THEORY OF CONTROLLED DIRECTIONAL RECEPTION (CDR)**

By

S. A. NAKHAMKIN*

At the present time the theory of the Controlled Directional Reception (CDR) method, developed in the MINX and GP seismic laboratories under the guidance of L. A. Ryabinkin has made further progress on the basis of signal frequency theory(1). The possibility of synthesizing the CDR system in the optimum manner for determining the necessary parameters were presented in the results. Some of the theoretical relations obtained in the work may however be simplified to ensure greater agreement with theory for certain cases.

The complex frequency response of CDR is obtained in the form:

$$H\left[\frac{\omega}{V}\left(1-\frac{m\delta_T V}{2x_0}\right)\right], \tag{1}$$

Where V denotes apparent wave velocity-
$2x_0$ = base of reception (i.e., cable spread)
δ_T = some minimal (time) lead for summation
m = —2, —1, 0, 1, 2 — characterizes the magnitude of the total lead (see Fig. 1).

Such form of CDR frequency response, reflecting the generality of the frequency approach in the problem of directional reception, nevertheless appears to be inconvenient in isolated cases.

In particular the presence of the value V in the argument masks the fact that the CDR receiver system posseses circular directivity characteristics similar to those of point source oscillations (2). Furthermore, such a characteristic form leads to complications in the basic relations which introduce difficulty in the application of theory for solving the design for experimental laboratory equipment.

It is expedient to modify formula (1) by examining the frequency dependence on the relative displacement between the inphase waveform axis and the axis of summation as made applicable to the CDR directivity response (3). Let $\theta/2$ be the displacement between the inphase waveform axis and the axis of summation at the profile point $x = x_0$ (Fig. 1). Then the argument of frequency response (1) may be rewritten in the form

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$$\frac{\omega}{V}\left(1-\frac{m\delta_T V}{2x_0}\right)=\frac{\omega}{x_0}\left(\frac{x_0}{V}-\frac{m\delta_T}{2}\right)=\frac{\omega}{2x_0}\theta$$

and consequently

$$H\left[\frac{\omega}{V}\left(1-\frac{m\delta_T V}{2x_0}\right)\right]=H\left(\frac{\omega}{2x_0}\theta\right).$$

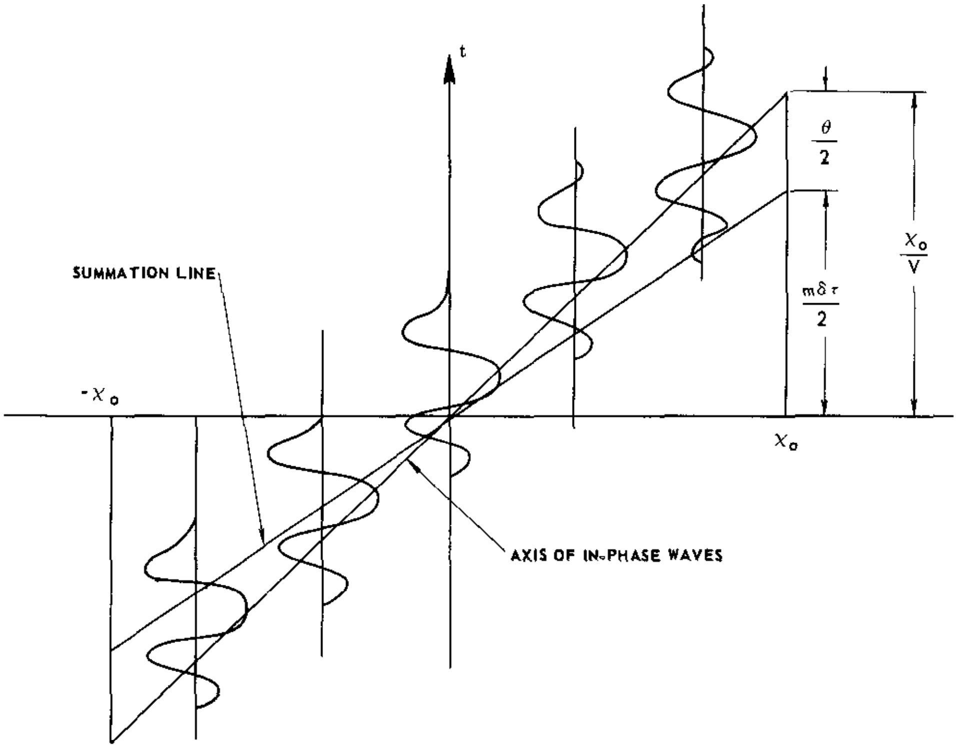

FIG. 1.—Signal summation in CDR construction.

