurately, the effectiveness of the synthesized array is greatly diminished. The relation between cable stretch and towing tension is known. Accordingly, a strain gauge 11 (Figure 1) of any well-known type is suitably connected to the stress members between the trailing elastic cable section 16 and the first active cable section 20. Output from strain gauge 11 is fed to the input of an auxiliary channel, located in the transceiver unit in connector module 13' at the leading end of the first elastic cable section. From knowledge of the towing tension, errors in sensor unit spacing that are due to cable stretch can be corrected.

As is well known in the seismic art, individual hydrophones seldom have identical sensitivities. A variation of $\pm 25\%$ is not uncommon. Accordingly, an arrangement is provided to calibrate the hydrophones. When it is desired to calibrate the hydrophones, an analog test signal having a known amplitude is transmitted to test driver 136 through the test-signal line 162 (Figure 5). A preferred test-signal frequency is 15.625 Hz. A test-control signal is transmitted over test-control line 163 to test-control relay 138 which moves a switch contact arm 164 from contact 165 to contact 166. A test signal is now applied to drive the elemental seismic sensor units 21, each through a resistor 168. A normal multiplexer scan cycle is initiated to transmit the output from each sensor unit 21 to the central station 2 in vessel 10. The amplitude of the output signal for each sensor unit is compared with the test-signal amplitude to provide a calibration factor for each sensor unit. Calibration of the sensor units is done at any time that seismic data is not being recorded.

The test signal is used to make an accurate measure of the sensitivities of all of the sensor units in the entire seismic sensor cable assembly 12 which may be as much as two miles long. Over such a distance, due to the IR drop, the test signal at the trailing end of the cable would become severely attenuated if the test-signal drivers 136 were connected in parallel across the test-signal line. Accordingly, a resistor 167 is connected in series with the test-signal line 162 in each transceiver unit. The inputs of the test-signal driver are connected across the series resistor 167. Since all resistors have the same resistance value, all of the test-signal drivers will see identical input voltages. In this way, a constant-amplitude test signal is guaranteed for each transceiver unit.

A power supply 134 is provided in each transceiver unit 111. Power is transmitted from vessel 10 to the connector module 13 through a pair of twisted wires 170, 172. Each power supply includes a current transformer and a shunt regulator. The transformer primaries in the respective transceiver units in connector modules 13 are connected in series. By transposing wires 170, 172 in each cable section 20, every alternate transformer is connected to an opposite side of the power line as shown in Figure 4, thereby to maintain a balance of the line loading. Since the power supplies are series-connected, the voltage drop along cable assembly 12 between vessel 10 and terminator section 18, will depend on the number of connector modules 13 that are connected together. For a 50-section cable assembly, the voltage drop will be on the order of 400 to 500 volts. Power is transmitted at 2,000 Hz, 4 Amp. This frequency is substantially above normal seismic frequencies and hence does not interfere therewith. In power supply 134, AC power from the power line is rectified and converted to $\pm 15V$ and $+5V$ for use by the logic circuits in the transceiver units. In the event of a defect, such as an open circuit in a transceiver unit, the voltage across the primary of the power transformer would rise to a very high level. A protective Triac crowbar circuit of any well-known type

shorts the primary if the voltage increases above a predetermined limit. Upon shutdown of the power supply, the fail-safe bypass relays (not shown) in repeater network 114, interrogation network 116 and command network 118 are released by default, thereby allowing command pulses and phase-encoded data words to bypass the defective module.

As described above, multiplexer 122 is provided with 14 inputs, of which channels #11-13 are used for transmission of data from the auxiliary sensors, next to be described.

Pressure transducer 64, discussed above in connection with Figure 2a and now described in detail, is of a type well known in the seismic art. For reference its function will be described briefly. Illustrated in Figure 7a, the transducer includes a sylphon bellows 174. Secured to the movable end of bellows 174 is a soft iron pole piece 176. Pole piece 176 moves longitudinally within a coil 178 which is mounted to the fixed end of bellows 174 by a support bracket 180. An oscillator, including an LC tank circuit, is contained within a housing 182. Coil 178 is the inductive portion of the tank circuit. In a fluid medium, a change in pressure against sylphon bellows 174 causes pole piece 176 to move within coil 178, thereby changing the inductance and hence the frequency of the oscillator. The output signal of pressure transducer 64 is therefore a frequency-modulated signal whose frequency is related to the ambient fluid pressure. This signal is transmitted over a coaxial cable to channel #11 of multiplexer 122, as indicated in Figure 7b.

Referring to Figure 7b, a leakage detector 186 is provided to detect the presence of saltwater inside skin 40 of a cable section 20. The leakage detector 186 consists of two wires 66, 68, imperfectly insulated by a porous plastic. The porous covering prevents physical contact between the wires, but permits water to make a fluid contact. The two wires 66, 68 extend the length of cable section 20. One wire 66 is connected to the oscillator output 184 of the pressure transducer 64. The other wire 68 is connected to auxiliary input channel #12 of multiplexer 122. As long as no water is present inside cable section 20, there will be no signal applied to the leakage-detect channel. If water should invade the cable section, a conductive path is established between the two wires 66 and 68. An amplitude-modulated signal will then appear on the leakage-detect auxiliary channel. The amplitude of the signal will be proportional to the resistance of the leakage path.

A water break detector 72 is connected to auxiliary input channel #13. Water break detector 72 is a special hydrophone used to sense an acoustic wave arriving directly from the sound source along a travel path near the water surface.

Although all of the active cable sections are identical and interchangeable one with another, it is necessary to provide an impedance matching termination to terminate the data, command and interrogation signal lines, i.e. transmission links, at the last section to prevent undesired reflections. Furthermore, the series-connected power, test and test control twisted wire pairs must be provided with a return circuit. Accordingly, a terminator section 18 is connected to the trailing end of the last cable section 20. The construction of the terminator section is shown in Figure 8a.

In Figure 8a, the terminal bulkhead 46 of the last cable section 20 is shown. Skin 40 is secured to the bulkhead by steel bands 54, 56. Cable bundle 52 and plug 186 extend beyond terminal bulkhead 46, along with stress members 42, 43 and clevises 45, 47. A tail-swivel plug 188 is provided at the trailing end of the terminator section 18. One end of three short stress members 190, 192 (the third not shown) is embedded in the body of the plug. Clevises 194, 196 matable with clevises 45, 47 are secured thereto by pins 198, 200.

Terminator module 202 is secured to stress members 190, 192 by a steel band 204. The leads contained in cable bundle 52 are electrically connected to terminator module 202 by plug 186 and mating plug 187. A plastic boot 206 is slipped over plug 188 and terminal bulkhead 46 of the last active section 20. The boot is secured in place by steel bands 208, 210, 212, 214. The space inside boot 206 is filled with light kerosene to provide flotation.

The electrical connections inside terminator module 202 are shown in Figure 8b. Coaxial data transmission lines D1, D2 and D3 are terminated by 50 ohm, 1/4 watt resistors 216. The twisted wire pairs for the lines IP1, IP2, IP3 of the interrogation link and the command lines for the signals DATEN and DATA BYPASS are terminated with 130 ohm, 1/4 watt resistors 218. Power, test signal and test control lines are shorted by bridging wires 220.

The lead-in cable section 17 is coupled to the leading end of elastic section 16 by a transceiver unit in connector module 13'. The other end of the lead-in cable

17 is secured to vessel 10, thereby providing means to tow cable assembly 12, as well as to provide connection to the central station 2. The lead-in cable 17 is shown in cross section in Figure 9. It consists of a central stress member 230, preferably a 3/8 of an inch diameter, non-rotating steel cable. Stress member 230 is jacketed with neoprene or other plastic 232. The conductors that make up the cable bundle 52 in the active cable section are spirally wrapped around jacketed stress member 230. The conductors are themselves encased in a suitable plastic jacket 234. The lines are identified in Figure 9 as coaxial data lines 236, double-twisted wire pair power lines 238, twisted wire pair command lines 240 and coaxial local data lines 242. Because lead-in section 17 may be up to 600 feet long, the data lines 236 are RG/59U coaxial cables to prevent signal degradation. The local data lines 242 extend from vessel 10 to connector module 13' where they are connected to the inputs thereof. The local data lines 242 may be used to introduce into the system those signals which are derived from special sensors 222 (Figure 1) close to vessel 10.

In order to discuss now the filter used in the illustrated embodiment of the present invention, reference is made to Figure 14, wherein is shown a simplified representation of the digital-to-analog conversion system having the multiplexer 122 with input channels C_1, C_2, C_n connected to a plurality of signal sources, such as seismic sensors 21. The input channels are all connected to multiplexer output bus line 312 through DC blocking capacitors 123, resistors 315 and switches 316. Each resistor 315, in combination with its capacitor 123, forms a high-pass R-C filter for its channel. Switches 316 are high-speed FET switches of any well-known type.

The output of multiplexer bus line 312 is shown connected to the non-inverting input of a unity gain buffer amplifier 320 which may be an operational amplifier, such as amplifier 142 of Figure 5, having a high-input impedance. The output of buffer amplifier 320 is connected to a sample-and-hold circuit 322 having a shunt capacitor 324 and a series switch 326. The output of circuit 322 is coupled to a binary gain-ranging amplifier 124, such as that shown in Figure 5 and described in conjunction with Figures 39 through 42, further below.

The state controller, which is control network 132, is interconnected with switches 316, 326 through a control bus line 341 having a plurality of control lines. Controller 132 sequences the multiplexer 122 to connect sequentially the signal-input channels C_1-C_n to the output bus line 312 during a multiplexer scan cycle, as described above. Controller 132 also controls the operation of the binary gain-ranging amplifiers system 124 through control lines 350.

The amplifier system 124 is coupled to the analog-to-digital (A/D) converter 126 that converts the sampled analog signals into corresponding digital numbers. Other networks which are not germane to the feature of the invention presently discussed have been purposely omitted from Figure 14, 15 and 16 for the sake of clarity.

In the circuit of Figure 14, each R-C high-pass filter comprises a series capacitor 123 and a shunt resistor 315 connected to ground. For seismic use, each high-pass filter has a low cutoff frequency f_0 in the order of one Hz, although other cutoff frequencies can, of course, be employed.

The capacitance C is related to the resistance R and the cutoff frequency f_0 by:

$$C = 1/(2\pi R f_0). \quad (C)$$

For practical design reasons, R must be relatively low, namely in the order of 10,000 ohms. Hence, for $f_0 = 1$ Hz, $C = 16$ microfarads. Such large-size capacitors are relatively expensive and bulky. Thus, the high-pass R-C filters of Figure 14, in addition to being costly, also impede subminiaturization.

The description of the filter arrangement of Figures 15 and 16 will be facilitated by designating the same parts either with identical reference characters as in Figure 14, or with identical reference characters followed by a prime (') to indicate a similarity in some respect.

Referring now to Figure 15, it illustrates the possibility of using a single common shunt resistor 315' on the output line of the multiplexer 122 instead of an individual shunt resistor 315 for each channel. As the multiplexer is advanced through its channel-select, i.e. scan, cycle, the capacitor 123', connected in series with each multiplexer selected channel, such as C_1, C_2 , etc., combined with common shunt resistor 315' now constitutes the desired R-C filter for that channel.

When the circuit of Figure 15 was tested, however, it was discovered experimentally (and later proven theoretically) that the capacitance C is determined by:

$$C = [1/(2\pi Rf_0)] [D/T] \quad (D)$$

wherein D is the dwell time, that is the length of time that each switch 316 is closed, and T is the channel-off time, that is the length of time that each switch 316 is open. The dwell time D is a function of the number of analog channels and the total time required to scan all of the channels. Thus, for a 16-channel multiplexer having a scan time of 1,000 microseconds (one millisecond), the maximum dwell time D would be 62.5 microseconds per channel and the channel-off time T would be 937.5 microseconds.

The dwell time D can be varied by means of dwell adjust circuit 360, shown in Figure 16. Dwell adjust circuit 360 may be a one-shot, such as National Semiconductor DM 74121. A one-shot is a circuit or device which can be used to modify the duration of a control pulse by stretching or shortening the pulse width. Pulse width adjustment is accomplished by means of a resistive-capacitive feedback network of a type well known in the electronic art. It is to be understood that, for any one multiplexer scan cycle, the desired dwell remains set at the same value.

Equation (D) can be rearranged as

$$f_0 = [1/(2\pi RC)] [D/T] \quad (E)$$

given constant values for R, C, T, the cutoff frequency of the filter can be changed by changing the dwell. In the above numerical example, the maximum dwell for a one-millisecond scan time is 62.5 microseconds. The shortest dwell time is set by the acquisition time of sample-and-hold circuit 322'. Typically, the acquisition time is 8 microseconds. Dwell adjust circuit 360 may be programmed to provide selectable dwell times ranging, for example, from a minimum dwell of 8 microseconds to a maximum dwell as set by the scan time, which is 62.5 microseconds in the above example. Thus, the cutoff frequency of the filter can be set to any desired value over a range of nearly 8:1.

The manner of employing the improved multiplexer-commutated R-C filter in the seismic data processing system described herein is shown in Figure 16. Since Figures 14 and 16 are in many respects similar, the description of Figure 16 will be limited only to the differences between these two circuits.

The most important feature of utilization of the channel-select cycle of the multiplexer employed in the multichannel seismic data processing systems is its combination with a common shunt resistor connected to the multiplexer's output. As a result, not only has the number of shunt resistors been reduced, but also the size of the required capacitors 123' has been reduced by a factor of 15:1 in the case of 16 input channels. In addition, by altering the dwell time, the cutoff frequency can be adjusted over a range of nearly 8:1.

Figure 16 illustrates that it is preferable to use a low-impedance operational amplifier 320'. Series resistor 315'' which, it will be realized, corresponds to resistor 140 in Figure 5, is the input resistor to the inverting input of amplifier 320'. The non-inverting input is to amplifier 320' connected to ground. Since both inputs must be at the same potential, junction 333 is virtually at ground potential. Therefore, the filter of Figure 16 is the equivalent of the filter of Figure 15.

Accordingly, the low-input impedance operational amplifier 320' having the filter's common resistor 315'' as its input resistor is the preferred filter circuit. The use of the operational amplifier 320' eliminates the serious design limitations imposed by the relatively high-input impedance amplifier 320 of Figure 14 which is less desirable.

It was found that the use of a common resistor 315'' (or 140 in Figure 5) which successively becomes connected by switches 316 to capacitors 123' results in a considerable saving in the number of needed resistors and in the volume occupied by the resistors and capacitors. These advantages are of particular significance in the miniaturized system needed for the purposes of this invention.

At this point of the description of the seismic data processing system of the invention, some general aspects need to be considered and thus reference is made to Figure 17 which is a block diagram representation of the general layout of the multichannel seismic system, which comprises the central station 2 and a plurality of transceiver units 111a-111n, spaced apart remotely from central station 2. Transceiver units 111a-111n are connected in series to the central station 2

through wideband data transmission links 1014a—1014n and interrogation links 1016a—1016n, corresponding to, and representing, the channels or links D1, D2, D3 and IP1, IP2, IP3, respectively, contained within a seismic streamer cable section as described above.

Each transceiver unit 111 is shown to include the interrogation network 116 and a repeater 114. Each repeater 114 includes a number of input channels 1022, 1022', 1022''. Three such channels are shown in Figure 17 for simplicity, but fourteen or more may be used in practice, as will be recalled from the above description. Elemental seismic sensor units 21, 21', 21'' are coupled to input channels 1022, 1022', 1022'', there being provided up to ten or more such sensor units in each cable section as also mentioned above, so that 50 or more such cable sections include 500 or more individual elemental seismic sensor units, each constituting a separate channel of information.

Referring now to Figure 18 wherein a transceiver unit is shown in still greater detail, each analog channel 1022 is connected to a separate preamplifier and "alias" filter 1036 which is coupled to an input terminal of the multiplexer 122 through a DC-blocking capacitor 123. Multiplexer 122 has input terminals C1, C2, C3, C4, C5 (five channels are shown, but fourteen or more may be used), one for each channel 1022. Channel C0 is the test channel. Channel C0 includes a capacitor 1043 connected to ground. The multiplexer's output is connected through the common series resistor 140 to the operational amplifier 142. Capacitors 123, multiplexer 122 and common series resistor 140 form the above-described multiplexer-commutated, high-pass R-C filter for each channel.

The output of amplifier 142 is applied to the sample-and-hold circuit 1044 which includes a series switch 1045 and a shunt capacitor 1046, all of which is in similarity with the above-described arrangement. The output of sample-and-hold circuit 1044 is connected to another sample-and-hold circuit 1050 through a buffer amplifier 1048. The buffer amplifier 1048 provides electrical isolation between the two circuits 1044 and 1050. The same sample-and-hold circuit 1050 includes a series capacitor 1051 and a shunt switch 1052 connected to ground. The output of circuit 1050 is coupled to the binary gain-ranging amplifier system 124. The test channel 1041, i.e. channel C0, in conjunction with the sample-and-hold circuit 1050 constitutes a DC-offset removal network which is described in greater detail below, in conjunction with Figure 37.

The binary gain-ranging amplifier 124 comprises four bi-gain amplifier stages, shown as amplifiers 124a, 124b, 124c and 124d, and are connected in cascade. Each amplifier normally has a low-gain state, such as unity gain. The feedback can be adjusted to obtain a discrete high-gain state for each amplifier and this can be done by switches 1055a, 1055b, 1055c and 1055d. The binary gain-ranging amplifier system 124 is described in greater detail below, in conjunction with Figures 39 through 42.

The output of the binary gain-ranging amplifier system 124 is applied to the analog-to-digital converter 126. Analog-to-digital converter 126 accepts a gain-conditioned analog signal sample and converts it into a binary number in a non-return-to-zero pulse code. The output of converter 126 is fed to the temporary output storage register and code converter 128. Code converter 128 converts the binary number from the non-return-to-zero pulse code to a self-clocking phase-encoded pulse code, suitable for application to transmission link 1014 through line 1057 regenerator 1060 and transmitter 1066f. It will be noted that the data transmission link 1014 schematically represents the data link D1, D2, D3 described above in conjunction with Figure 5.