Let $\theta = Kv_i\delta_T$, where δ_T is some minimal relative shift, Kv_i is a number characterizing the overall shift θ for a given wave.

The index (subscript) v_i denotes in the assumed condition the reading of the value θ for each wave from the cophasal axis of this wave and, generally speaking, from any axis taken as the origin on the assumption that it is the axis of cophasality of some proposed wave with velocity v_i. Therefore in contrast to m, Kv_i is not necessarily a whole number. The complete CDR effect is determined by the influence of the frequency response from each of the waves v_i on the $S_i(\omega)$ spectrum.

$$H\left(\frac{\omega}{2x_0}Kv_i\delta_T\right),\ S_i\text{out}(\omega)=S_i\,(\omega)\,H\left(\frac{\omega}{2x_0}\,Kv_i\delta_T\right). \tag{2}$$

Expression (2) *allows all the basic relations to be readily obtained* in somewhat simplified form.

*The limiting frequency of the frequency response for the even distribu*tion function h(x) is determined by the expression

$$\omega_i\lim=\frac{c}{Kv_i\delta_T}, \tag{3}$$

where c = coefficient of proportionality depending on the type of frequency response.

From (3) it follows, in particular, that the behaviour of the frequency response (2) is governed only by the values Kv_i and δ_T and does not *depend on* x_0.

This facilitates use of the CDR frequency response from (2) in the design of experimental laboratory apparatus. *The half period repetition* of frequency response $H_{per}\left(\frac{\omega}{2x_0}Kv_i\delta_T\right)$ of the distribution function for discrete data with interval Δx will be:

$$\omega_{0i}=\frac{2\pi x_0}{Kv_i\delta_T\Delta x}=\frac{\pi(n-1)}{Kv_i\delta_T},$$

where $\frac{2x_0}{\Delta x}=n-1$, *and n denotes the number of summation channels.*

The formula for computing the number of summation channels for conditions of complete exclusion of spurious expansions in summing will be:

$$n>1+\frac{c}{2\pi}+\frac{\delta_T}{2\pi}\,(\omega_i''Kv_i)_{max},$$

where ω''_i denotes the upper limiting frequency of the wave spectrum and $(\omega''_iKv_i)_{max}$ is the largest of all the φ''_iKv_i products.

It is expedient moreover in examining the value K_0v_i to introduce the corresponding value $\omega_i\lim=\omega'_i$ where ω'_i signifies the lower limiting frequency of the wave spectrum.

From (3) it follows that:

$$K_0v_i=\frac{c}{\omega'_i\delta_T}. \tag{4}$$

The value K_0v_i refers to that condition of frequency response $H\left(\frac{\omega}{2x_0} K_0v_i\,\delta_\tau\right)$ for which the value has completely emerged from the range of the wave spectrum. For a severe restriction of frequency response and wave spectrum limited by frequencies corresponding to $\omega_i$lim and ω'_i such a condition of frequency response will give the first summed record in which the amplitude expansion for the given wave equals zero.

Formula (4) may be utilised in the design of the apparatus for determining the necessary δ_τ values. In addition ω'_i is to be chosen a maximum for the anticipated spectra.

The value K_0v_i is chosen on the basis of the requirement to ensure separation of the useful wave in summing the desirable number of amplitude expansions. *Moreover the number of amplitude expansions* r_i, in which form the wave is fixed in summation, will be $r_i = 2K_0v_i - 1$.

THE RESOLVING POWER OF THE CDR METHOD

A necessary condition for the complete resolution of two waves by the CDR method appears to be the freedom from interference of amplitude growth on the basis of which the waves are fixed in summation. Furthermore the interpolation of summed recordings according to their amplitudes in the interval between conditions of cophasal summation of the overlapping wave should ensure obtaining at least one summed recording with zero amplitude growth for both waves. It is evident that the indicated condition will be achieved if a certain arrangement of the summation axes can be found for two waves with velocities V_1 and V_2, for which the frequency response $H\left(\frac{\omega}{2x_0} Kv_1\ \delta_\tau\right)$ and $H\left(\frac{\omega}{2x_0} Kv_2\delta_\tau\right)$ simultaneously satisfy the equation (Fig. 2):

$$K_0v_1 = \frac{c}{\omega'_1\delta_\tau}; \quad K_0v_2 = \frac{c}{\omega'_2\delta_\tau},$$

where ω'_1 and ω'_2 are the lower limits of the wave frequency spectrum. Moreover the velocities V_1 and V_2 should in turn accommodate the condition (Fig. 2)

$$\frac{2x_0}{V_1} - \frac{2x_0}{V_2} = \delta_\tau\,(K_0v_1 + K_0v_2).$$

Hence the full resolving power for the CDR method is:

$$R = \frac{c}{2x_0}\left(\frac{1}{\omega'_1} + \frac{1}{\omega'_2}\right), \tag{5}$$

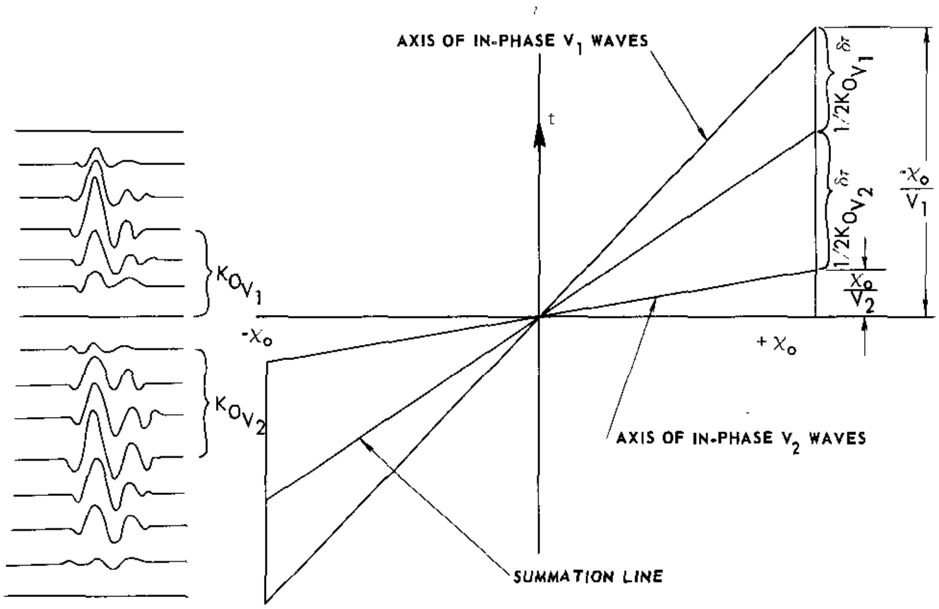

FIG. 2.—Derivation of formula for Resolving Power of CDR Method

where $R=\frac{1}{V_1}-\frac{1}{V_2}$

In this way the necessary resolving power of the CDR method for given wave spectra is attained with corresponding choice of receiver base $2x_0$. Resolution does not depend on the parameters of the equipment. However for best results it is necessary to choose realistic δ_T values, making use of formula (4).

In the original work [1] the formula for the resolving power of the CDR method appears to be erroneous.