The timing functions of the various networks in each transceiver unit 111 are controlled by the controller 132, also mentioned above, which receives an interrogation pulse from the interrogation network 116 in series with the interrogation link 1016, schematically illustrating link IP1, IP2, IP3, see above. A master controller 1019 in the central station 2 transmits over link 1016 the wide S1 pulse, followed by a number of narrow S2 pulses, within each scan cycle. With the illustrated thirteen input channels and the one test channel, one scan cycle requires transmission of one S1 pulse, followed by thirteen S2 pulses, it will be recalled.

The interrogation network 116 consists of pulse width detector 1031 and of a delay line 1029. When pulse width detector 1031 detects a wide S1 pulse, it sends a control SYNC pulse over line 1035 to controller 132 to cause it to reset multiplexer 122 to channel C0, thereby initiating DC-offset removal and the transmission of a phase-encoded data word from the last channel of the preceding scan. When pulse detector 1031 detects a narrow S2 pulse, it sends a pulse over line 1033 to cause

controller 132 to advance multiplexer 122 to the next channel and to also transmit the data from the preceding scan. The S1 and S2 pulses propagate through delay line 1029 to provide sufficient time delay to allow separation between the end of a local data word, as from transceiver unit 111a and the beginning of the data word arriving from the next down-link transceiver unit, such as unit 111b. A gap between data words from adjacent transceiver units is desirable in order to distinguish there-between.

As explained above, a phase-encoded data word is 1,000 nanoseconds (billionths of a second) long. Lines 1016a and 1014a, Figure 17, are each 200 feet long and the velocity of propagation over these lines is 1.6 nanoseconds/foot. Lines 1014a and 1016a, therefore, require a pulse travel time of $(400 \text{ feet} \times 1.6 \text{ nanoseconds/foot}) = 640 \text{ nanoseconds}$. The desired gap or dead space between consecutive data words is about one-fourth the word length, i.e. 250 nanoseconds. Hence, the delay line 1029, Figure 18, is adjusted for a delay time given by

$$D = L + S - T,$$

(F)

wherein L is the length of the phase-encoded data word, S is the desired word separation and T is the sum of the travel times of a pulse through lines 1014a and 1016a. As a numerical example, the artificial delay D is

$$D = (1000 + 250 - 640) = 610 \text{ nanoseconds.}$$

The operation of polling, i.e. interrogating, each transceiver unit 111 through the interrogation link 1016 is described in greater detail in conjunction with Figures 43 through 48, see further below.

A data word consists of 20 bits, of which bits 1 to 3 are the preamble, bit 4 is parity, bits 5 to 8 are the exponents, bit 9 is the sign bit and bits 10 to 20 are the mantissa. From analog-to-digital converter 126, the data are formatted in binary NRZ (non-return-to-zero) code. This code is illustrated in Figure 22, by diagram 6a. One bit interval is 50 nanoseconds. Since there are 20 bits, the word length is 1,000 nanoseconds. In the example shown, bit 9 is assumed to be a ONE-bit, while the remainder are ZERO's.

In code converter 128, the data are formatted in the phase-encoded NRZ pulse code, illustrated in diagram 6b of Figure 22. For a ZERO bit, there is one logic-level transition at each bit-interval boundary. For ONE bit (such as bit 9), there is a mid-interval logic-level transition. In the absence of data, as between data words, the signal level remains at zero. The leading edge of the first bit of a data word must always be a positive-going pulse.

Phase-encoded NRZ data, diagram 6c of Figure 22, are converted into a phase-encoded RZ (return-to-zero) pulse code by transmitter 1066 for constant current mode transmission into data link 1014. No-data is represented by a zero logic level. Fifty nanoseconds before the beginning of a data word, the logic level drops to $-5V$ for one bit interval, thereby insuring a positive-going leading edge for the first data bit. There must be one polarity transition, from $-V$ to $+V$ (or $+V$ to $-V$) at every bit-interval boundary for a ZERO-bit. In addition, a ONE-bit requires a mid-interval polarity change (bit 9 for example). At the end of a data word, the logic level drops to $-V$ for 75 nanoseconds and then goes to zero.

From diagrams 6b and 6c of Figure 22, it is clear that there must be at least one positive-going pulse within any two bit intervals. For a more complete description of various pulse codes, reference is made again to "The Interface Handbook" by Kenneth M. True, see above.

It is desirable that a self-clocking pulse code, such as that just described, be used because the clocks 1108 in each transceiver unit, see Figure 19, although operating at substantially identical frequencies, are asynchronous relative to each other. In the absence of a self-clocking pulse code, separate timing pulses would necessarily accompany the data word, thereby increasing the system complexity.

Data arriving at a transceiver unit 111b, Figure 17, from a down-link transceiver unit 111a will be received by data receiver 1068, Figure 18, in repeater 114. The regenerator 1060 receives either a local data word from storage register and code converter 128 or a down-link data word from receiver 1068. The regenerated word is applied over line 1063 from the data transmitter 1066, for transmission over data link 1014 to the next up-link transceiver unit 111a.

Referring now to Figure 19, this figure illustrates any one of the repeater networks 114 in greater detail. Receiver 1068 is a linear amplifier 1100 having positive

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feedback to create hysteresis. Amplifier 1100 amplifies incoming phase-encoded RZ data, received over data link 1014 and because of the hysteresis converts it to suitable phase-encoded NRZ logic levels. Regenerator 1060 includes OR gate 1102 which outputs to line 1103 either data from receiver 1068 or local data from line 1057 connected to the output of storage register 128, Figure 18.

A data detector circuit 1104 detects a zero crossing, more specifically the negative-to-positive transition at the first bit interval boundaries, to enable a data synchronizer 1106. The data detector 1104 also detects the absence of data, such as the gap between data words, when no polarity transitions occur at the output of OR gate 1102 within a specified time interval. Thus, line 1101 receives only down-link data words, while line 1103 receives either local or down-link data words.

Each transceiver unit 111 has a precise 80 MHz crystal oscillator or clock. The clocks in the respective transceiver units are free-running, thus asynchronous with one another. Because of noise contamination and high-frequency degradation through data transmission link 1014, the phase-encoded data words may become distorted. Furthermore, because of line losses, signal levels become attenuated. Accordingly, it is suitable to amplify and regenerate the data pulses at each transceiver unit 111, but, in order to regenerate the data pulses at each transceiver unit, they must first be resynchronized with the local clock.

Local clock 1108 (Figure 19) synchronizes phase-encoded NRZ data words in data synchronizer 1106. Line 1107 receives resynchronized data which is sent to transmitter 1066 under the control of a control pulse from line 1112 connected to data detector 1104. Line 1113 from data detector 1104 also sends control pulses to data synchronizer 1106.

The regenerator and synchronizer network 1060 includes flip-flops 1070, 1071, a counter 1072, a crystal oscillator which is clock 1108 and a divide-by-two module 1074. Initially, flip-flop 1071 is reset, setting its Q output to ZERO, thereby resetting the Q output of flip-flop 1070 to ZERO. Divider 1074 is also reset so that no clock pulses are transmitted over line 1109 to counter 1072. When the first bit of a data word is received over line 1103, the first data pulse on line 1103 will be a positive-going pulse, rising from ZERO to ONE. This positive-going pulse will clock the Q output of flip-flop 1071 to a ONE, thereby releasing, through line 1113, flip-flop 1070 and divider 1074. Divider 1074 will transmit a 40-MHz clock pulse over line 1109. The clock pulse that is most nearly in phase with the positive-going data pulse on line 1103 will trigger flip-flop 1070 to transfer the logic-one at the D input to the Q output as a regenerated, resynchronized data pulse.

Data detector 1104 includes the counter 1072 to test for the presence of a data word on line 1103. The first positive-going pulse of a data word on line 1103 resets counter 1072. The clockline 1109 sends a gated 40-MHz clock pulse to counter 1072. The counter counts three clock pulses. Since the pulses occur every 25 nanoseconds, the three counts occupy 75 nanoseconds, 25 nanoseconds more than one bit interval. If the counter is not reset by a positive-going data pulse within the 75-nanosecond interval, counter 1072 will time out after three pulses. When counter 1072 times out, it sends a reset pulse over line 1114 to reset flip-flop 1071, causing line 1113 to go to ZERO, thereby resetting flip-flop 1070, divider 1074 and disabling transmitter 1066 via line 1112.

Figure 20 is a set of timing diagrams illustrative of the operation of regenerator 1060. The first diagram 1200 illustrates binary data formatted as a phase-encoded NRZ data word. The bit interval is 50 nanoseconds. For a ZERO bit, there is no polarity reversal between the bit interval boundaries, while for a ONE bit the polarity changes at mid-interval. A polarity reversal must occur at each bit interval boundary. The bit interval boundaries are indicated by arrows above the diagram. The bit values are written between the arrows. A complete data word consists of twenty bit intervals and is therefore 1,000 nanoseconds long. From the diagram, it is seen that there must be at least one positive-going pulse within any two bit intervals. It is upon this feature that the operation of data detector 1104, Figure 19, depends as discussed above.

The second diagram 1202 of Figure 20 represents a train of 80 MHz clock pulses 1224. Diagram 1204 shows the waveform of an incoming data word that has been translated by receiver 1068 from phase-encoded RZ pulse code to phase-encoded NRZ pulse code. Due to noise and distortion effects, the original pulses illustrated in diagram 1200 have deteriorated. The received pulses are out of phase and unsymmetrical.

Referring now to Figures 19 and 20, the first positive-going transition 1220, see diagram 1204, of the data word clocks the Q output of flip-flop 1071 to a ONE.

The logic ONE on line 1113 creates an enable signal 1222 to divider 1074 and flip-flop 1070, see timing diagram 1206. The next 80 MHz clock pulse 1224, which is most nearly in phase with rising bit edge 1220, will become the first 40 MHz clock pulse 1226, see timing diagram 1208. Clock pulse 1226 clocks the logic ONE at the D input of flip-flop 1070 to the Q output through line 1107 as the leading edge 1228 of the first resynchronized, regenerated data bit. As long as a logic ONE is present on lines 1112 and 1113 a transmit-enable signal 1230, see timing diagram 1212, enables output transmitter 1066. The data bits on line 1107 can then be converted from phase-encoded NRZ data to phase-encoded RZ data for transmission to the next up-link transceiver unit. Once the first rising bit edge has been resynchronized, the 40 MHz clock pulses will resynchronize and regenerate the remaining data bits. Timing diagram 1214 illustrates the output through line 1114 from counter 1072. When a data word remains zero for three 40 MHz clock pulses, counter 1072 will send out a pulse 1232 to reset flip-flop 1071, counter 1074 and to disable transmitter 1066.

Transmitter 1066, Figure 19, includes a voltage-to-bipolar current converter 1076 and an NRZ-to-RZ converter 1077. To reliably send data over a transmission link, such as a coaxial cable, the signals should be AC in nature with no low-frequency components. Preferably, constant current mode transmission is utilized to avoid the necessity for using wide dynamic-range receivers 1068. Voltage losses per unit length of the data link 1014 cause severe signal attenuation. Constant current mode transmission will provide substantially constant voltage levels at the terminating resistor 1150 at the input of receiver 1068, regardless of losses in data link 1014 between adjacent transceiver units 111.

To provide constant current mode transmission, the phase-encoded data words are converted from a voltage to a constant current by current converter 1076. Voltage logic gate 1075 includes both inverting and non-inverting outputs 1075a and 1075b. Resistors 1073a, 1073b (which have the same value R) and transistors 1078a, 1078b convert the voltage levels of logic gate 1075 to constant currents.

The bases of transistors 1078a and 1078b are set at voltage V_1 , V_1 being equal to the ZERO state of logic gate outputs 1075a and 1075b. The exact voltage of the ZERO state depends upon the type of logic selected. The voltages V_R appearing across resistors 1073a and 1073b will be, respectively, output voltage states ($V_a - V_1$) and ($V_b - V_1$). Therefore, the current through the two resistors will be respectively

$$I_{high} = (V_R, \text{ ONE state} - V_1) / R,$$

or

$$I_{low} = (V_R, \text{ ZERO state} - V_1) / R = 0.$$

The output current in data link 1014 will therefore be equal to

$$I_{a_{high}} - I_{b_{low}},$$

which changes to

$$-I_{b_{high}} + I_{a_{low}}$$

for a bit interval polarity transition, see Figure 22. Since $I_{a_{low}}$ and $I_{b_{low}}$ are zero, the current in data transmission link 1014 will be $I_{a_{high}}$, switching to $-I_{b_{high}}$ at a bit polarity transition. These data are in bi-polar, NRZ current mode. At the end of a data word a low frequency component would result, because of the time constants of transformer 1079 and coaxial data link 1014. To prevent the low-frequency component, the NRZ signal is converted to RZ by the action of circuit 1077. When the transmitter is enabled by a pulse through line 1112, switch 1077a is connected to voltage V_1 . For simplicity, the switch 1077a is shown as a mechanical switch. However, in actual practice, it is a solid state switch, such as a transistor or FET. When the end of a data word has been sensed by data detector 1104, Figure 19, a pulse through control line 1112 connected to data detector 1104 will cause switch 1077a to switch to V_2 . V_2 is equal to the ONE state of outputs 1075a and 1075b, thus turning off transistors 1078a and 1078b. The current in transmission link 1014 will go to zero, thus converting the bipolar NRZ output of transformer 1079 to bipolar phase-encoded RZ pulse code. Windings 1079a, 1079b, 1079c of transformer 1079 have a 1:1:1 turns ratio.

Referring now to Figures 17 and 21, central station 2 includes a data receiver 1028 which receives the phase-encoded RZ data words telemetered from the transceiver units 111 over data transmission link 1014, which, it will be recalled, is the triple-redundant coaxial link D1, D2, D3 in Figure 5. Data receiver 1028

preprogrammed to combine the digital signals from selected subarrays in order to synthesize a composite digital signal which is characteristic of a much larger desired array. The weight, or contribution, that the digital signal of an individual subarray makes to the total composite digital signal is controlled by the coefficient memory 1055. The methods and techniques for applying weighting coefficients are described more fully further below.

The seismic data channel signal in scan data channel memory 1047 are read out in data channel sequence, data channel 1 being first and data channel 10n being last. The data channel signals are transmitted over data bus line 1082 to multipliers 1053a and 1053b. Under control of controller 1080 and the programmed array pattern that is stored in control memory 1067, each data channel signal is multiplied by the appropriate weighting coefficient stored in coefficient memory 1055. If the signal from a data channel is not to be used in an array, its coefficient will be zero and, hence, the result of the multiplication will be zero. The weighted data channel signals are then algebraically added in adders 1064a and 1064b to the outputs of registers 1065a and 1065b. The accumulated results in registers 1065 and 1065b will be the sum of weighted data channel signals. Controller 1081 in response to memory 1067 will transfer the contents of registers 1065a and 1065b into output register 1080 as one data sample for each composite array when the previously programmed number of individual data channel signals forming each composite array has been summed. The process will continue until all the data channels in scan data channel memory 1047 have been processed into composite array signal samples and transferred to output memory 1080. The contents of output memory 1080 will then contain one scan of composite signal samples for the composite arrays. Auxiliary channel data are similarly formatted under control of controller 1081.

By way of example, it is assumed that a seismic cable assembly has 500 individual short subarrays. The output signals from consecutive sets of twenty subarrays could be combined to produce composite signals representative of twenty-five much longer arrays. By use of dual multipliers 1053a, 1053b, dual adders 1064a, 1064b and dual registers 1065a, 1065b, some of the signals from some of the twenty subarrays making up each of the consecutive array grouping can be combined with adjacent groupings, i.e. sets, to create composite signals representative of fifty overlapping, longer arrays.

The contents of output memory 1080 will be sequentially transferred to formatter 1032 and then to recorder 1034. As this cycle of processing is being completed for the first scan, the next scan of new data is being remapped in memory 1083a and 1083b. At the completion of processing of the first scan, as determined by controller 1081, the new data are transferred to scan data control memory 1047 where the processing commences for forming a second scan of signal samples for the next composite array.

The process recited above continues until the recording and processing cycle is completed as determined by present controls in master controller 1019.

The operation of the system thus far described is as follows:

A number of transceiver units 111 are disposed at regular intervals remotely with respect to the central station 2. Each transceiver unit has fourteen input channels to which are connected seismic sensor subarrays, as well as a channel selector, which is the multiplexer 122, and common signal-conditioning electronics of the transceiver unit. Of the fourteen channels ten are data channels. The remainder are test and auxiliary channels. The output of the common signal-conditioning electronics is connected to the repeater network 114. Internally of each of the transceiver units is the interrogation network 116.

The repeater networks 114 of the transceiver units are all connected in series and to the data receiver 1028 in central station 2 through the wideband transmission link 1014. The interrogation networks 116 are all interconnected in series and with the master controller 1019 in central station 2 by the interrogation link 1016 which is the triple-redundant line IP1, IP2, IP3 of Figure 3, it will be recalled.

Periodically at the beginning of each scan interval, such as every millisecond, master controller 1019 sends a wide S1 pulse, which is an interrogation pulse, through interrogation link 1016. As the interrogation network 116 in each transceiver unit 111 identifies the S1 pulse, the channel selector is reset to channel #0. The digital data word from the last channel of the previous scan is converted into a self-clocking phase-encoded RZ data word and is applied by transmitter 1066 of repeater network 114 to transmission link 1014 for transmission to data receiver 1028 in central station 2. An S2 pulse is then transmitted from master controller

translates the phase-encoded RZ data words into a binary NRZ pulse code first as floating point numbers, and then it reconverts from floating to fixed-point numbers representing data words. The fixed-point data words are arranged in a channel-sequential matrix in a remap memory in array former 1030 as will be discussed below. Each elementary seismic sensor unit 21 constitutes a subarray, as it comprises three individual detectors in the described embodiment. The output signals from a number of such subarrays are combined in array former 1030 to synthesize a new composite signal characteristic of a much larger, i.e. more extended, array. The synthesized composite signal is transferred to a formatter 1032 and thence to a magnetic tape unit 1034 where the signals are recorded for later use in providing a seismic cross section of the earth.