In the derivation of the formula the relation

$$\frac{\omega}{V_2}\left(1-\frac{M\delta_T V_2}{2x_0}\right)=\frac{\omega'_2}{\omega'_1}\frac{\omega}{V_1}\left(1-\frac{M\delta_T V_1}{2x_0}\right), \qquad (6)$$

is used which determines the value m=M for conditions of various bands of frequency response for the V_1 and V_2 waves per ω'_2/ω'_1 occurrences. The value M found from relation (6) is substituted in the formula for limiting frequencies of both responses.

$$(\omega_1 \lim)_M = \frac{cV_1}{2x_0\left(1 - \dfrac{M\delta_T V_1}{2x_0}\right)} ; \quad (\omega_2 \lim)_M = \frac{cV_2}{2x_0\left(1 - \dfrac{M\delta_T V_2}{2x_0}\right)} \tag{7}$$

Furthermore, it is normally assumed that:

$$(\omega_1 \lim)_M = \omega'_1 \text{ and } (\omega_2 \lim)_M = \omega'_2 \tag{8}$$

Equation (7) is solved in relation to the value of $\frac{1}{V_1} - \frac{1}{V_2}$ and then incorporated by means of addition to the left and right portions. It is evident however that relation (6) holds true for all frequencies; the limiting ones among them. Therefore equation (7) should be incorporated in the form of the relation

$$\frac{(\omega_1 \lim)_M}{(\omega_2 \lim)_M} = \frac{\omega'_1}{\omega'_2},$$

which, however, does not lead to formula (5) obtained. The latter may be obtained through solution of equation (7) providing (8) as a system of equations with the unknowns M and $\frac{1}{V_1} - \frac{1}{V_2}$.

We note in concluding that the formulae in which the selected frequency limits of the spectrum provisionally enter, lead to approximate results in calculation.

Their accuracy however is shown to be adequate in practice.

ACKNOWLEDGMENTS

The contribution by Imperial Oil Ltd. in providing drafting services is gratefully acknowledged.—Editor.

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EXPLORATION GEOPHYSICS — OIL AND NATURAL GAS

Last year the Canadian Association of Physicists prepared a comprehensive review on the status and future of physics in Canada for the Science Secretariat of the Privy Council.

The subject was treated in twelve parts, one of which related to the "Physics of the Earth" under the convenorship of Professor R. D. Russell, University of British Columbia. Professor Russell invited the C.S.E.G. Executive to submit a brief on the significance of geophysics from the viewpoint of society members. The report below was undertaken by the C.S.EG. Research Committee comprising the following members:

Mr. C. H. Acheson, Chairman
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Mr. E. T. Cook
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INTRODUCTION

Within the general field of the earth sciences, lies the subfield of "Exploration Geophysics." This study concerns itself with the application of the tools and methods of physics to explore the first few miles of the earth's crust. It attempts to identify rock types and delineate their gross structure. The ability to do this has proved to be invaluable in the exploration for oil and gas, and in the mining and construction industries. It is an essential field of endeavour for the development of Canada's natural resources.

As it makes use of the tools and methods of physics, students trained in this discipline are essential to its further development. The research carried out by government and universities has been, and will prove to be, a valuable asset to exploration geophysics, the most recent examples being provided by advances in Communication Theory and Laser Research.

In what follows, we present a survey of the present status and outlook of the geophysical industry exploring for oil and gas in Canada.

GEOPHYSICAL ACTIVITY

During the past thirty years, geophysical exploration for oil by seismic, gravity and magnetic methods has grown to be a substantial industry.

The greatest activity, to date, has been in western Canada. Here geophysical effort was greatly intensified in 1947 with discovery of the Leduc oilfield, and for several years was expanded even further as many new discoveries gradually developed a giant oil industry.