At the beginning of a seismic operation, a calibrate-address mode is initiated at central station 2. An interrogation pulse is sent from master control 1019 through interrogation line 1016 to the respective transceiver units 111. As each transceiver unit detects the interrogation pulse, a data word is set back to data receiver 1028 over data link 1014. A time converter 1015 measures the time between transmission of the calibrate interrogation pulse and the arrival of the resulting data words from the transceiver units 111. There is, of course, a unique time delay associated with the data words from each transceiver unit. The time delays are encoded as binary numbers to form an address code and are stored through line 1027 in address memory 1017. During a normal operation, time converter 1015 times the interval between respective interrogation pulses and the returning phase-encoded data words. The time intervals are compared with the stored address codes. Address memory 1017 then identifies each received data word as to the transceiver unit of origin and causes array former 1030 to place the received data word in the proper location in the matrix in a core memory.

Figure 21 includes a schematic representation of the array former 1030. The array former 1030 includes controller 1081, remap memory 1083a, 1083b, memory write control 1037, data channel scan memory 1047, read control 1049, multiplier 1053a and 1053b, coefficient read-only (ROM) memory 1055, adder 1064a and 1064b, accumulator registers 1065a and 1065b, output memory 1080 and read-only control memory (ROM) 1067.

As noted above, receiver 1028 receives the phase-encoded data words from the down-link transceivers 111a—111n and converts the phase-encoded RZ data words into NRZ binary floating point numbers which are reformatted to fixed-point numbers. Simultaneously, upon the receipt of the data words, time counter or converter 1015 and address memory 1017 identify each one as to its origin in terms of transceiver unit number and data channel number. The fixed-point numbers from receiver 1028 are transmitted to array former 1030 and stored in the remap memory 1083 of the array former, where they are written in data-channel sequence under the control of controller 1081 and write control 1037, after data channel identification by address memory 1017.

The data channels are numbered from 1 to 500, starting with the first elemental seismic sensor unit associated with the nearest down-link transceiver unit 111a and ending with the last seismic sensor unit associated with the most remote down-link transceiver unit 111n. The phase-encoded data words, however, are not received in numerical sequence from the data transmission link 1014. They arrive, as described above, as transceiver channel 1 from all the transceiver units 111a—111n, then as transceiver channel 2 from all transceiver units 111a—111n, and so forth. In data channel numbering, channel 1 of transceiver 111a becomes channel 1 in the remap memory matrix 1083a; transceiver 111b, channel 1, becomes data channel 11; transceiver 111c, channel 1, becomes data channel 21; and transceiver 111n, channel 1, becomes data channel 1+10n. Transceiver channels 0, 11, 12 and 13 are auxiliary channels in the described embodiment.

The function, therefore, of the remap memory 1083a, Figure 21, is to assemble the incoming, fixed-point data from receiver 1028 into the correct data-channel sequence in a memory matrix and to separate the auxiliary channels into their correct sequence in an auxiliary channel memory location 1083b. When one scan of seismic data and auxiliary channel data has been written in remap memory 1083a, 1083b, the data channel signals from remap memory 1083a are written into data channel scan memory 1047 and the auxiliary channel data 1083b is written into output memory 1080.

As stated above, the digital numbers stored in remap memory 1083a represent the signals from the 500 individual elemental seismic sensor units, each one of which constitutes a short subarray. Control memory 1067 and coefficient memory 1055 are

1019, actually 71.4 microseconds later. As each transceiver unit receives and identifies the S2 pulse, the channel selector, i.e. multiplexer 122, is advanced to channel 1. The seismic signal present in channel 1 is sampled, conditioned and digitized as a phase-encoded NRZ digital word as a local data word. The local data word is converted into a phase-encoded RZ data word and is applied to data transmission link 1014.

Each transceiver unit first transmits a local data word. It then awaits the arrival of a remote data word from the next down-link transceiver unit and, subsequently, the arrival of a data word from the down-link transceiver next to the next one, and so forth. Each remote data word thus received is regenerated and retransmitted up-link to data receiver 1028 in central station 2. Thus, transceiver unit 111a transmits its local data word and then receives, regenerates and retransmits remote data words, one after the other, from the other 49 transceiver units, assuming that there are 50 transceiver units in all. The last, 50th transceiver unit, of course, transmits only its own local data word.

In order to sample all channels in all transceiver units, one S1 pulse and thirteen S2 pulses are thus transmitted during one scan cycle. Thus, data words are transmitted to data receiver 1028 in a time-sequential/channel-sequential, two-stage multiplexing cycle. That is, data words from the respective transceiver units 111a—111n are separated in accordance with the interrogation pulse travel time between consecutive transceivers. An artificial delay is inserted in each interrogation network 116, as mentioned above, to insure separation. Data words from the respective channels within each transceiver unit are separated one from another in accordance with the channel-select sequence.

As the data words arrive at data receiver 1028, they are directed to the remap memory 1083a where they are ordered in a channel-sequential matrix. The first data channel of the first transceiver unit 111a is channel 1. The last data channel of the last transceiver unit 111n is channel 500. Thus, in response to the first interrogation pulse, data words from data channels 1, 11, 21 and so forth are received. In response to the second interrogation pulse, data words from data channels 2, 12, 22 and so forth are received, and so on.

In central station 2, the control memory 1067 is preprogrammed to extract signal samples originating from selected sets of seismic subarrays from remap memory 1083a. The selected signal samples are transferred to data channel scan memory 1047. From memory 1047, the signal samples are transferred to multipliers 1053a, 1053b where they are multiplied by selected weighting coefficients under the control of coefficient memory 1055. The weighted samples are then composited in adders 1064a, 1064b as a single composited signal sample representative of a much larger array having preselected properties. The composed data are stored in output memory 1080 for subsequent transfer to formatter 1032 and ultimate recordation in the recorder 1034, such as a magnetic tape.

Thus, it can be seen that the seismic data processing system described provides a single seismic cable which will permit the formation of any desired seismic sensor array configuration from a plurality of subarrays. It is not necessary to physically change the seismic cable or other data acquisition system components in the field, in order to provide different arrays to cope with changing geological conditions.

Proceeding now to a description of a further specific aspect of the described embodiment of the invention, reference is made to Figures 23 through 35.

With particular reference to Figure 23, in similarity with Figure 1, it is a diagrammatic showing of seismic survey arrangements illustrating one embodiment of a seismic survey or exploration system. As shown, a ship 10 with a large cable reel 2054 mounted at the stern is pulling a long marine seismic cable 2056, which is unreeled from the reel 2054. The ocean floor is designated by the horizontal line 2058, and various geological strata interfaces are designated by the horizontal lines 2060, 2062 and 2064.

The cable 2056 has a first section 2056' which is located closer to the vessel 10 and a remote section 2056'' which is farther away from the ship. As is customary in seismic marine cables, a large number of seismic sensors are imbedded in the cable. As also mentioned above, the cable may be approximately 10,000 feet long and include 500 sets of elemental seismic sensor units, each such set including three interconnected seismic sensors. With this arrangement, consecutive sensors will be located between six and seven feet apart, preferably 6.25 feet, and each elemental sensor unit, made of three sensors, will extend for approximately 12.5 feet, with the center-to-center distance for adjacent sensor units being 18.75 feet, i.e. about 20 feet.

The diagrammatic showing of Figure 23 brings out certain aspects of a specific feature of the illustrated embodiment which will now be considered in greater detail. Initial consideration will be given to the elemental sensor unit located at point 2066. The sensor unit located at point 2066 will pick up successive reflections after a shot at point 2068 is detonated near the stern of the vessel and close the proximate end of the cable 2056. Following the initial impulse, known as the "first break", which usually travels directly through the top layer of the water to the sensor unit 2066, the first reflected seismic wave will be that from the ocean floor 2058. This initial reflected signal received at sensor unit 2066 travels over the relatively short path 2070. It may also be noted that the ray, i.e. path, 2070 as it is incident upon the sensor unit at point 2066 makes a relatively shallow angle θ_1 with the horizontal. Subsequent reflections from the geological interfaces 2060 and 2062 follow paths including the lines 2072 and 2074, respectively. These rays make successively larger angles θ_2 and θ_3 with the horizontal. Accordingly, it may readily be seen that the direction of signals incident upon the sensor unit 2066 changes during the course of the recording of seismic reflections and, more specifically, that the angle of received signals relative to the horizontal increases with increased time. Further, the signals reflected along rays 2070, 2072 and 2074 and successively received at sensor units 2066 may, from an oversimplified standpoint, be considered to represent a trace of reflected signals from point along the vertical line 2075 including points 2070', 2072' and 2074'.

In Figure 23, an additional sensor unit 2076 located at the remote end of the seismic cable is also shown. For convenience and reference, the inner half of the marine seismic cable is designated by reference numeral 2056' and the outer half is designated 2056'', with sensor unit 2076 being located at the outer end of the remote, outer half of the cable 2056''.

At a later point in time, sensor unit 2076 will pick up signals reflected from geological interface 2062 along the path 2078. At a still later point in time, sensor unit 2076 will receive reflections along path 2080 from the deep geological interface 2064. It may be particularly noted that sensor units 2066 and 2076 receive signals from any given stratum at different angles and at different times.

As in other types of wave propagation analysis, the waves may be approximately represented by advancing spherical wavefronts or alternatively by rays forming part of such advancing wavefront. Further, the ray forms 2072 and 2074 which are shown straight in Figure 1 would actually be refracted at the interfaces 2058 and 2060 at angles which are related to the physical properties of the strata, in a manner well known in the art, and as shown in Figure 1.

Of course, strictly horizontal geological interfaces, as shown by horizontal interfaces 2058, 2060, 2062 and 2064 in Figure 23 are uncommon and are not of great interest to the geologist. Of greater interest are geological anomalies, including faults, domes and other tipping, slanted or "dipping" geological interfaces. In Figure 23, the tilted plane 2082 is shown making a positive dip angle relative to the horizontal plane 2064. The dashed line showing a dipping plane 2082 is shown to illustrate the subject matter which is dealt with in the description of Figures 24 and 25 further below.

Attention is directed to the dashed line seismic path 2083, in Figure 23, which meets the dipping plane 2082 at point 2083'. In the case of a plane which dips downward away from the direction of travel of the ship, using the geometry of Figure 23, the resultant seismic signal detected at sensor unit 2076 will be reduced in intensity, as compared with the signal produced by reflection from a plane which is tilted, i.e. dipped, in the opposite direction. This will be developed in greater detail in connection with Figures 24, 25 and 30. On a qualitative basis, however, it is noted that conventional seismic arrays are more sensitive to signals arriving vertically at the array and are less sensitive to waves arriving at relatively shallow angles of incidence. Further, this increased sensitivity is more pronounced for conventional seismic arrays at higher acoustic signal frequencies. As indicated in Figure 23, the seismic path 2083 points toward sensor unit 2076 at a more nearly horizontal angle of incidence than path 2080. Of course, if the plane 2080 is dipped in the opposite direction, the angle of incidence at sensor unit 2076 would be even more nearly vertical, and the response intensity would accordingly be increased. This phenomenon will be considered on a more quantitative basis below in connection with the description of Figures 24, 25 and 30.

In the present specification, reference is made to the difference in seismic survey results obtained with one direction of traverse, as compared with the opposite direction of traverse, in performing a marine survey. As developed above, this

difference is due to the difference in the direction of transmission of the seismic energy, which for marine surveys originates with a seismic impulse from the ship. Of course, with systematic land surveys, the seismic impulse could be initiated from various points including points at the rear or at the front of a linear cable array along the traverse. In applying the present analysis to land surveys, the location of the seismic impulse source relative to the seismic cable is a determinative factor.

Figure 24 is a plot of the relative response to reflected signals of an unsteered sensor array having the known configuration shown in Figure 26, located at a distance of 1,000 feet from the shot-point along cable 2056 in Figure 23 at various indicated frequencies and following a time interval of one second from the shot along the reflection path to the sensor array. The response at 200 Hz is identified by x's, at 100 Hz by +s, at 50 Hz by triangles and at 20 Hz by circles. The one-second time interval, together with the velocity, determines the depth of penetration of the reflected signals. In Figure 24, the velocity is taken from the high-velocity plot of Figure 28 and is therefore equal to 6,000 feet per second, and the depth of penetration is therefore approximately 3,000 feet. In Figure 24, the horizontal axis represents the layer dip angle, corresponding to the dip angle between the dashed line 2082 and the horizontal line 2064 in Figure 23. With an offset of approximately 1,000 feet from the shot-point, it may be seen that the maximum response at all frequencies occurs at a layer dip angle of approximately -10° , which would reflect the seismic waves from the shot-point substantially vertically toward the sensor array. This condition of maximum response is indicated by the vertical line 2084 in Figure 24.

Most seismic work up to the present time has been accomplished at relatively low frequencies for the reasons indicated in Figure 24. Specifically, note that at the second vertical line 2086 in Figure 24, which corresponds to a positive dip angle of 10° , in the direction shown in Figure 23, tending to reflect signals toward the seismic sensors at a more horizontal angle of incidence, virtually no energy at 200 cycles per second, or 200 Hz, is picked up by the sensor array.

Note further that along the vertical line 2086 the energy received at 100 cycles per second is at a level of approximately -18db , and is thus greatly attenuated relative to normal full amplitude represented by the 0 db level at the top of the chart in Figure 24.

Figure 25 represents a more extreme condition than that pictured in Figure 24, for an unsteered array. It involves a distance of approximately 4,000 feet from the shot-point to the sensor pickup point, a relatively low velocity of approximately 5,000 feet per second, characteristic of water or of near-surface materials in some parts of the world, and a time of only one second, corresponding to reflections from a relatively shallow geological layer. As may be seen by reference to the vertical line 2088 in Figure 25, with a dip angle of $+10^\circ$, even the 50-Hz seismic signals are cut off, and only the very low frequencies, such as the 20-cycle per second frequencies shown by plot 2090 are detected by the sensors. Incidentally, certain side lobes for 200 Hz are visible at 2092, 2094 and 2096, but these do not provide significant information as they are erratic or distorted in phase and have other anomalies.

The charts of Figure 24 and 25 represent in some detail the problems encountered with fixed, unsteered arrays of the type disclosed in some of the publications mentioned above.

More specifically, Figure 26 shows a 26-element array using uniform weighting of the sensor inputs and variable spacing. The overall length of the array is 210 feet, and the spacing is given by the following numerical values: $\pm 3'$, $\pm 8'$, $\pm 14'$, $\pm 19'$, $\pm 25'$, $\pm 30'$, $\pm 38'$, $\pm 44'$, $\pm 52'$, $\pm 61'$, $\pm 71'$, $\pm 80'$, $\pm 105'$, where the 26 elements are spaced from the center of the array by the indicated number of feet.

In Figure 26, the uniform height of the lines 2098 indicates the uniform weighting of the sensors, and their horizontal locations indicate the relative spacing of the sensors along the seismic cable. The resultant sensitivity is symmetrical about the vertical center line, is relatively broad and discriminates against horizontally travelling waves. The sensor array of Figure 26 was employed in the preparation of the plots of Figures 24 and 25.

The array of Figure 27 is made up of ten elemental sensor units, each including three detectors. In the tapered array of Figure 27, the end sensor units 2102 and 2104 have a weighting of "1", as compared with an increasing weighting of 2, 3, 4 and 5 for the sensor units toward the center of the array, with the two sensor units 2106 and 2108 near the center having weightings of "5". The array elements are uniformly spaced and extend for a total distance from the first sensor to the last of 230 feet.

This tapered array shown in Figure 27 has a response characteristic with a rather sharply defined principal lobe. As discussed below, the tapered configuration of Figure 27 may be employed in accordance with the presently discussed aspect of the invention.

Figure 28 is a plot of velocity in feet per second against reflection time in seconds. In Figure 28, the low velocity plot 2110, also designated V_L , appears as a horizontal line indicating a constant velocity of 5,000 feet per second. This is the velocity of seismic waves in water or near the surface of the earth, and is particularly significant for a wave travelling nearly horizontal in water. The high-velocity plot 2112, also designated V_H , however, increases in velocity with increasing depth, through the earth (as contrasted with water conditions). Accordingly, with greater reflection times, the root mean square, or RMS, velocity in feet per second increases significantly up to a maximum value at a four-second reflection time, of 11,000 feet per second. The high-velocity plot is representative of the actual velocity conditions in many parts of the world. Incidentally, the analysis of Figure 24 is based on the high-velocity characteristic V_H of Figure 28, while Figures 25 and 30, representing more extreme conditions, are based on the low velocity plot V_L of Figure 28.

In accordance with one important aspect of the embodiment presently explained, a large number of arrays are formed along the length of a seismic cable, and each of these arrays is individually directable, so as to be sensitive to seismic reflections reflected from distinct, predetermined depths of a geophysical terrain under survey. This may be accomplished by initially transmitting a large number of seismic signals from elemental seismic sensor units spaced along the cable. Then, a large number, perhaps 30, 50 or more arrays are established at 30, 50 or more spaced points along the cable from the signals picked up by the elemental sensor units. These arrays which are spaced along the cable are directed to sense seismic signals from selected depths along adjacent vertical lines of the geophysical area under survey. This directivity may be accomplished by appropriately delaying signals originating from adjacent elemental sensor units. Subsequently, the seismic signals from adjacent vertical lines are combined to produce a cross section or a composite geophysical survey of the terrain under study.

In providing the proper amount of delay between signals from adjacent elemental sensor units forming an array, it is important to determine the differences in time of arrival of seismic signals to the adjacent elemental sensor units. Figure 29 and the following mathematical analysis indicate how this delay may be calculated. In Figure 29, a seismic impulse from the shot-point 2116 is reflected from the geological boundary 2118 to the sensor array 2120, with the seismic signals travelling along the ray paths 2122 and 2124.

In the following mathematical analysis, the letters "s", "x" and "d" refer to the distances and points shown in Figure 29. For convenience of analysis, the point 2116 is reflected to point 2126 which would be the virtual image of point 2116 relative to the plane 2118.

For purposes of mathematical analysis, the following definitions shall obtain:

x—Distance of sensor array from shot-point

v—Velocity of propagation of seismic wave

d—Depth of reflecting boundary

s—Length of path of reflected signal

t—Time of transmission of reflected seismic wave along the path

t_0 —Time of transmission of reflected vertical seismic wave over distance 2d

In general,

$$s = vt$$

(G)

In the geometry of Figure 29,

$$s = \sqrt{x^2 + 4d^2} \quad (H)$$

$$s = vt = \sqrt{x^2 + v^2 t_0^2} \quad (I)$$

From the square of this equation, it is seen that t and t_0 are related by the following expression:

$$v^2 t^2 = x^2 + v^2 t_0^2 \quad (J)$$

or

$$v^2 t_0^2 = v^2 t^2 - x^2 \quad (K)$$

Now, from equation (I),

$$t = \sqrt{\left(\frac{x}{v}\right)^2 + t_0^2}$$

and the derivative

$$\frac{dt}{dx} = \frac{x}{v \sqrt{x^2 + v^2 t_0^2}} \quad (M)$$

Now substituting from equation (K) into equation (M) yields:

$$\frac{dt}{dx} = \frac{x}{v \sqrt{x^2 + v^2 t^2 - x^2}} = \frac{x}{v^2 t} \quad (N)$$

If we assume:

$x=6,000$ feet

$v=7,000$ feet/sec

$t=1.000$ sec, and

an elemental sensor unit spacing $dx=20$ feet, we can solve for dt as follows:

$$dt = dx \frac{x}{v^2 t} = 20 \frac{6,000}{(7,000)^2 (1.000)} = 2.45 \text{ milliseconds} \quad (O)$$

which represents the desired delay between elemental sensor units spaced 20 feet apart, required in order that the seismic signals at time t arrive at adjacent units in an array simultaneously.

The angle θ in Figure 23 at time $t=1.000$ sec is equal to

$$\theta = \cos^{-1} \frac{x}{s} = \cos^{-1} \frac{x}{vt} = \cos^{-1} 6/7 = 31^\circ \quad (P)$$

Of course, as the time t increases, reflections will come from deeper strata, θ will increase and the required delay between elements of the array located at point 2120 (Figure 29) will decrease for maximum response and maximum signal-to-noise ratio.

Figure 30 is a plot of response-versus-dip angle which is useful for comparison with Figures 24 and 25. For Figure 30, the individual arrays having a highly directional configuration of the type shown in Figure 27 are located along the length of the seismic cable and are directed to receive energy reflected from a horizontal plane at the depth corresponding to the elapsed time from the time of the shot to the time of reception of seismic reflections. Thus, for example, with reference to Figure 23, this would correspond to directing the array located at point 2066 to receive maximum energy from the ocean floor 2058 along path 2070. At a slightly later point in time, the array 2066 would be directed more downwardly to receive energy from interface 2060 along path 2072. This change in direction could be accomplished, by way of specific example, by changing the delay between the various elemental seismic sensor units making up the array at the location 2066 along the cable.

Figure 30 represents the response of a steerable array centered at a point located 4,000 feet from the shot-point, and "looking" in a direction corresponding to an elapsed time for the arrival of reflected seismic signals equal to 1.000 second. It is based on the low velocity plot 2110 (V_L) of Figure 28, and is thus fully comparable with Figure 25. In Figure 30, as in Figures 24 and 25, the response at 200 Hz is identified by x's, at 100 Hz by +s, at 50 Hz by triangles and at 20 Hz by circles. At each instant in time, the array is directed to receive energy from a horizontal geological layer boundary at the proper depth to produce reflected signals at the sensor units. Accordingly, unlike the arrangement of Figures 24 and 25, the plot of Figure 30 shows maximum response at all frequencies at a dip angle of 0° , corresponding to the central line 2128 in Figure 30. Note further that the response at each frequency, including the plot 2130 of the highest frequency, 200 Hz, is substantially symmetrical about line 2128. Thus, for negative dip angles, the 200 Hz response curve hits -40 db at about 22° as indicated by point 2132, and for positive dip angles the intercept is about 28° as indicated by point 2134. Further, the loss of

100 Hz signals at dip angles of $\pm 15^\circ$ is less than 3 db, and the loss of 50 Hz signals is in the order of one or two decibels. This is in dramatic contrast to the plots of Figure 25, in which no useful information is obtained at the 50 Hz, 100 Hz or 200 Hz frequency levels, at the $+15^\circ$ dip angle.

It may also be noted that arrangements employing individually and continuously variable directed arrays along the length of the seismic cable have the additional advantage of not being sensitive to the direction of traverse to any significant extent. More specifically, if a seismic traverse were being made from east to west, for example, using a system having the response of Figures 24 or 25, a significantly different result would be obtained, as compared with the same system used in a traverse from west to east. However, using a system having the response characteristics of Figure 30, no significant discrepancies would be observed between seismic traverses taken in one and the opposite direction.

Now that the broad principles of this feature of the illustrated embodiment of the invention have been outlined and some of the advantages of the novel method and system to be described have been considered, an illustrative embodiment of the new seismic system and method will be considered in detail.

In Figure 31, which is a block diagram of such illustrative embodiment, the cable 2152, which may correspond to cable 12 of Figure 1 and to cable 2056 of Figure 23, includes a large number of cable sections 2156a, 2156b, 2156c . . . 2156n. These cable sections are interconnected by the electronic connector modules 2164a, 2164b, 2164c . . . 2164n, corresponding to connector modules 13 of Figure 1 and thus containing the transceivers. The cable assembly 2152 may be disposed in water in the course of a marine survey, as indicated in Figure 23 or, in the case of a land cable, it is spread out over the terrain to be surveyed with the seismic sensors, then geophones, lying on the surface of the earth.

The remainder of the system shown in Figure 31 in block diagram form is located at the central station 2 in the ship 10 or a truck, for example, or in some cases certain of the operations indicated in Figure 31 are accomplished at a central processing point remote from the seismic survey. As shown in Figure 31, the data word output from the cable is routed to the data receiver and system control unit 2172, corresponding, in essence, to the data receiver 1028 of Figure 17, and the seismic data received from the cable at the unit 2172 may be processed to produce both of the following: (A) a monitor seismic section 2174 for examination by the survey crew, and (B) a final high-resolution cross section 2176 for study by geologists. Seismic data from the control unit 2172 is transmitted to a first array former 2178, corresponding to array former 1030 in Figure 17, and to a conventional monitor seismic section plotter 2180. The output from the array former 2178 may also be recorded on a conventional digital tape recorder 2182.

The monitor seismic sections provided by the plotter 2180 generally conform to those presently obtained in the field using various different seismic cables. Various types of surveys which have previously been accomplished by substituting one cable for another can now be realized through the use of the special cable disclosed herein and the special control circuitry 2172 and array forming circuits 2178, without the need for physically changing the two-mile long seismic cable.

The output from the control unit 2172 is also applied to a second array former 2184 which is also referred to as the beam steerer. If desired, the beam steerer 2184 may be operated directly from the control unit 2172. However, it is contemplated that it will often be desirable to merely record the seismic information from control unit 2172 on the high-speed, high-density recorder 2186 and later apply it to the beam steerer 2184 through the use of the additional tape apparatus 2188. Recorders 2186 and 2188 may, for example, be RCA Versabit video recorders. The output from the beam steerer 2184 may be applied to the conventional digital tape recorder 2190 and may be applied to a normal seismic data processor 2192 to produce the final high-resolution cross section 2176 by the use of a conventional seismic plotter 2194. Normal moveout correction for the array signals may be accomplished by processor 2192. Alternatively, normal moveout correction may be accomplished within beam steerer 2184, see below.

As disclosed and discussed above in greater detail, the cable 2152 of Figure 31 may include, as shown in Figure 32, a series of data transceiver units within connector modules 2164a, 2164b, 2164c, . . . 2164n, so that Figure 32 corresponds, in essence, to the upper portion of Figure 17, but is here repeated to enhance understanding of the beam steerer aspect.

Connecting the control unit 2172 (Figure 31) to the transceiver units are the two broadband transmission links, the first being the data link 1014 and the second

being the control and interrogation link 1016, as shown in Figure 32, which also illustrates each transceiver unit having an interrogation network 116 and a repeater network 114.

As mentioned above, the fifty cable sections 2156a, 2156b, 2156c . . . 2156n of Figure 31 have disposed uniformly along their length a series of sensors, with each three sensors being interconnected to form an elemental sensor unit. Three of the ten elemental seismic sensor units 21 associated with each cable section are shown in Figure 32. Analog seismic signals from each of the seismic sensor units 21 are multiplexed and converted into digital form in the repeater-converter circuit 114 in the transceiver unit and are applied, again, by a second multiplexing step, to the broadband transmission link 1014, as explained above. The timing of the transmission of the multiplexed signals is controlled by the interrogation signals applied on transmission link 1016 to the interrogation network 116, as more fully described above.

Figure 33 shows a portion of the block diagram of Figure 31 in much greater detail, and corresponds in some respects to Figure 21. In Figure 33, the array former 2178 is enclosed within the large block outlined with dashed lines bearing the same number, and corresponds to array former 1030 of Figure 17. The system control unit 2172 of Figure 31 is implemented in Figure 33 by the blocks 2212 and 2214. Data from the transmission link 1014 of cable 2056 is received in the data receiver and processor 2214, corresponding to data receiver 1028 of Figure 17, which applies the data words to the array former 2178 under the control of master controller 2212, which finds its counterpart in master control 1019 of Figure 21. Receiver and processor 2214 converts the transmitted seismic digital data words from data channel 1014 into binary numbers and reformats them into fixed-point binary numbers, suitable for processing in the digital array former 2178. Simultaneously, with the receipt of data information at receiver 2214, a memory address and time control circuit 2216 (1017 in Figure 21) is set into operation to identify the originating seismic sensor unit location and number, and associate it with the received seismic information. The seismic data from processor 2214 is applied to the remap memory 2218 (1083 in Figure 21) where it is rearranged and written in data channel sequence in accordance with instructions from the write control circuit 2220 (1037 in Figure 21). From the remap memory 2218, the seismic information is transmitted to the data channel scan memory 2222, corresponding to memory 1047 in Figure 21. The data channels are numbered from 1 to 500 starting with the elemental seismic sensor unit 21a closest to the system control unit and ending with the most remote seismic sensor unit 21n (see Figure 32). This sensor unit numbering scheme is also shown in Figure 35. The remapping step is employed to accommodate the different sequence of application of seismic data signals to the data link 1014, as discussed in more detail above. The detailed internal control of the array former 2178 is provided by control unit 2224 (see controller 1081, Figure 21). Associated with controller 2224 is the array control read-only memory 2226, corresponding to memory 1067, Figure 21. Information with regard to the desired array combinations of the seismic signals from the 500 elemental seismic sensor units is entered into the control read-only memory 2226. This array information may, for example, establish an array such as that shown in Figure 27. This would be a ten-element array with tapered weighting coefficients, as described above. Incidentally, the desired array weighting coefficients are entered into the array former 2178, specifically into the read-only memory 2228, see memory 1055 of Figure 21.

In forming the combinations of seismic values needed to form the weighted arrays, the data stored in memory 2222 is weighted in accordance with the coefficients stored in the read-only memory 2228 in multipliers 2230 and 2232, and the elements of each array are thereafter added in adders 2234 and 2236, with these components being identified by numerals 1047, 1055, 1053a, 1053b, 1064a, and 1064b, respectively. Of course, a read control circuit 2238 (1049 in Figure 21) is provided for timely outputting of the seismic data from memory 2222. The sums of the seismic data making up each array are stored temporarily in registers 2240 and 2242, (1065a, 1065b in Figure 21). Incidentally, the dual channels including the multiplier 2230, the adder 2234 and the register 2240, and the multiplier 2232, the adder 2236 and register 2242 are employed to accommodate overlapping arrays including the use of seismic data from a single elemental sensor unit in two different arrays, with optional different weighting of seismic information from a single channel as it is used in different arrays. From the output registers 2240 and 2242, the array signals are stored in the output memory 2244 (1080 in Figure 21) from which they are applied to the formatter 2246 and the recorder 2248, see circuits 1032 and 1034 of Figure 21. Of course, as indicated in Figure 31, a real time plotter 2180 may be

connected to the output of the formatter 2246. Alternatively, the plotter 2180 may be operated from tapes of data recorded in recorder 2248.

With reference to Figure 31, the beam steering array former 2184 is similar in certain respects to the array former 2178 of Figure 33, but also includes the significant additional capacity of selecting array signal elements from different times of arrival at the various sensor units.

Array former 2184 (No. 2) of Figure 31 is shown in functional block form in Figure 34, and its operation will be described further below in connection with the diagram of Figure 35. In Figure 34, the high-speed, high-density recorder 2188 is shown at the far left-hand side and the master control circuitry, shown as block 2252, controls all of the functions in the beam steerer. Within the beam steerer 2184, the high capacity of the matrix input memory 2254 constitutes one of the significant differences from the array former 2178. Instead of a memory storing a single value of the seismic data from each of the 500 channels, the matrix memory 2254 stores data words representing 128 values of seismic information from each of the 500 channels. The memory 2254 may, for example, be implemented by a core memory. The beam steerer 2184 of Figure 34 also includes the array specification read-only memory 2256, the channel coefficient storage memory 2258, the delay selector and processor 2260 and the special data processing circuitry 2262. In addition, the array former includes the input and output buffer circuits 2264 and 2266.

In operation, the array former of Figure 34 selectively combines a large number of seismic data input signals to form arrays which are continually changing in their direction of maximum signal reception. This change in direction is to accommodate the changes in the angle θ discussed in connection with Figure 23, as signals are expected to be reflected from successively deeper boundaries along the seismic section corresponding generally to the line 2075 in Figure 23. To steer the arrays, the delays among the individual channels of seismic information which are being combined must be changed, as successive complete cycles of forming array outputs are completed during successive one-millisecond periods. This is accomplished by the delay selector 2260, Figure 34, which provides address information to the large scale memory 2254 to output from the memory 2254 seismic data from each channel, properly delayed with respect to seismic data from adjacent channels.

The nature of the operation of the beam steerer 2184 will now be considered from certain other aspects to more clearly bring out its mode of operation.

With reference to Figure 35, an example is given in which a recording vehicle 10 is shown to the right-hand side and in which the cable 2056 extends to the left. In Figure 35, the 500 elemental seismic sensor units (each including three spaced detectors) located along the length of the cable are shown by numbered dots located along cable 2056. The first eight sensor units included in the first cable section are shown in Figure 35 as extending from point 2302 to point 2304. Sensor units Nos. 251 through 270 are shown extended from point 2306 to point 2308, and the final sensor units Nos. 491 through 500 are shown extending from point 2310 to point 2312. Each of the dots shown in Figure 35 in the matrix 2254' represents a multidigit binary number stored in the large scale memory 2254 of Figure 34. In matrix 2254' of Figure 35, data received from specific channels is located below the associated numbered sensor unit, and the data received in successive one-millisecond time intervals from a specific channel are located along a vertical line, with the time intervals being indicated at the right-hand side margin in Figure 35. During each one-millisecond time interval, the entire 500 channels corresponding to the 500 seismic sensor units along the cable are sampled, and the resultant seismic data is stored in memory 2254. As the time cycle progresses, old data is deleted from memory 2254 and new up-to-date information is inserted. However, a time "window" or time frame interval of 128 milliseconds, corresponding to 128 samples from each of the 500 seismic sensor units, is stored in memory 2254. This permits the combination in array former 2184 of seismic data from sensor units to be included in an array, with the permissible displacement in time of reception of the samples being up to 128 milliseconds.

To give a specific example of how the system of Figure 34 functions in practice, the diagram of Figure 35 identifies the memory location for three overlapping signal arrays by the lines 2314, 2316 and 2318 which extend diagonally across the memory representation area designated 2254' in Figure 35. Each of these signal arrays includes signals from eight sensor units (each including three sensors) as shown in Figure 27.

The example is based on distance x (see Figure 29) corresponding to the 251st sensor unit, which is located at a distance of 6,000 feet from the shot point, normally adjacent one end of the cable. In addition, the time t is assumed to be equal to one second, and a seismic velocity of 7,000 feet per second is assumed. The spacing dx between sensor units is equal to 20 feet in the present example. Substituting into formula (O), dt turns out to be 2.45 milliseconds. This is the desired delay between seismic signals originating from adjacent elemental seismic sensor units spaced 20 feet apart to be included in the array. In its implementation, as seen with reference to line 2314 in Figure 35, the first sample from sensor unit No. 251 is taken at time t equals 1.000 second. The second array signal is taken from sensor unit No. 252 at time t equals 1.002 seconds. Similarly, the third sample, from sensor unit No. 253, is taken at time t equals 1.005 seconds. The remaining five units of eight units thus sampled are those appearing above the dots along line 2314, i.e. up to the 258th unit which is sampled at time t equals 1.017 seconds. These selected delays, of course, approximate the desired 2.45 milliseconds per channel and result in the in-phase summation of the reflected seismic signals.

In Figure 35, lines 2316 and 2318 represent overlapping arrays. More specifically, the array indicated by line 2316 includes elemental seismic sensor units Nos. 256 through 262, and the array represented by line 2318 includes sensor units Nos. 261 through 268. The array represented by line 2316 starts at a distance of 6,100 feet from the shot-point, and the array represented by line 2318 starts at a distance of 6,200 feet from the shot-point. Using formula (O), dt for these two arrays turns out to be 2.49 and 2.52 milliseconds, respectively, assuming time t equals 1.000 second. The desired 2.49 milliseconds differential delay per channel for the array corresponding to line 2316 produces the same pattern of relative delays for line 2316 as for the array of line 2314. However, the array represented by line 2318 has a sufficiently greater difference in delay between channels so that the fourth element of the array is selected from the memory slot corresponding to a time t equal to 1.008 seconds, instead of 1.007 seconds as in the case of arrays corresponding to lines 2314 and 2316. Similarly, the sixth and eighth samples are taken at times of 1.013 and 1.018 seconds, respectively, instead of at 1.012 and 1.017 seconds, respectively, for the arrays corresponding to lines 2314 and 2316. This increase in the required delay between samples which are being combined to produce in-phase summation would, of course, be expected in the case of arrays more remote from the shot-point, and with increased angularity of the incident seismic waves. More generally, for each array along the length of the cable the stored seismic samples may be selected in accordance with formula (O).