The plat in Figure 1 depicts seismic crew activity and Society of Exploration Geophysicists Canadian membership for the period 1949 to 1966. The membership was obtained from the Geographical member-

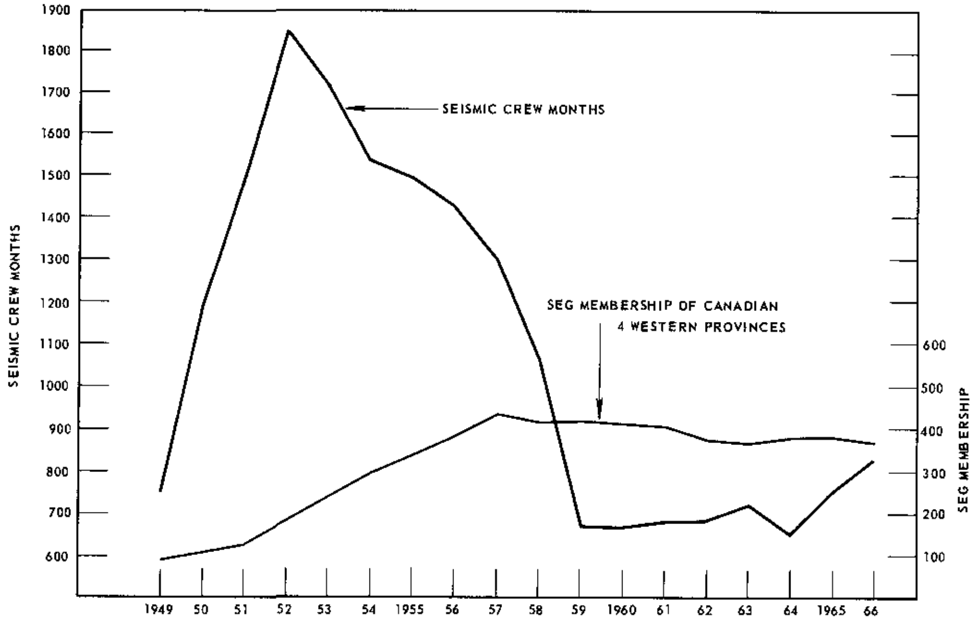

FIG. 1.

ship list counting only the members in the four western provinces. This should be relatively representative of the number of geophysicists employed.

It can be noted that the average membership during the years 1957 to 1961 was about 420 and the average from 1962 to 1966 was about 375. It can also be noted that the number of crew months dropped from 1,845 in 1952 to 670 in 1959. During the first five years of this drop the S.E.G. membership was rising. It appears then that there is considerable delay before the manpower curve indicates any significant changes due to a change in crew activity.

In 1965, the geophysical activity consisted of 756 seismic crew months, 45 gravity crew months, and some 100,000 miles of airborne magnetometer coverage.

Using these figures, it is estimated that in 1966 there will be about 825 seismic crew months, and about 35 gravity crew months. Since no data are available at present on projected airborne magnetic work for 1966, the 1965 figure is our best estimate. There are indications that this magnitude of increase may continue for the next one or two years.

It should be pointed out that although geophysical crew activity is a measure of industry spending, and gives an indication of the number of people needed, it does not tell the whole story. When crew activity falls off, as it does periodically, more of a geophysicist's time is spent on reviewing and reprocessing data, and less on current crew interpretation and supervision.

The new digital technology will result in more reprocessing of old data. This type of reprocessing and re-interpretation, to be effective, requires highly trained geophysicists, and we anticipate our needs for well-qualified graduates will increase.

In summary, the industry's requirements for technical personnel should not fluctuate with changes in the number of geophysical crews operating, but should, in fact, reflect a steady demand for skilled geophysicists and graduates in the physical sciences.

COSTS — 1966

Seismic: The cost for obtaining and processing seismic data in 1966 is estimated to be at least $52,650,000. This is based on an average cost of $75,000 per month for crews operating in bush areas, and $35,000 per month for crews operating in the plains.

Gravity Meter: The cost for obtaining and processing 35 crew months of gravity data is estimated at approximately $250,000.

Airborne Magnetometer: The cost of airborne surveys may vary from $7 to $40 per line mile. Using the world wide figure cost for mining geophysics of $8.45 per line mile, this figure applied to the 100,000 miles flown for petroleum exploration, plus data processing costs totals about $1,000,000.

The estimated total to be spent in 1966 for petroleum geophysics in Canada then is $53,900,000.