Of course, still with reference to Figure 35, arrays involving the first few sensor units closest to the shot-point would be receiving signals along paths oriented very nearly perpendicularly to the cable and therefore would not require much delay between channels being combined. On the other hand, for the final array at the end of the cable, the incoming reflections would be at a more shallow angle than those at the center of the cable and will therefore require significantly more delay between adjacent channels, as the signal information is being combined. In addition, the required delays between channels will change with time, and will be reduced with increased time, as reflections come from progressively deeper geologic interfaces at more nearly vertical incidence on the arrays. From a mathematical standpoint, the arrays may be expressed in terms of equations of the following form:

$$Y_t^J = C_{iJ} \cdot Y_{(t+tz)}^K \quad (Q)$$

$$Y_{1.000}^J = C_{1J} \cdot Y_{1.000}^{251} + C_{2J} \cdot Y_{1.002}^{252} \dots$$

$$+ C_{8J} \cdot Y_{1.017}^{258} \quad (R)$$

wherein Y_t^J is an array sample from the J^{th} array output at time t , $Y_{(t+tz)}^K$ is a sample from K^{th} input channel at time t , with t increasing by the slope z multiplied by the sample number m , and C_{iJ} is the i^{th} coefficient applied to an input channel for J^{th} array output. Equation (Q) above is limited to short arrays, such as the eight-element arrays indicated by lines 2314, 2316 and 2318 in Figure 35, as equation (Q) assumes that the slope z is constant, and this assumption is only valid for short arrays.

In the example of the computer implementation of equations (Q), (R), note that the successive array signal outputs are a combination of signals from eight adjacent sensor units taken at different discrete sampling intervals selected to

approximate the slope of the delay versus distance of the arriving seismic wave. In the present instance, this slope was 2.45 milliseconds for the 20-foot sensor unit spacing. Accordingly, the selected samples were spaced apart by either two or three-milliseconds.

It may also be noted that, for the ten-sensor unit array of Figure 27, the ten coefficients would be 1, 2, 3, 4, 5, 5, 4, 3, 2, 1. Thus, for example, for the eighth of the ten samples to be included in an array as shown in Figure 27, $C_{8,7}=3$.

Alternatively, and for other surveys, a uniform weighting could be applied to all samples. In addition, of course, a greater or lesser number of channels may be employed in the formation of array signals. However, it is contemplated that from eight to thirty-two elemental seismic sensor units will normally be included in each array. The present invention provides the additional capability of processing data using arrays steered toward the expected direction of arrival of seismic signals, and then reprocessing the data to steer the arrays in modified directions tailored to the special geologic conditions to provide a better "look" at the terrain under survey, without the need for additional field work.

In connection with marine systems, as noted above, the seismic impulse is normally initiated on the ship, as the cable is being towed behind it. Accordingly, the beam steerer forms the arrays so that their direction of maximum reception is toward the ship and downward, and pointing increasingly further down with increasing time, as seismic reflections are returning from deeper geological boundaries. Similarly, in connection with land surveys, where the seismic impulses may originate at either end of the seismic cable, or near the middle, the arrays are again directed initially toward the expected points of reflection of the seismic impulse from horizontal geological boundaries. It may also be noted, with regard to normal moveout correction, that this may be accomplished, if desired, within the beam steerer 2184 instead of in processor 2192. This is accomplished, with reference to Figures 34 and 35, by selecting seismic array samples from memory 2254 which are displaced in time as a group from the samples included in adjacent arrays. In Figure 35, this would correspond, in a qualitative way, to shifting line 2316 downward, i.e. later in time, in field 2254', thus displacing the corresponding array in time, so that the array signals from the arrays, represented by lines 2314 and 2316 would, at any instant of time, both represent reflections from the same depth. Of course, memory 2254 would have to be increased in capacity to accommodate the large delays required. In this way, normal moveout correction in addition to array formation, may be accomplished in beam steerer 2184.

In continuation of the description of the seismic data processing system disclosed herein, attenuation is now directed to a feature of the illustrated embodiment which is implemented in the area of analog signal pickup by the elemental seismic sensor units.

For a better understanding of the feature now to be explained, reference is made to Figure 36 which, in some respects, involves a simplified schematic of what is illustrated in Figure 14. Thus, Figure 14 shows the multiplexer 122 connected to a plurality of receiving channels $C_1, C_2, \dots, C_n$, all connected to the multiplexer bus line 312 through DC blocking capacitors 123, resistors 315 and switches 316. The signal-receiving channels are coupled to seismic sensors 21. Each resistor 315, in combination with its capacitor 123 forms a high-pass R-C filter for its channel. The filter removes the DC components of the incoming analog signals. Suitably, switches 316 are high-speed FET switches of any well-known type.

The output from the multiplexer 122 on bus line 312 is shown connected to a signal-conditioner-and-amplifier network (SCAN) 3011 which schematically represents circuitry shown in detail in Figure 16 and thus includes amplifier 320' and sample-and-hold circuit 322', for example. This network conditions and suitably amplifies the sampled analog signals prior to applying them to a utilization device 3033. Network 3011 may include a fixed-gain buffer amplifier, sample-and-hold circuitry and other circuits for preconditioning a signal sample before transmittal to utilization device 3033, wherein the utilization device is, in practice, the gain-ranging amplifying system 124 and analog-to-digital converter 126 of the above description. Internally generated spurious noises in multiplexer 122 will appear across each capacitor 123 as a spurious voltage V_1 which can be of either polarity with respect to ground, and the internally generated spurious noise voltage V_2 across the network 3011 will appear on its output and become algebraically added to voltage V_1 . When the voltage amplitudes of the incoming desired signals become comparable to the spurious voltages V_1+V_2 , then the noise-to-signal ratio will be excessive. In

the seismic art, a trace which is excessively noisy must frequently be discarded, thereby wasting valuable seismic information.

The spurious voltages $V_1 + V_2$ have many origins including: thermoelectric effects, Peltier effects, offset drifts of the amplifier stages in network 3011, etc. Each of the FET switches 316 employed in multiplexer 122 induces the noise voltage V_1 across a capacitor 123. It is well known that FET switches, being semiconductor devices, include feedthrough capacitors and leakage resistors between their control and switching elements (not shown). Moreover, each control element in each FET switch is activated by a relatively large control pulse provided by the network 3011 to a control line 3021. This control pulse will pass onto each DC blocking capacitor 123 through the feedthrough capacitor and leakage resistor of its associated FET switch 316.

The capacitors 123 are identical and the feedthrough capacitors and leakage resistors of the FET switches are substantially identical one with another. Therefore, the spurious voltages across capacitors 123 are uniform.

Referring to Figure 37, in accordance with an improved modification, one of the input channels to the multiplexer 122 is grounded. This channel, referred to above as the C0 or "test" channel, is in all respects similar to the signal-receiving multiplexer input channels $C_1 - C_{n-1}$, where n is the number of channels, except that the input terminal to channel C0 is connected to ground, so that no external signals can be applied to the test channel C0. The test channel includes a capacitor 123' which has the same capacitance value as capacitors 123. Associated with capacitor 123' is a multiplexer switch 3023.

Between network 3011 and the utilization device 3033 is connected the sample-and-hold (S/H) network 1050 (Figure 18) comprising the series capacitor 1051 and the normally open, shunt FET switch 1052 connected to ground, as discussed above, when explaining Figure 18.

The output from multiplexer 122 on bus line 312 is connected to network 3011 which typically includes the unity gain amplifier 142 (Figure 18) whose output is connected to the signal sample-and-hold circuit 1044 (Figure 18), not shown in Figure 37.

The state controller 132 controls all the operative networks of the circuitry of Figure 37 through control lines 3021. For example, controller 132 sequences the multiplexer channels $C_0 - C_{n-1}$ through a multiplexer scan cycle and controls signal utilization device 3033 which includes the binary gain-ranging amplifier system 124 coupled to the analog-to-digital (A/D) converter 126, as described above. Converter 126 converts the multiplexed analog signals from channels $C_1 - C_{n-1}$ into corresponding digital numbers. Other networks which are not germane to the feature presently discussed have been purposely omitted from Figure 37 for the sake of clarity.

In operation of the system shown in Figure 37, at the start of a multiplexer scan cycle, the multiplexer 122 is reset to test channel C0 at which time switch 3023 and a further switch 3026 will be closed. The spurious voltage V_1 developed across a capacitor 123' will become algebraically added to the spurious voltage V_2 developed across network 3011. The thusly combined voltage $V_1 + V_2$ will be transferred to a capacitor 3025 to develop thereacross a sample voltage V' which, when switch 3026 is open, will be in opposite polarity to the voltage $V_1 + V_2$. Thus, each time that the multiplexer is reset to test channel C0, the sample-and-hold network 3024 acquires the spurious voltages from the test channel C0 and from network 3011. Thereafter, switches 3023 and 3026 will remain open while multiplexer 122 sequentially scans the active, signal-receiving channels $C_1, C_2, \dots, C_{n-1}$.

If capacitors 123 and 123' have the same capacitance values and if the overall gain of the network 3011 remains constant, then $V' = V_1 + V_2$. Therefore, as multiplexer 122 scans channels $C_1 - C_{n-1}$, each channel will have at the output of network 3011 a signal voltage V_e , as well as the spurious noise voltage $V_1 + V_2$ which will

be successively and algebraically added to the sample voltage V' held by capacitor 3025 in accordance with the following equation:

$$V_e + V_1 + V_2 + (-V') = V_e$$

so that each spurious voltage $V_1 + V_2$ from each signal-receiving channel will be substantially cancelled by the sample voltage V' .

Figure 38 shows the principle of cancellation of spurious voltages as applied

to the circuit of Figure 16. Thus, the single resistor 315'' is employed in place of the individual resistors 315 in Figure 37. Further, for the reasons set forth above, the capacitors 123 and 123' are of substantially lesser capacitance than the corresponding capacitors of Figure 37. Accordingly, a given current leakage from a switch 316, for example, would develop a larger voltage across capacitors 123 or 123' of Figure 38 than across the corresponding larger capacitors of Figure 37.

In Figure 38, other circuit elements not identical with those of Figure 37 but corresponding to circuit elements of Figure 18 include multiplexer buffer amplifier 142, the signal sample-and-hold capacitor 1046 and the buffer amplifier 1048. Apart from these minor circuit differences, the foregoing description of Figure 37 is fully applicable to Figure 38, and the compensating voltage is developed across capacitor 1051 (which is also shown only in the more detailed circuit of Figure 18), to compensate for the spurious voltages appearing on capacitors 123.

In continuation of the description of the seismic data processing system of this invention, a more detailed explanation of the gain-ranging amplification system will now be given with reference to Figures 39 through 42.

In Figure 39, the left-hand side illustrates the analog-to-digital acquisition system including the multiplexer 122 with signal input channels $C_1, C_2, \dots, C_n$, the output of the multiplexer on bus line 312 being connected to the non-inverting input of a unity gain buffer amplifier 320 that may be an operational amplifier such as an LF 356, made by National Semiconductor, Inc., whose output is connected to the sample-and-hold circuit 322, these circuit components having been described above in detail, particularly in connection with Figure 14.

The gain-ranging amplifier system 124 has an input terminal 3130 and an output terminal 3132 and basically consists of at least two, preferably four, bi-gain amplifiers, i.e. amplifier stages $A_1, A_2, \dots, A_m$ connected in cascade. Each amplifier, i.e. stage, would typically include a pair of input terminals 3133, 3134 and an output terminal 3135 (Figure 40). The non-inverting input 3133 to the first amplifier stage A_1 is coupled to the input terminal 3130 which receives the output signal from the sample-and-hold circuit 322. The output voltage of the last amplifier stage A_m on output terminal 3132 is applied to a signal utilization device, which is the analog-to-digital (A/D) converter 126 in the presently discussed system, as well as to a window comparator 3138. The gain of each amplifier stage may be set, i.e. adjusted, to one of two states, namely a low-gain state, preferably equal to unity, or a high-gain state G_i , wherein G_i is a discrete high-gain value for the i th ($i=1, 2, \dots, m$) amplifier.

The state controller 132, mentioned above in conjunction with Figure 14, is interconnected with switches 316 and 326 through the control bus line 341 having a plurality of control lines. Controller 132 sequences the signal input channels C_1-C_n through a multiplexer scan cycle, as described above.

Associated with state controller 132 are a variable reference decoder 3144 and the window comparator 3138. Gain-control lines 3150 and noise-cancelling control lines 3160 interconnect state controller 132 with each one of the amplifier stages A_1-A_m . For simplicity, only one gain-control line 3150 and one noise-cancelling control line 3160 are shown in Figure 39, but it should be understood that there will be as many such control lines as there are amplifiers, i.e. stages.

In a preferred embodiment, state controller 132 is a synchronous programmable counter, such as a 74S161 integrated circuit made by Texas Instruments. Reference decoder 3144 is a digital-to-analog converter, such as MC 1408L, made by Motorola. Comparator 3138 may be an LM 311 voltage comparator, and each one of amplifiers A_1-A_m is a high-input impedance operational amplifier, such as LF 156, both devices being made by National Semiconductors, Inc.

Each one of the amplifiers A_1-A_m has a gain-control circuit and a noise-cancelling circuit, both shown in detail in Figure 40. The control circuit includes a voltage divider network formed by resistors 3170, 3172, FET switches 3174, 3176 and the specific gain-control line 3150. In the gain-setting operation, when switch 3176 is closed and switch 3174 is open, the amplifier's output signal is fed back from output 3135 to the inverting input 3134, thereby setting the amplifier to its low-gain state which is equal to one. When switch 3174 is closed and switch 3176 is open, the amplifier is set to its high-gain state, such as G_i for amplifier A_i , since resistor 3170 is then in the amplifier's feedback loop. The desired gain state is set in response to a control signal from controller 132 through that control lines 3150 which pertains to the specific amplifier stage, such as A_i in Figure 40.

The noise-cancelling circuit comprises FET switches 3182, 3184, 3186, a capa-

citor 3188, and a noise-cancelling control line 3160. When switch 3182 is closed, switches 3184 and 3186 will open.

In the noise or offset removal mode by means of which the characteristics of each amplifier are corrected, controller 132 sends a signal through the control line 3150, to close switch 3176 and open switch 3174, thereby setting each amplifier to unity gain state. Simultaneously, controller 132 disconnects the input terminal 3130 to the amplification system 124 by opening switch 3182 and establishes connection, by closing switch 3184 (Figures 40 and 41), between junction 3190 and the output terminal 3135 of the amplifier. Input terminal 3133 to the amplifier is grounded by closing switch 3186. Switches 3182, 3184 and 3186 are actuated by a signal arriving on the control line 3160. Any DC noise ("offset") will then appear on the amplifier's output terminal 3135. A capacitor 3188, connected as shown, will become charged with the polarities across its plates 3188a, 3188b, as illustrated in Figure 42 for an offset voltage $+V$ appearing on input terminal 3133. When the offset removal mode has been completed, controller 132 will close switch 3182 and open switches 3184 and 3186 by means of a second signal through control line 3160, thus reconnecting the input terminal 3130 with the amplifier system 124 and restoring the amplifiers to their normal operating mode.

The charge voltage $+V$ across capacitor 3188 will now be algebraically added to the incoming signal V_{in} , and will substantially completely cancel the amplifier's inherent offset signal $+V$ as demonstrated in Figure 42. The amplifier's output signal will, therefore, become free of DC noise, regardless of the gain to which the amplifier may have been set. The factors which determine how often it is necessary to go into the offset-removal mode will depend on the rate at which the offset noise drifts and on the value of the amplifier's input impedance.

In the gain-ranging operation, the gain-determination cycle for each channel (such as channel C_1) starts with all of the amplifiers set to unity gain. State controller 132 provides a sequence of digital codes representing a corresponding sequence of variable reference voltage steps. The digital codes are converted to corresponding discrete reference voltages V_R by reference decoder 3144. The reference voltages can be stepped through the sequence

$$V_{R1} = V_B/G_1, V_{R2} = V_B/G_2 \dots V_{Rm} = V_B/G_m$$

wherein $G_1, G_2 \dots G_m$ are the higher gain values of amplifiers $A_1, A_2 \dots A_m$, respectively, and V_B is a base voltage equal to a preselected fraction of the full-scale voltage of analog-to-digital converter 126. The gains G_1, G_2 , etc. are proportional to a preselected power of some number base, say two. The preselected power is unique for each amplifier. The variable reference voltage steps V_{R1} are inversely proportional to the unique gain values of their corresponding amplifiers. It may be noted in passing that the controller 132 includes as part of both offset removal mode and the gain-ranging mode, the setting of the amplifier to their unity gain state. This common step simplifies the implementation of these functions.

In a preferred embodiment, $G_i = 2 \exp 2^{(m-i)}$. For an amplifier system 124 comprising four amplifiers ($m=4$), the respective high-gain values for the amplifiers would be: $G_1=256, G_2=16, G_3=4, G_4=2$. With only four high-gain settings, the overall gain of the binary amplifier system 124 can be made to range from the minimum of 2 to the zeroth power (i.e. one) to the maximum of 2 to the 15th power (i.e. 32,768) in steps of powers of 2. To accomplish the above, only four gain decisions need to be made. The gain comparisons must be made using the amplifier having the highest gain setting first, and thereafter the comparisons are made in order of descending amplifier gain, regardless of the electrical position of the particular amplifier in the cascade.

The gain-ranging operation will now be explained in greater detail. With all four amplifiers set to unity gain, the absolute value of the system's output voltage $|V_o|$ appearing on output terminal 3132 is compared with the first reference voltage $V_{R1} = V_B/256$ by comparator 3138. Comparator 3138 rectifies voltage V_o and compares its absolute value with reference voltage V_{R1} . The decision based on this comparison is applied to controller 132. If $|V_o| \geq V_{R1}$ controller 132 causes the gain of amplifier A_1 to remain at unity gain. If $|V_o| < V_{R1}$ controller 132 sets the gain of amplifier A_1 to G_1 , i.e. 256. The variable reference voltages V_{R2}, V_{R3}, V_{R4} are then sequentially compared with the successive values of the output voltage $|V_o|$ that appear after the sequential switching decisions are made. As each comparison is made, a gain decision is also made by controller 132 for the amplifier having the

next successive lower gain corresponding to the reference voltage used for the comparison.

In sum, the comparator 3138 compares the output voltage $|V_o|$ on terminal 3132 with reference voltage V_{R1} corresponding to amplifier A_1 . When the comparison is negative, that is when the absolute value of V_o is less than V_{R1} , then comparator 3138 will instruct controller 132 to open the normally closed switch 3176 and close the normally open switch 3174 (Figure 40). Amplifier A_1 is now at its high-gain setting. The sampled signal held by the sample-and-hold circuit 322 is again amplified by the binary gain-ranging system 124, with amplifier A_1 adjusted to its high-gain setting and the other amplifiers A_2 — A_4 remaining at their unity gain settings. If the new value $|V_o| < V_{R2}$, i.e. if the result of the second comparison is again negative, then comparator 3138 will instruct the controller 132 to set amplifier A_2 to its high-gain setting. The sampled signal will again be amplified by the binary gain-ranging system 124 having amplifiers A_1 and A_2 at their high-gain settings and amplifiers A_3 , A_4 at their unity gain settings. If the next value $|V_o| < V_{R3}$, i.e. if the result of the third comparison is again negative, controller 132 will cause amplifier A_3 (not shown) to assume its high-gain setting. If after the fourth comparison $|V_o| < V_{R4}$, then controller 132 will cause amplifier A_4 (which may be amplifier A_m) to assume its high-gain setting but if $|V_o| \geq V_{R4}$ controller 132 will hold the amplifier at unity gain. After completion of the fourth comparison, comparator 3138 will instruct controller 132 to cause the analog-to-digital converter 126 to accept the voltage V_o that then appears at output terminal 3132 and to convert it into a digital number.

After the completion of each gain-selection sequence, the overall gain of the cascade of four amplifiers is encoded by controller 132 as a digital gain-code word which will include as many bits as there are stages, i.e. amplifiers in the amplifier system 124. Each bit of the gain code word represents the state of switch 3176. The gain code is ONE if switch 3176 is open, it is ZERO if the switch is closed. Thus, in the case of four amplifiers, if all of the amplifiers are set to unity gain, the gain code will be 0000. If the overall gain is 64, the gain code will be 0110.

Thus, with four amplifiers, requiring only four decisions, the binary gain-ranging amplification system 124 disclosed and described will provide 2^{15} gain steps. To achieve this result, previously known systems required fifteen amplifiers and sixteen distinct decisions and executions. Hence, the binary gain-ranging amplification system 124, with its control circuitry thus described, can accomplish the job of selecting a suitable gain in a fraction of the time previously required by the known systems, and it will occupy a fraction of the volume previously needed to house a conventional binary gain-ranging amplifier system.

In the course of explaining the diagram of Figure 13, the concept of using signal interception between a relatively slowly propagating interrogate signal and a relatively rapidly propagating command signal, namely the DATEN signal, has been disclosed. This feature will now be further developed, as it is generally used for the purpose of initiating a switching action, by reference to Figures 43 through 48.

Figure 43 is an overall schematic, simplified illustration of the seismic data processing system thus far explained, as it includes the common, central data processor, i.e. station, 2, and the plurality of identical spaced-apart multi-channel data acquisition, i.e. transceiver units 111a, 111b, 111c, 111d, interconnected in series and to the central station 2 by transmission lines, discussed above and shown simplified in Figure 43 as a three-channel, signal-transmission link 4016. The separation between the acquisition, i.e. transceiver, units is preferably constant, typically about 200 to 300 feet.

Central station 2 includes a control unit 4018 and a recording unit 4020, which are schematic representations of circuitry explained above. Thus, the simplified showing of units 4018 and 4020 is to be understood to represent the system control unit and data receiver shown as block 2172 in Figure 31, with a more detailed block diagram of central station 2 being explained above and illustrated in Figure 21. The recording unit 4020 may be a magnetic tape recorder of any well-known type, as described above. Control unit 4018 includes a signal transmission means, such as a clock circuit of any well-known type for transmitting the multi-state interrogation signals IP, i.e. pulses S1 and S2, at preselected sample intervals and/or a control signal through channels 4090 and 4091, respectively, of the three-channel signal transmission link 4016, as will be recalled from the above description.

After each transceiver unit 111a, 111b has completed transmission of its local data, it receives, regenerates and retransmits to central station 2 data from more remote data acquisition or transceiver units. Thus, the data acquisition unit 111a,

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closest to station 2, transmits its local data first and then receives and retransmits data from the remaining 99 down-link units, assuming that there are 100 such units included in the system. The last data acquisition unit, of course transmits only its local data.

As also explained above, an interrogation signal may have one of a plurality of states or properties. The preferred interrogation and control signals are square wave pulses, although other types of signals may be used. The propagation velocity of a pulse through the interrogation channel 4090 is different from the propagation velocity of a pulse through the control channel 4091, where the interrogation channel 4090 schematically represents transmission lines IP1, IP2, IP3, while the control channel 4091 represents the DATEN and DATA BYPASS lines of Figures 5 and 8b. In the presently discussed implementation, the propagation velocity is greater through the control channel 4091 than through interrogation channel 4090.

If and when a data acquisition unit, such as transceiver 111b, becomes defective, it must be bypassed so that data transmitted from a more remote unit, such as 111c, will not be affected. A control pulse is transmitted from control unit 4018 over control channel 4091. At a selected unit, such as transceiver 111b, the control pulse overtakes, and thus becomes coincident with, the interrogation pulse due to the different propagation velocities in channels 4090 and 4091. Coincidence of the two pulses at unit 111b will cause that unit to be bypassed.

Referring now to Figures 43 and 44, the identical data acquisition, i.e. transceiver units 111a, 111b, 111c, 111d are provided with a plurality of input channels, each input channel being connected to an elemental seismic sensor unit 21, as described above. Each of these units contains the signal-conditioning logic including the multiplexer 122, sample-and-hold circuit 3024, gain-conditioning amplifiers 124, analog-to-digital converter 126 and the output signal storage register 128. These circuit components interconnect the seismic sensors 21 at the signal input channels with the data channel 4092'. They may be of conventional types well known in the seismic art. The gain-conditioning amplifier 124 is suitably the instantaneous floating point binary gain-ranging amplifier described above in conjunction with Figures 39 through 42, which provides a four bit gain code to indicate the gain-setting for each data sample. The analog-to-digital (A/D) converter 126 may, for example, be a Micronetics MN 5212 12-bit converter, although a converter of greater or lesser resolution may be used. Output signal storage register 128 may be a conventional 16-20 bit serial-in, serial-out shift register. In a preferred embodiment, register 128 has a capacity at least for 12 data bits from the analog-to-digital converter and four gain code bits from the gain-conditioning amplifier.

As also described above, and shown in Figure 44, the controller 132 is provided which is activated by signals S1 or S2 on lines S1 or S2 respectively. Signals S1 (scan-interval interrogation pulse) or S2 (submultiple interrogation pulse) are generated in response to interrogation pulses having either a first state or a second state, respectively. The corresponding interrogation pulses, which are generally designated by the letters "IP", and which are transmitted over channel 4090, i.e. links IP1, IP2, IP3 of Figure 5, are also designated S1, S2, with S1 having one state (namely width) and S2 having another state (namely another width). In response to a signal S1, the controller 132 resets multiplexer 122 to channel C0, the test or dummy channel. In response to a signal S2, following a signal S1, controller 132 advances multiplexer 122 to the first input channel in sequence, to allow sample-and-hold circuit 3024 to sample an input from the first channel. It is to be understood that the S1 pulse sets controller 132 to enable output of data in response to S2 pulses for the duration of the scan cycle, wherein, it will be recalled, the scan cycle is the multiplexer operation of sampling all fourteen of its input channels.

As the signal sample is amplified by the gain-conditioner 124 and is presented to analog-to-digital converter 126, the amplification factor is suitably expressed as a four bit gain code, see above. When the next S2 signal is received, the controller 132 advances multiplexer 122 to the next channel and, at the same time, causes analog-to-digital converter 126 to convert the gain-conditioned sample from the first channel into a digital number. At the beginning of the convert cycle, the four bit gain code is transferred in serial order from gain-conditioner 124 to output register 128 over line 3036. As the analog-to-digital conversion proceeds, the 12 bits representing the digital number are sent serially to output register 128 from analog-to-digital converter 126. In register 128, the 12 data bits are combined with the four gain code bits to form a 16-bit digital data word corresponding to

the sample from the first channel. Four preamble bits may be added to provide a 20-bit word.

When the convert cycle for any channel, such as a channel K (for example) begins, controller 132 transfers to data channel 4092', the digital data word for channel K-1, previously stored in output register 128. A counter-decoder 3037 counts the bits serially strobed out of register 128 and instructs controller 132 to terminate the transfer of the data bits when the count is complete. Data channel, 4092' of each transceiver unit 111 is normally connected to the data transmission link 4092, as can be seen from Figure 45, now to be described. Link 4092 of Figures 43 and 45 corresponds to link D1, D2, D3, see above.

Figure 45 shows further details of one of the data acquisition, i.e. transceiver, units 111a, 111b, etc., including a signal property identifier 4038 and first and second signal coincidence detectors 4040 and 4042, shown enclosed by dashed lines. Connected in series with interrogation channel 4090 are power-loss bypass switch 4044, 4046, lines receiver 4048, interrogation-signal disable switch 4050 and line driver 4052. Control channel 4091 is provided with a line receiver 4054 and a line driver 4056. Data channel 4092 is furnished with a line receiver 4058, and an OR gate/line driver 4062. The two inputs to line driver 4062 are the input 4092 from down-line data acquisition, i.e. transceiver units and input 4092' from the local data output register 128, see Figure 44. Switches 4064 and 4066 cause data output to be bypassed over bypass line 4068 when deactivated. Note that the direction of data flow in Figures 44 and 45 is reversed with respect to that in Figures 43 and 46.

Signal property identifier 4038, consisting of tapped delay line 4072, AND gate 4074 and inverter 4076, identifies the state, i.e. property, of an interrogation signal in a manner now to be described. The interrogation signal is substantially a square wave, having a specified width. The state, also referred to above as property, of a pulse is herein defined by its width, although with appropriate circuitry any other property thereof, such as pulse height, could also be used as a discriminant. A wide pulse is an interrogation pulse in the first state. The width of a wide pulse must be greater than the delay time of delay line 4072, but less than one-half of the preselected sample interval. An interrogation pulse in the second state must be clearly distinguishable from an interrogation pulse in the first state and preferably is less than half the width of a wide pulse. In the described embodiment, the delay time of delay line 4072 is 1,000 nanoseconds (ns), a wide pulse is 1,200 ns long and a narrow pulse is 400 ns long. Additional pulse widths could be used to provide a multi-property pulse if suitable changes are made to the signal-property identification logic.

In the following description of logic circuit diagrams, reference will be made to the two states which are normally found in any such logic circuits. These two states may be considered to represent binary number signals and are often referred to as a Logic-One and Logic-Zero. In addition, the low and high voltage states respectively are sometimes referred to as a "Binary-Zero" and a "Binary-One", or as "false" and "true" signals or states. In the case of an AND gate, for example, if the two inputs are raised to a predetermined voltage level (which may be referred to as "true"), the output similarly changes to that voltage level (referred to as "true"), while, if either of the inputs remains at a different, perhaps lower voltage level (known as "false"), the output of the AND gate stays at the low level (in the "false" state). Similarly, in the following discussion, the two states of a logic circuit will frequently be referred to as "true" and "false" states.

When controller 132 (Figure 44) transmits an interrogation pulse in the first state, the pulse propagates, as shown in Figure 45, through interrogation channel 4090, through switch 4044 to line receiver 4048, through switch 4050 to line driver 4052, switch 4046, and on to the next transceiver unit in sequence. The pulse also passes through delay line 4072. At the end of 1,000 ns, the leading edge of this pulse emerges from the exit of the delay line, but at this point the trailing edge of the pulse is still "visible", i.e. present, at the entry of the delay line. Accordingly, both inputs to AND gate 4074 go "true", i.e. to active, high levels for activating AND gate 4074, thereby generating a 200 ns signal on line S1, having a positive-going leading edge. As described above, when controller 132 (Figure 44) detects a signal on line S1, it resets multiplexer 122. The trailing edge of the wide interrogation pulse will generate a positive-going logic level on line S2, which is the output of inverter 4076, 200 ns after S1 has gone "true".

It is now assumed that later an interrogation pulse in the second, narrow state propagates through channel 4090 to delay line 4072 and to inverter 4076.

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Since the pulse width is too narrow to be seen simultaneously at the entrance and at the exit of delay line 4072, no signal will be generated on line S1. However, the trailing edge of the narrow pulse will appear at the output of inverter 4076 as a positive-going signal on line S2. When controller 132 detects a positive-going S2 signal, as mentioned above, it will advance multiplexer 122 to the next input channel in sequence, it will initiate a convert cycle and it will output a data signal through line 4092' onto channel 4092 and thus to recording unit 4020.

As above-described, each transceiver unit may have 14 analog input channels. Accordingly, to sample each input channel in sequence, an interrogation pulse in the first state is first transmitted by control unit 4018. As the wide interrogation pulse S1 propagates along interrogation channel 4090 to each transceiver unit 111a, 111b, etc., in sequence, it resets the multiplexer 122 contained in each unit. Thereafter, a series of 13 interrogation pulses S2 in the second state are transmitted. Each pulse in the second state advances multiplexer 122 to sample, in turn, each one of the input channels from the elemental seismic sensor units 21 and to transmit the corresponding data signals from the transceiver units 111 to the recording unit 4020 through data channel 4092.

It will be recalled that in the described embodiment, the 14 channels are sampled within one millisecond (thousandth of a second). Accordingly, the interval between S2 pulses will be 71.4 microseconds (millionths of a second). The two-way pulse propagation delay through the transmission link 4016 between any two transceiver units provides a time window during which the data signals can be transmitted from the transceiver units 111 without mutual interference.

The bypass switches 4044, 4046 and 4064, 4066 are relay-activated by any well-known means and are shown in Figure 45 in the power-on position. In the event of power failure in a particular transceiver unit, both sets of switches will switch to connect bypass lines 4068 and 4070 respectively into channels 4092 and 4090. Then, interrogation pulses and data words to and from other, more remote transceiver units pass freely through the defective unit over bypass lines 4070 and 4068, respectively.

A transceiver unit, such as unit 111b, may become defective, requiring it to be bypassed, or it may become desirable to terminate further transmission of an interrogation pulse at a specified unit. These special functions are enabled by a control signal, in a manner to be described below.

The total travel time of the interrogation pulse to a remote transceiver unit depends on the propagation delay time through the interrogation channel to the unit. The travel time to unit n is the sum of the propagation delays between all previous data acquisition units. Similarly, the propagation delay time of a control pulse through the control channel to unit n is the sum of the delays in the control channel between all previous units closer to control unit 4018 than unit n . Since the propagation velocities through the two channels are different, at the n th data acquisition unit, a pulse propagating through the faster channel will arrive by a time interval $(n-1)R$ earlier than the pulse through the slower channel, where $n-1$ is the number of spaces between the first n transceiver units and R is the signal travel-time difference through the two channels, between consecutive units. Preferably, the lead-in cable section 17, see above, between the central station and the first transceiver unit is so constructed that the propagation delays for both, namely command and interrogate, signals through channels 4090 and 4091 are the same. Thus, all differential delays are suitably generated in the lines between successive transceiver units.

It is assumed that the pulse propagation velocity is greater in the control channel 4091 than in the interrogation channel 4090. Accordingly, if an interrogation pulse is transmitted from control unit 4018 (Figure 43) and $(n-1)R$ later a control pulse is transmitted by control unit 4018, the control pulse will overtake and intercept the interrogation pulse at unit n .

It should be understood that both the interrogation and control transmission links could be characterized by identical propagation velocities. Delay lines can be inserted in one of the two channels at each transceiver unit, to create an effective propagation velocity difference. For example, a delay line 4078, shown by a dashed-line box in Figure 45, can be inserted in the interrogation channel 4090 between line receiver 4048 and disabling switch 4050. Additionally, delay line 4078 could serve as a substitute for delay line 4072.

The first signal, or pulse coincidence, detector 4040 includes a D-type flip-flop 4080 and a relay 4082 associated with switches 4064 and 4066. The switches

are shown in the relay power-on position. D-type flip-flop 4080 may be one-half of a 74S74 dual, positive edge-triggered flip-flop, such as that made by Texas Instruments Co. A D-type flip-flop is a bistable memory circuit with a single input D, and Q and

$\bar{Q}$ outputs. The logic level present at the D input is transferred to the Q output when the proper edge (i.e. transition from one logic level to another) occurs at the CK (clock) input. The flip-flop remains in that state until it will be reset. Flip-flop 4080 responds to the rising edge (negative-to-positive transition) of a pulse. The

$\bar{Q}$ output always assumes a logic level opposite to the Q logic level. The flip-flop may be reset by applying a pulse to the CL (clear) input. When reset, the logic

level of the Q output is a logic ZERO and the $\bar{Q}$ output is a logic ONE.

In response to the simultaneous presence of both a control pulse and an interrogation pulse in any state, first signal coincidence detector 4040 becomes active. The leading edge of an interrogation pulse sets, i.e. activates, the D input of D-type flip-flop 4080 to a logic-ONE. The Q output of flip-flop 4080 is normally false (logic-ZERO), thereby energizing relay 4082 to hold switches 4064 and 4066 closed, as illustrated in Figure 45. If a control pulse arrives from link 4091 at the CK input, while the D input is a logic-ONE, flip-flop 4080 will be toggled to set the Q output to a logic-ONE, i.e. true. When Q goes true, relay 4082 is released, causing switches 4064 and 4066 to make contact with bypass line 4068 because the logic-ONE voltage level is the same as +V.

Referring now to Figure 46, controller 132 (Figure 44) transmits an interrogation pulse through interrogation channel 4090, which is assumed to have the lesser propagation velocity. Control channel 4091 is connected to controller 132 through a tapped delay line 4132 having taps to provide integral multiples of the delay time, such as O, R, 2R, 3R, (n-1)R via tap selector switch 4100.

To bypass transceiver n, an interrogation pulse is first transmitted by control unit 4018 (Figures 43 and 46) and then (n-1)R later a control pulse is transmitted. The control pulse will intercept and become coincident with the interrogation pulse at transceiver n, deenergizing relay 4082 (Figure 45), thereby switching switches 4064 and 4066 to bypass line 4068. Expressed more simply, the control pulse is delayed with respect to the interrogation pulse by an integral multiple of the delay time R, wherein the integral multiple is equal to the number of transceiver units connected between transceiver unit n and the central station 2.

It may become desirable to prevent further travel of an interrogation pulse to transceiver units positioned beyond unit n. To perform this function, the control pulse is time-shifted so as to follow an interrogation pulse after a delay of (n-1)R + d, wherein d is the time shift. This function is performed by second pulse coincidence detector 4042.