GEOPHYSICAL PERSONNEL — GRADUATES

Our best estimate of the number of graduates employed in western Canada is as follows:

Bachelors	440
Masters	50
Doctors	10
TOTAL	500

These data are probably accurate within ±10%. No exact figures are available at present, but the estimate is based on membership totals of three geophysical societies, modified as best we could to remove non-degree people. The number and types of degrees held by these people is based on percentages established in a canvass of 10 major oil companies, whose total degree holding geophysicists number 269. Among these, 82.6% are bachelors, 14.8% are masters and 2.6% are doctors. Figures were further somewhat modified, as it is felt that most of the doctors and masters are working for the major companies. Canadian graduates working in United States laboratories of parent companies with subsidiaries in Canada, are not considered in this study.

We estimate the work distribution among these men to be, very roughly, as follows:

Supervision	15%
Research	10%
Service	5%
Advanced Interpretation	20%
General Interpretation	50%
TOTAL	100%

CURRENT QUESTIONS IN GEOPHYSICS

Current questions that arise in the three main exploration methods—gravity meter, magnetometer and seismograph—are considered separately.

GRAVITY

The application of the gravitational method in exploration is dependent on mass distributions in the outer crust of the earth that are related either directly or indirectly to the accumulation of the particular mineral sought. Modern gravity meters can, under operational conditions, detect changes in the earth's field in the order of 1 part in 100 million. The gravitational field can be recorded not only by the conventional land meter and under-water meter, but also by shipborne meters, airborne meters and down-hole meters. Traditionally, the gravity method has been used in the petroleum industry as a reconnaissance tool. However, in some areas it has and is being used as a means of accurately defining geological structures. Its use in this regard is dependent on a thorough understanding of the observed density changes. The gravitational method will find wider use as more parameters become more precisely defined for the observed gravitational field. The volume of density information becoming available from drill holes has added significantly to the interpretation of gravity data.

Density contrasts are not restricted to any particular part of the geologic column and, for practical purposes, may originate anywhere from the surface down to the Mohorovicic discontinuity. The gravitational field is very complex, for this reason, and a variety of geological solutions may be possible. It is the responsibility of the geophysicist interpreting the data to eliminate as many of the ambiguities as possible, and arrive at the solution that most nearly fits the conditions.

Sophisticated digital computer techniques are available for relating gravity anomalies to geological features. These techniques do not eliminate the need for the trained geophysicist, but rather enable him to analyze more data faster in his quest for the solution that represents the existing geological conditions.

The gravitational field of the earth offers a wide variety of possibilities for study, particularly from the point of view of potential theory. The basic instrumentation is relatively inexpensive, and innumerable possibilities exist for improvement in the handling of basic and interpretive data. This makes it very suitable for university research, both by the student and the professor.

MAGNETICS

The magnetic method, insofar as the petroleum industry is concerned, is almost entirely limited to the airborne technique. The objective of the aeromagnetic method is to map the geomagnetic field in such detail that the magnetic interface can be determined and related to the geological column. The magnetic method is less complex than the gravity method in that the majority of local magnetic anomalies are associated with igneous rocks. Anomalies from other sources are generally readily identifiable. Magnetic anomalies on the other hand are more complex in form than gravity anomalies because their expression changes with latitude and orientation.

The magnetometer presently in widest use is capable of measuring the magnetic field to ±1 gamma (10^{-5} oersteds). Instruments with a capability of two orders of magnitude greater sensitivity (± .01 gamma) have appeared in recent years. They are capable of at least one order of magnitude greater sensitivity under survey conditions than the older Flux-Gate models.

The depth to the magnetic interface can be determined to an accuracy of ±10% of the depth of burial or better. A reasonably accurate map of the contact between sedimentary and igneous rocks can be constructed that is valuable in outlining basinal configurations, and thicknesses of sediments. With the advent of the high sensitivity magnetometer, magnetics is finding more and more need for computer applications in the processing of basic data and in interpretation. Since this is a relatively new area for computers it offers a challenging future for the trained geophysicist. Research into some of the more basic aspects of high sensitivity magnetics is in order. One of many of these is the effect of diurnal variations of the magnetic field with time and space.