Referring again to Figure 45, in second pulse coincidence detector 4042, the D input of flip-flop 4084 is connected to a tap 4085 on tapped delay line 4072. The delay time between entry of the leading edge of the pulse at tap 4085 is equal to or slightly longer than the width of the pulse, the delay time d to tap 4085 being 600 ns in the described embodiment. When the interrogation pulse arrives, it will first activate flip-flop 4080 in pulse coincidence detector 4040. At a time d later (600 ns later, for example), the leading edge of the pulse appears at tap 4085 of delay line 4072. The time-shifted control pulse is too late to trigger the CK input of the flip-flop 4080, hence the pulse coincidence detector 4040 is unresponsive. However, the D input of flip-flop 4084 will now become activated by the delayed interrogation pulse. Therefore, a time-shifted control pulse arriving at the CK input of flip-flop

4084 will toggle flip-flop 4084, causing the normally true $\bar{Q}$ output to go false (logic-ZERO). When $\bar{Q}$ of flip-flop 4084 goes false, a relay 4086 is activated, opening the disabling switch 4050, thereby terminating further travel of the interrogation pulse to units positioned beyond the transceiver unit n.

Referring now to Figure 46, the time shift d is imparted to the control pulse by a fixed delay line 4102 when switch 4104 is in the position shown. The time delay d through delay line 4102 is the same as the time delay at tap 4085 of delay line 4072, i.e. 600 ns in the illustrative embodiment.

If either flip-flop 4080 or 4084 is toggled by the simultaneous presence of an interrogation pulse and a control pulse, it will remain in the toggled condition until cleared. Flip-flops 4080 and 4084 will be cleared only in response to an interrogation

pulse in the first state, i.e. S1, but, in the absence of a coincident control pulse, when the output of AND gate 4074 goes to a logic-ONE.

In a specific embodiment, in addition to the features described above, it is also desired to enable, i.e. activate, certain switching sequences and to output data from a subset of consecutive transceiver units, selected from among the totality of all of the units. These functions are also accomplished by use of two transmission links having different delays. The selected subset may include as few as one, or as many as all, of the transceiver units deployed, as above described. If more than one unit comprises the selected subset, there is a first selected unit and a last selected unit, of which the first selected unit is closest to the central station 2.

In Figure 47, which in some respects resembles Figure 13, seven transceiver units 111a—111g are shown connected to central station 2 through transmission link 4016, consisting of the three channels which are the interrogation channel 4090, the control channel 4091 and data channel 4092. Note that the array of Figure 47 is reversed in direction as compared to the array of Figure 43 and that, for simplicity, input channels 21 are not shown. Also, in the illustrative example of Figure 47, the double arrows on control channel 4091 indicate that the signal propagation velocity is greater in that channel than the signal propagation velocity through interrogation channel 4090.

In accordance with the example intended to be illustrated by Figure 47, it is desired to activate and initiate a scan cycle, or other switching sequence, in those multiplexers 122 which form part of the subset of transceiver units 111c—111e exclusively, thereby to enable output of data from the respective input channels only of this subset of units. Thus, units 111a, 111b and 111f and 111g are to remain inactive. Circuitry to activate, i.e. enable, the desired subset of units is shown in Figure 48.

In Figure 48, the data bypass circuit is substantially the same as that of Figure 45. However, signal property identifier 4038 is, in Figure 48, designed around the optional delay line 4078 of Figure 45. Pulse coincidence detectors 4040, 4042 of Figure 45 are differently designed in Figure 48 to allow greater flexibility of operation.

Interrogation channel 4090 is shown as a single physical channel in Figure 47. Control channel 4091 is also shown by a single line in Figure 47, but it will be remembered that, actually, it consists of three redundant lines. As more fully discussed above, in the illustrated embodiment, the interrogation and control channels may be twisted wire pairs. The pulse propagation velocity through the wire lines comprising the interrogation and control channels may then have the same value. However, delay line 4078 in each transceiver unit is connected in series with the interrogation channel. Hence, in the illustrative system, the effective velocity is less in the interrogation channel 4090 than in the control channel 4091. Thus, delay line 4078 retards the propagation of an interrogation pulse by a fixed time interval at each transceiver unit. Delay line 4078 has a maximum delay of 1,000 ns with taps to provide shorter delays and to adjust for minor differences in the lengths of the wire line making up the interrogation channel. The preferred delay, i.e. retardation, is 600 ns.

In Figure 48, an interrogation pulse transmitted from controller 132 propagates along line 4090, to line receiver or buffer amplifier 4048 via power failure bypass switch 4044, into delay line 4078. Six hundred nanoseconds later, the pulse proceeds through tap 4101 to line driver 4052 and on to the transceiver unit next in line, i.e. the next down-link transceiver unit.

An AND gate 4103 detects the presence of a wide S1 pulse, as described in connection with AND gate 4074, Figure 45. Since the S1 pulse is 1,200 ns wide and the maximum delay of delay line 4078 is 1,000 ns, the output line 4105 of AND gate 4103 will change to logic-ONE, as discussed above, triggering the CK (clock) input of D-type flip-flop 4106. If a logic-ONE is present at the D input of flip-flop 4106 (from a control pulse, as discussed below), the Q output will also become and remain a logic-ONE, thereby causing the output of AND gate 4108 to go to a logic-ONE. The trailing edge of the S1 pulse will therefore also generate an S2 pulse to cause controller 132 (Figure 44) to initiate a convert cycle. As long as the D input of flip-flop 4106 remains at logic-ONE, AND gate 4108 will remain enabled. For the remainder of a scan cycle, subsequent incoming S2 pulses will appear on the S2 output, i.e. line 4110. Conversely, if the D input of flip-flop 4106 is logic-ZERO, output of S2 pulses through AND gate 4108 will be inhibited and the circuitry of Figure 44 will not be activated.

Control pulses, corresponding to the above-described DATEN (data enable)

pulses, are transmitted in parallel over triple-redundant control channel 4091. The DATEN pulses are received by line receivers 4112, 4112', 4112'' and are transmitted to a further majority-vote circuit 4114. Circuit 4114 consists of AND gates 4116, 4116', 4116'' and OR gate 4118. A DATEN pulse present on any two of the three lines CON 1, CON 2 and CON 3, schematically represented by the DATEN link in Figure 5, will cause the output of OR gate 4118 to become a logic-ONE, setting the D input of flip-flop 4106 also to logic-ONE, thereby enabling AND gate 4108. Thus, the simultaneous presence of an S1 pulse from AND gate 4103 and a DATEN pulse on any two of the three lines CON 1, CON 2 and CON 3 will generate a unique signal to enable data output from output register 132 (Figure 44) in response to subsequent S2 pulses received during the remainder of the scan cycle. The system will remain enabled as long as a DATEN pulse is present each time that an S1 pulse is received. DATEN pulses propagate outwards from any specific transceiver unit to more remote units, through line drivers 4126, 4126', 4126''.

A desired switching action in a selected transceiver unit may be initiated by sending a DATEN control pulse over a single control line, such as line CON 1 only. When a DATEN pulse appears on only one line, such as line CON 1, the output of majority-vote circuit 4114 will be a logic-ZERO. The output of inverter 4120 will therefore go to logic-ONE, enabling AND gate 4122. When an S1 pulse is received at the same time as the DATEN pulse over the single line CON 1, the output of AND gate 4122 will go true, setting the CK input of flip-flop 4124. Since the D input of flip-flop 4124 is also true, because of the presence of the DATEN pulse on line CON 1, the Q output will go true, generating a C1 pulse. A C1 control pulse may be used, for example, to deactivate data bypass relay 4082'. Bypass relay 4082' is normally held in the position shown, unless C1 pulse or a power failure (PF) deactivates the relay, via NOR gate 4142, thereby to cause data from a more remote data acquisition unit to be bypassed around the specific transceiver unit considered in this explanation. Similarly, relay 4140 is used to switch to bypass conditions in case of power failure, as can be seen easily from the circuit of Figure 48. DATEN pulses sent through individual lines CON 2 or CON 3 will similarly generate control signals C2, C3 to perform other selected control functions. The width of a DATEN pulse, used for activating a desired switching action in a selected unit will be one-half the width of an S1 interrogation pulse, i.e. about 600 ns.

Referring now to Figure 47, which in various respects corresponds to Figure 13, a specific effect is illustrated which is based upon the fact that activation of one or more transceiver units requires the simultaneous presence of an S1 pulse and a DATEN pulse at each of the units. In Figure 47, a plurality of data acquisition, i.e. transceiver, units 111a through 111g are disposed remotely with respect to the central unit, i.e. station, 2. It is assumed to be desired to activate, i.e. enable only the three consecutive units 111c—111e, but no others.

An S1 pulse is transmitted from central station 2 through the interrogation channel to each unit 111 in sequence. Let the instant of arrival of S1 at unit 111a be $t_a=0$. The S1 arrival time at unit 111b will then be $t_b=856.8$ nanoseconds. The pulse propagation time delay between units 111a and 111b is made up of the cable delay and the 600 ns delay in delay line 4078 (Figure 48). The length of the cable between the two units is 196.8 feet; the pulse propagation velocity is 1.305 feet/ns. Accordingly, since the cable delay is therefore 256.8 ns and the delay line time is 600 ns, the total delay is 856.8 ns. Hence, the S1 arrival time at unit 111c will be $t_c=1,713.6$ nanoseconds, etc., as shown in Figure 47. The six timing lines in Figure 47, labelled IPA—IPF, represent the location of the same S1 interrogation pulse with respect to each of the transceiver units 111a—111f at the end of each 856.8 nanosecond interrogation-pulse travel-time interval.

Some time after an S1 pulse is transmitted through interrogation channel 4090, a DATEN pulse is transmitted through the control channel 4091. The signal propagation velocities in the twisted wire pairs of the interrogation and control channels 4090 and 4091 are the same. However, because of the 600-nanosecond delay line 4078 in each transceiver unit, the effective S1 pulse velocity is lower than the control pulse velocity because there are no corresponding delay lines in the control channel. Of course, in an alternate embodiment, the cable velocities for the two channels can be chosen such that the required delays would be inherent in the channels themselves. The taps in delay line 4078 would then be used only to compensate for slight differences in cable lengths.

Referring again to Figure 47, a DATEN pulse transmitted 1,200 nanoseconds after transmission of a corresponding S1 pulse will intercept the S1 pulse at the third

unit, i.e. transceiver 111c. The six timing lines labelled DATEN A—DATEN F show the position of a DATEN pulse with respect to the S1 pulse at the end of each 856.8-nanosecond interrogation-pulse travel-time interval. When an S1 pulse arrives at the unit 111a, no action will occur at unit 111a because the DATEN pulse is lagging 1,200 nanoseconds behind the S1 pulse. At unit 111b, the DATEN pulse is 600 nanoseconds behind the S1 pulse, so that, again, no action will take place at 111b. The DATEN pulse intercepts the S1 pulse at unit 111c, so that the data processing circuitry in unit 111c is enabled. At unit 111d, the leading end of the DATEN pulse is ahead of the S1 pulse by 600 nanoseconds, but, because of the width of the DATEN pulse, a control signal is still available to enable the unit 111d. At unit 111e, although the leading edge of the DATEN pulse is 1,200 nanoseconds in advance of the S1 pulse, its trailing edge has not yet passed the S1 pulse; hence, unit 111e is also enabled. Finally, by the time the S1 pulse arrives at unit 111f, the trailing edge of the DATEN pulse is well ahead of the S1 pulse. Therefore, transceiver unit 111f and all subsequent down-link units will not be enabled. All units that are enabled by coincident S1 and DATEN pulses will be active for one entire scan cycle. That is, they will be responsive to all subsequent incoming S2 pulses for the remainder of the scan cycle. The desired delays are applied by means of tapped delay line 4132 (Figures 46 and 47).

The width W of the DATEN pulse is equal to

$$W = (L - 1) \times DLY + dt$$

wherein

L = number of transceiver units to be enabled,

DLY = artificial delay line time (delay line 4078), and

dt = a small time increment of arbitrary length to allow for slight propagation time differences.

In the example of Figure 47, the width of the DATEN pulse is

$$W = (3 - 1) \times 600 + 300 = 1,500 \text{ nanoseconds.}$$

The width of the control pulse can be varied by means of the pulse width adjust circuit 4130, Figure 47, connected to controller 4018 in central station 2. The pulse width adjust circuit may be a monostable, also called "one-shot", multivibrator, such as National Semiconductor device DM 74121. A one-shot multivibrator is a circuit, or device, which can be used to modify the duration of a control pulse by stretching or shortening the pulse width. Pulse width adjustment is accomplished by changing the time constant of a conventional R-C feedback network connected to the control inputs of the one-shot circuit.

The initial delay time ID, to be applied to the DATEN pulse by delay line 4132, is

$$ID = M \times DLY,$$

wherein M is the number of intervening transceiver units to be skipped between the central station 2 and the first active transceiver unit, see Figure 47.

As discussed above, a CON 1 pulse, when coincident with an S1 pulse, is used to bypass data around a selected transceiver unit. The delay BD to be applied to the CON 1 pulse by delay line 4132, relative to an associated S1 pulse, is

$$BD = K \times DLY,$$

wherein K is the number of transceiver units intervening between the central station and the selected transceiver unit.

Note that the triple-redundant control lines 4091 of Figure 48 are shown as single lines in Figures 43 through 47, and in Figures 5 and 8b, where they are labelled DATEN, in order to simplify the drawings.

From the above description and formulas, it may be seen readily that by proper selection of control pulse width and control pulse delay with respect to an S1 pulse, any subset of consecutive transceiver units can be enabled. As an example, for a first scan, the three units 111a, 111b and 111c would be activated. For the second scan, units 111b, 111c and 111d may be enabled, the third scan may involve units 111c, 111d and 111e, and so forth.

Employing this so-called roll-along technique, for the first scan noted above, the control pulse width will be $(3 - 1) \times 600 + 300 = 1500$ ns. The initial delay will

be zero, because there are no intervening transceiver units between unit 111a and central station 2. For the next scan, the control pulse width will remain the same, but the initial delay will be 600 ns, because there is one unit, namely unit 111a, between the first selected unit 111b and central station 2, and so forth.

Of course, in conducting a seismic survey, an acoustic wave is generated and seismic reflection data are received during a recording cycle of many seconds. Accordingly, many successive scans will be made, employing the same subset of data acquisition units. For a six-second recording, using a sample interval of one millisecond, there will be 6,000 scans. After the first recording cycle, the system is "rolled along" to the next subset of data acquisition units, by shifting the delay and a new recording cycle of 6,000 scans is commenced.

As mentioned above, an S1 pulse is transmitted from the central station to the data acquisition units once every millisecond (thousandth of a second), thus defining a one-millisecond sample interval. Thereafter, if there are fourteen input channels C0—C13 with elemental seismic sensor units 21, a series of thirteen S2 pulses is transmitted, the pulses being generated at 71.4 microsecond intervals.

As discussed above, the frequency of the transmitted interrogation pulses is related to the frequency of the reflected seismic signals. For high-frequency signals in the order of 200 Hz, the sample interval should be one-half to one millisecond (2,000 to 1,000 samples per second). For seismic signals at the lower end of the spectrum, such as 20—30 Hz, the sample interval may be two or even four milliseconds (500 Hz or 250 Hz).

As is well known in the seismic art, for the first part of a seismic recording cycle, say the first one-half to one second, high frequency signals, from shallow subsurface geological layers, are received. Further, these signals are received at sensor units nearer the shot-point as the reflected signals have not had time to reach sensor units at more remote parts of the cable. Later in the recording cycle, the seismic signals reflected from deeper geologic layers are characterized by much lower signal frequencies.

At the beginning of a recording cycle, for the first one second, for example, it may be desirable to sample the seismic data at a one-half millisecond sample interval, using only transceiver units and associated seismic sensors close to the central station 2, such as units 111a—111d. Accordingly, an S1 pulse and a DATEN control pulse are transmitted from central station 2. The width of the DATEN pulse will be for the four units 111a—111d.

$$(4-1) \times 600 + 300 = 2,100 \text{ ns.}$$

The initial delay of the DATEN pulse will be zero, because there are no units intervening between central station 2 and the first transceiver unit 111a.

At the end of the 2,000th scan (one second) and for the remainder of the recording cycle, the seismic data from the seismic sensor units 21 at the input channels in Figure 43 may be sampled at less frequent intervals, such two-millisecond sample intervals and all of the transceiver units will be enabled. Thus, for the 2,0001st scan, a new control pulse having a greater width will be transmitted concurrently with the S1 pulse. The width of this new control pulse will be

$$(7-1) \times 600 + 300 = 3,900 \text{ ns}$$

to enable the seven transceiver units 111a—111g. The initial delay will be zero, as above. Alternatively, if all transceiver units are to be enabled, the DATEN pulse may be "on" during the entire recording cycle, i.e. be of "infinite" length.

While this invention has been described with respect to a particular embodiment, with modifications, it is not limited thereto. For example, interrogation and control channels may be combined into one physical transmission channel by any of several well-known multiplexing means, such as code-modulation. For example, interrogation signals and control signals may be coded differently and decoded at each transceiver unit after which different delays are applied to the two signals prior to transmission to the next transceiver unit. Even though the physical transmission lines are the same, in the terminology of the communications art, two separate channels would be considered to exist. Also, while the present invention has been described in terms of equally spaced transceiver units, it is possible to apply the same principles to unequally spaced units by constructing the sequential delay taps of Figure 46 to correspond in sequence to the actual differences between delays in the signal and control transmission channels. Moreover, the gain states of the amplifier

stages A_1 — A_m could be based on a ternary, octal or decimal number base instead of binary.

The cable assembly disclosed has been described in terms of a marine application wherein the towing vehicle is a vessel. It is, however, readily adaptable to land use by means of modifications obvious to those skilled in the seismic art. For example, sensors for measurement of parameters, such as ambient water pressure, water leakage and direct water breaks are not needed. The buoyant marine streamer-type cable would be replaced by a conventional land cable. Hydrophones would be replaced by geophones, etc.

It may also be noted that the seismic data telemetry system of the invention may be used with any seismic impulse source, such as using explosives, air guns or swept frequency vibrators, for specific examples. Of course, in the case of signals received from a swept frequency vibrator source, prior to processing in the beam steerer, which is array former 2184, the received signals would be correlated and transformed to impulse response form, for each of the 500 sensor unit locations or channels.

Generally speaking, the foregoing description represents the preferred embodiment of the invention, the various alternative circuits or structures may be included or substituted for some of the individual circuits and structures disclosed herein without departing from the scope of the invention as defined in the appended claims. Thus, for example, other techniques for multiplexing signals from the individual transceiver units may be employed. Similarly, various alternative special circuits may be employed to implement the beam steering and array forming arrangements as described herein.

Altogether, it can be seen that lateral features, such as the gain-ranging amplifier system, the multiplexer-commutated high-pass filter and various other aspects may be of general usefulness in conjunction with equipment other than that described and illustrated herein.

Reference should also be made to related description and claims in copending Applications No. 9462/78 (Serial No. 1,550,797), No. 10140/78 (Serial No. 1,550,798), No. 17329/78 (Serial No. 1,550,799) and 28670/78 (Serial No. 1,550,800).

WHAT WE CLAIM IS:—

1. A system for seismic data telemetry having: a central station a plurality of seismic data acquisition units; a common digital-data signal link coupling the central station and the acquisition units; a first and a second control-signal link coupling the central station and the data acquisition units, said two control-signal links having different signal propagation velocities; and control circuit associated with the data acquisition units and responsive to the coincidence of control signals received over the respective control-signal links for performing a desired control function in a data acquisition unit when signal coincidence is detected in that unit.

2. A system according to claim 1, wherein the central station has selection circuitry for applying control signals to the control-signal links at adjustably different times so that the control signals will be coincident in a selectable data acquisition unit.

3. A system according to claim 2, wherein the selection circuitry has means for varying the duration of one of the two control signals so that the control signals will be coincident in a selected plurality of data acquisition units.

4. A system according to claim 3, the selection circuitry having means for varying a characteristic of the other of the two control signals for activating the control circuits to perform additional control functions.

5. A system according to any one of the preceding claims, and comprising delay lines connected in one of the control-signal links in tandem with associated data acquisition units, so as to decrease the signal propagation velocity of signals through that control link.

6. A system according to claim 5, wherein each of said delay lines has an input and an output and each of the data acquisition units includes a detector circuit responsive to the coincident presence of a control signal at the input and output of a delay line for performing a second desired control function in the data acquisition unit.

7. A system according to claim 5 or 6, wherein the control-signal delay times through the delay lines are the same.

8. A system according to claim 7, when appended to claim 2, wherein the selection circuitry is operable to make the difference in application time equal to an



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stages A_1 — A_m could be based on a ternary, octal or decimal number base instead of binary.

The cable assembly disclosed has been described in terms of a marine application wherein the towing vehicle is a vessel. It is, however, readily adaptable to land use by means of modifications obvious to those skilled in the seismic art. For example, sensors for measurement of parameters, such as ambient water pressure, water leakage and direct water breaks are not needed. The buoyant marine streamer-type cable would be replaced by a conventional land cable. Hydrophones would be replaced by geophones, etc.

It may also be noted that the seismic data telemetry system of the invention may be used with any seismic impulse source, such as using explosives, air guns or swept frequency vibrators, for specific examples. Of course, in the case of signals received from a swept frequency vibrator source, prior to processing in the beam steerer, which is array former 2184, the received signals would be correlated and transformed to impulse response form, for each of the 500 sensor unit locations or channels.

Generally speaking, the foregoing description represents the preferred embodiment of the invention, the various alternative circuits or structures may be included or substituted for some of the individual circuits and structures disclosed herein without departing from the scope of the invention as defined in the appended claims. Thus, for example, other techniques for multiplexing signals from the individual transceiver units may be employed. Similarly, various alternative special circuits may be employed to implement the beam steering and array forming arrangements as described herein.

Altogether, it can be seen that lateral features, such as the gain-ranging amplifier system, the multiplexer-commutated high-pass filter and various other aspects may be of general usefulness in conjunction with equipment other than that described and illustrated herein.

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2. A system according to claim 1, wherein the central station has selection circuitry for applying control signals to the control-signal links at adjustably different times so that the control signals will be coincident in a selectable data acquisition unit.

3. A system according to claim 2, wherein the selection circuitry has means for varying the duration of one of the two control signals so that the control signals will be coincident in a selected plurality of data acquisition units.

4. A system according to claim 3, the selection circuitry having means for varying a characteristic of the other of the two control signals for activating the control circuits to perform additional control functions.

5. A system according to any one of the preceding claims, and comprising delay lines connected in one of the control-signal links in tandem with associated data acquisition units, so as to decrease the signal propagation velocity of signals through that control link.

6. A system according to claim 5, wherein each of said delay lines has an input and an output and each of the data acquisition units includes a detector circuit responsive to the coincident presence of a control signal at the input and output of a delay line for performing a second desired control function in the data acquisition unit.

7. A system according to claim 5 or 6, wherein the control-signal delay times through the delay lines are the same.

8. A system according to claim 7, when appended to claim 2, wherein the selection circuitry is operable to make the difference in application time equal to an



integral multiple of said control-signal delay time so that the control signals will be coincident in a desired data acquisition unit.

9. A system according to claim 7 or 8, when appended to claim 3, wherein the selection circuitry is operable to vary the duration of the control signal applied to the control-signal link that has the greater signal propagation velocity by an integral multiple of said control-signal delay time.

10. A system according to any one of claims 5 to 9, and comprising a bypass control-signal link interconnecting the central station with the data acquisition units and bypass-control circuitry in said data acquisition units responsive to the coincidence of signals on the bypass control-signal link and the control-signal link that has delay lines, for disconnecting a data acquisition unit from the digital signal data link when bypass signal coincidence is detected in that unit.

11. A system according to any one of the preceding claims, and comprising a plurality of seismic signal input channels and an output channel and a channel selector switch connected therebetween in each data acquisition unit, the switch being responsive to control signals from the central station for selectively connecting said input channels to said output channel for transmission of the seismic signals on said input channels to said digital data link.

12. A system according to claim 11, when appended to claim 2, wherein said selection circuitry has means for applying a first control signal to one control-signal link and reset circuitry for applying a second control signal having a first characteristic to the other control-signal link, and each data acquisition unit has detector circuitry to reset the channel selector switch to a preselected input channel in a data acquisition unit when coincidence of said first and second control signals is detected in that data acquisition unit.

13. A system according to claim 12 and having channel-selector circuitry in the central station for applying control signals having a second characteristic to said other control-signal link, said channel selector switch being responsive to control signals having said second characteristics for switching other input channels to said output channel in a predetermined sequence.

14. A system according to claim 11, 12 or 13 and comprising means in the central station for applying a series of control signals to the control-signal links to operate the channel selector switches in a subset of data acquisition units to connect, one at a time, each member of a subset of the input channels in each member of said subset of data acquisition units to the output channels in a predetermined order.

15. A system according to claim 14, wherein said predetermined order is a first channel from a first data acquisition unit followed by the first channel of the next data acquisition unit until all the first channels of all the data acquisition units in the subset have been connected, followed by a second channel of the first and then subsequent data acquisition units repeated until all the channels in the subset have been connected.

16. A system according to any one of claims 11 to 15 and comprising a commutated high-pass filter in each data acquisition unit, said filter including series capacitance in each seismic signal input channel and a common resistor coupled to said output channel and time-shared, through said channel selector switch, between said seismic signal input channels.

17. A system according to claim 16 and having cutoff-frequency-adjusting circuitry for varying a filter parameter of the commutated filter by varying the duration of the time during which any one of said seismic signal input channels is connected to the common resistor by said channel selector switch.

18. A system according to claim 16 or 17, wherein said high-pass filter has a cutoff frequency f_c that is determined by $f_c = \{1/(2\pi RC)\} \{D/T\}$ where R is the resistance of the common resistor, C is the capacitance of each series capacitance, D is the duration of the time any one of the input channels is connected to the shunt resistor and T is the time required for the channel selector switch to scan the remaining input channels.

19. A system according to any one of claims 16 to 18, wherein the resistor is connected in shunt with the output channel.

20. A system according to any one of claims 16 to 18, wherein the resistor is in series with the output channel and is the input resistor of an operational amplifier.

21. A system according to any one of claims 16 to 20, wherein in each data acquisition unit, the selector switch has a further, offset-removal, input channel to which a seismic signal is not applied, an offset, removal capacitor being connected between said common resistor and said output channel and offset-removal circuitry



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being provided for applying a bias signal across the offset-removal capacitor, the bias signal being equal in magnitude and opposite in polarity to the unwanted offset signal present at the junction between the channel selector switch and the offset-removal capacitor when the channel selector switch is operated to connect the seismic signal input channels to the output channel.

22. A system according to any one of claims 11 to 21 and comprising an amplifier cascade including a plurality of bi-gain amplifiers connected between said channel selector switch and said output channel, each amplifier being switchable to a unity gain state and a high gain state, the high gain state being different for different amplifiers;

a variable voltage reference source for selectively providing a discrete reference voltage, one for each amplifier, the level of each reference voltage being inversely proportional to the gain of the associated amplifier;

a controller responsive to a control signal for switching all of said amplifiers to unity gain;

a comparator for comparing the absolute value of the amplifier-cascade output voltage, due to an input signal, with the first discrete reference voltage associated with the amplifier having the highest gain and in cooperation with said controller, for switching said amplifier to the high gain state if the output voltage is less than the reference voltage; and

additional circuitry, cooperating with said comparator and said controller, for switching the other bi-gain amplifiers to a selected gain state following comparison of the respective output voltages with the sequence of discrete reference voltages associated with the respective amplifiers.

23. A system according to claim 22, wherein the gain, in the high gain state, of a selected amplifier is greater than the gain of an amplifier having the next lower high-gain state by a value equal to a number base raised to a power equal to the gain of the amplifier having the lowest high-gain state.

24. A system according to claim 22 or 23, when appended to claim 13, wherein the controller is responsive to a control signal having the second characteristic for switching the amplifiers to unity gain.

25. A system according to claim 22, 23 or 24 and having an offset-removing capacitor coupled in series with the input to each bi-gain amplifier;

a reset circuit in said controller responsive to a control signal for connecting said amplifier cascade to an input channel to which a seismic signal is not applied and for setting all of said amplifiers to unity gain; and

feedback loop means for switchably coupling the amplifier output signal to said offset-removal capacitor to store said output signal therein with equal magnitude and opposite polarity.

26. A system according to claim 25 when appended to claim 24, wherein said reset circuit is responsive to said control signal when it has the first characteristic.

27. A system according to claim 25 or 26, and having an analog to digital converter connected between said amplifier cascade and said output channel for digitizing the amplified signals and for applying said digitized signals to said digital signal data link; an elemental seismic sensor unit coupled to each seismic signal input channel; and a seismic signal processor in the central station coupled to the digital signal data transmission link for receiving digital data signals from said sensor units and for selectively combining digital data signals from members of different sets of elemental seismic sensor units to form different seismic-sensor array configurations.

28. A system according to claim 27 and having: a weighting-coefficient storage means for programmably providing a desired weighting function to selected digital data signals from desired sensors; calibration circuitry for determining normalizing coefficients to compensate for relative differences in the signal output levels of each seismic sensor unit; and multiplier circuitry for multiplying a weighting coefficient by a corresponding normalizing coefficient and for applying the product to the selected digital data signals prior to combination thereof.

29. A system according to any one of the preceding claims, and comprising the combination of component parts which are:

a plurality of seismic cable sections containing portions of said digital-data-signal transmission link, and said control links, said cable sections being interconnected by said data acquisition units;

elemental seismic sensor units contained within said cable sections, distributed therealong and connected to corresponding input channels in said data acquisition units; and

steering circuitry included in the signal processor for applying selected phase



delays to said digital data signals prior to the combination thereof to vary the directivity of the array signals.

30. A system according to claim 1 for enabling from said central station a desired control sequence in a subset of the seismic data acquisition units disposed in spaced-apart relationship the system comprising:

circuitry in said central station for applying a first control signal to said first control link at timed intervals;

delay circuitry for retarding propagation of said first control signal to reduce the signal propagation velocity thereof along said first control-signal link by a known time increment at each data acquisition unit;

additional circuitry in said central station for applying a second control signal to said second control-signal link after a time delay following application of said first control signal, the time delay being a first integral multiple of said known time increment; and

a signal coincidence detector associated with the control circuit in each said data acquisition unit for sensing the simultaneous presence of the two control signals.

31. A system according to claim 30, wherein said additional circuitry includes roll-along circuitry for varying the duration of said second control signal by a second integral multiple of said known time increment to vary the number of data acquisition units included in said subset and for varying the application time delay of said second control signal to change the selection of the units to be included in said subset.

32. A system according to claim 30 or 31, wherein each data acquisition unit includes:

a plurality of analog input channels coupled to receive seismic signals from respective seismic sensor units;

common signal processing electronics responsive to said signal coincidence detector for filtering, sampling, gain conditioning and converting an analog seismic signal from one input channel to a digital data signal, while applying a digital data signal derived from another channel to said digital data-signal transmission link.

33. A system according to claim 32, wherein the control circuitry is operable in a manner so that said digital data signals are received by, and stored in, said central station from said digital data signal transmission link by ranks, corresponding to the sequence of distribution of the respective data acquisition units, and by files corresponding to the analog input-channel sampling-sequence in the respective data acquisition units.

34. A system according to any one of the preceding claims, wherein said digital data-signal transmission link includes triple-redundant, broadband conductors; and said central station includes error-detect and majority-vote circuitry for accepting digital data-signal signals from any two of the three conductors and for detecting a fault when a one of said conductors is broken.

35. A system according to any one of the preceding claims, wherein one of the control-signal links has delay lines and includes triple-redundant conductor pairs, and each data acquisition unit includes a majority-vote circuit for accepting control signals from any two of said conductor pairs as a valid signal and an error detect circuit for sensing a fault when any one of said conductor pairs is broken.

36. A method for signalling members of a subset of seismic data acquisition units in a system according to any one of the preceding claims, the method comprising the steps of

transmitting a first signal to the seismic data acquisition units;

transmitting a more rapidly travelling second signal to the seismic data acquisition units; and

delaying transmission of the second signal with respect to the first signal, so that the first and second signals are present substantially simultaneously at the members of the selected subset of seismic data acquisition units.

37. A method according to claim 36, the method comprising the steps of adjusting the duration of the delayed second signal so that the leading edges of the first and second signals arrive substantially simultaneously at a first selected unit and the trailing edge of the second signal and said first signal are coincident at the last selected unit, whereby the two signals are coincident at every unit to be selected but at no other units.

38. A method of seismographic signalling comprising the steps of:

providing a central station;

disposing a plurality of substantially-identical, multiple-input-channel, data



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acquisition units in spaced-apart relationship, remotely with respect to said central station;

connecting seismic sensors to the input channels of the units;

interconnecting said data acquisition units with said central station by a digital data-signal transmission channel and by two control-signal transmission channels;

initiating a seismic disturbance;

transmitting from said central station a first control signal having a desired duration through one control signal channel;

transmitting from said central station a second control signal having a first characteristic through the other control channel and retarding propagation of said second signal by a known time increment per data acquisition unit;

delaying the transmission of said first control signal with respect to said second control signal by an integral multiple of said known time increment, so that said first and second signals are coincident at the members of a desired subset; and

sensing, in each data acquisition unit, the coincident presence of said two signals as a data-acquisition-unit selection signal.

39. A method according to claim 38 and comprising the steps of:

transmitting from said central station a second control signal having a second characteristic through said other control signal transmission channel;

sensing, in each selected data acquisition unit, said second control signal having said second characteristic and, in response thereto, sensing seismic signals from a seismic sensor connected to a first input channel and processing said signals by the steps of sampling, filtering, amplifying, and digitizing, and transmitting said processed digital seismic signals from each selected data acquisition unit, in sequence, to said central station through said digital-data-signal transmission channel; and

receiving and storing said digital seismic signals in said central station.

40. A method according to claim 39 and comprising the further steps of:

repeatedly transmitting from said central station said second control signal having said second characteristic;

sensing in each selected data acquisition unit said repeatedly-transmitted control signals and, in response to each repetition, selecting a different input channel, processing the seismic signals therefrom and transmitting the processed digital seismic signals from each selected data acquisition unit to said central station until digital seismic signals from a desired number of input channels have been transmitted; and

receiving and storing said transmitted digital seismic signals in a storage matrix in said central station.

41. A method according to claim 40, and comprising the further step of combining, in a predetermined manner, in said central station the stored digital seismic signals originating from selected input channels of selected data acquisition units to form desired seismic-sensor array configurations.

42. A method according to claim 41, and comprising the additional step of applying a desired weighting function to the digital seismic signals originating from selected input channels before the step of combining.

43. A method according to claim 41 or 42 and comprising the additional step of varying the directivity of the array configuration by applying phase delays to respective ones of the digital seismic signals originating from selected input channels during the step of combining.

44. A method according to any one of claims 38 to 43 and comprising:

interconnecting said central station with said data acquisition units by a third control signal channel having a signal propagation velocity different from that of said other control signal channel;

transmitting said second control signal having a first characteristic from said central station to said data acquisition units through said other control signal channel;

transmitting a third control signal through said third control signal channel and delaying transmission of said third control signal by an integral multiple of said known time increment; and

sensing, in a selected data acquisition unit, the coincident presence of said second and third control signals as a data acquisition-unit disconnect signal.

45. A method according to any one of claims 36 to 44 and comprising repeatedly transmitting the first signal and the delayed second signal a plurality of times and delaying transmission of said second signal by a different amount each time so that different subsets of data acquisition units are selected.

46. A system for seismic data telemetry according to claim 1 and substantially as hereinbefore described with reference to the accompanying drawings.

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47. A method of seismographic signalling using a system according to claim 1 and substantially as hereinbefore described with reference to the accompanying drawings.

HASELTINE, LAKE & CO.,
Chartered Patent Agents,
Hazlitt House,
28, Southampton Buildings,
Chancery Lane, London WC2A 1AT

— also —
Temple Gate House, Temple Gate, Bristol BS1 6PT
— and —

9 Park Square, Leeds LS1 2LH, Yorks.
Agents for the Applicants.

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