SEISMIC

The seismic method is concerned with geologic interpretation of wave motion artificially induced at or near the surface of the earth. Waves of all kinds are generated and transmitted through the earth, but the seismic method at present is concerned mainly with the "primary" wave, which travels the fastest. The seismic signal at first is a high amplitude pulse of short duration; on travelling through the earth from source to receiver however, it is modified for many reasons. The sharp impulse that left the source thus arrives at the receiver, as a wave form of considerable duration, where the first arrival may be difficult, if not impossible, to recognize.

Modification and distortion may take place by interference of surface and other waves arriving at the same time, and poor geophone coupling. Further modification occurs when the signal is processed through the amplifiers, given suitable volume control, filtered and played back for interpretation.

Substantial challenge is offered to physicists and mathematicians by pressing current problems that may be classified broadly as follows:

1. *Problems in Seismic Sources and Shooting Techniques*

Considerable study has been made of seismic sources, and despite an extensive literature, there is still considerable controversy. Should the source be impulsive or continuous, single or multiple, explosive or mechanical? What is the best way to apply the source of seismic waves to the ground?

With the advent of digital recording, the problem of determining the best possible means of introducing energy into the ground will undoubtedly receive renewed attention:

2. *Problems in Seismic Detection and Recording*

As with the source, considerable study has been made of seismic receivers, and an extensive literature exists on the subjects. What is the best type of geophone, how faithfully does it transfer the signal received, how is it best coupled to the ground, and what is the best distribution of geophones to record the seismic signal.

Again with the advent of digital recording procedures, this subject will receive continued attention.

3. *Problems in Optimum Data Processing*

The energy recorded at the geophone is usually amplified, controlled, filtered, and displayed in a cross-section for interpretation. In this state the seismic message contains both wanted signal and unwanted noise. Noise may undoubtedly be reduced by improving the source, shooting techniques, and recording; but it exists also independent of these, and must be dealt with in the data processing phase.

For this purpose, "filter processes" are employed that discriminate against noise, in favour of the signal. Many of these are based on Fourier's theory that any seismic message (signal plus noise) is the sum of sinusoids of various amplitudes and phases. Reasoning, for example, that the noise due to unwanted surface waves is low frequency, we remove the very low frequency components by filtering, hoping to leave the main signal relatively undisturbed. Similarly, we may remove the high frequency components due to wind noise.

Several modern filters are designed from considerations of statistics and communication theory, applied to the Fourier concept of the seismic message. There are filters for example that discriminate against dipping events and against repeating events caused by resonance. The theory of inverse filtering is that if we are able to define any systematic distortion, we can frequently design a filter that will eliminate it.

With the advent of digital recording and processing, a system of data processing has been evolved by contract companies, wherein the field data is automatically filtered for ringing, ghosting, and is processed for many other effects before presentation in final form, as a section to be interpreted. This "Black Box" system requires that the geophysicist fully understand the nature of the processes that have been applied, in order to evaluate them critically.

Design and/or programming any kind of sophisticated processing technique is an important field for future research. Extensive use is often made of communication theory in such considerations. Diffraction theory in physical optics is closely associated with the Fourier transform, and a wide field of research and technology is opening up to analyze wave motion by means of lasers.

4. *Problems in Interpretation*

Many problems arise in relating the seismic signal to stratigraphy and structure.

Initially an impulse, the seismic energy is modified during transmission by many effects such as re-reflection, refraction, diffraction, dispersion, attenuation, etc., and is finally recorded as a wave motion containing a series of reflected pulses, each of considerable duration. Problems occur in picking exact reflection times, and relating these in depth, to the corresponding reflecting horizons. The seismic wave travels at different velocities in different parts of the section; its reflectivity is dependent on geologic conditions and its basic form changes with geology. Recognition and removal of spurious seismic features due to velocity anomaly is an interesting study that relates to velocity variation in the earth. Relationship of changes in the seismic pulse to variations in geology is a further study offering fascinating possibilities.

5. *Fundamental Studies*

The following are only a few of the many questions that involve fundamental studies:

What is the physical nature of the half-space through which the seismic message is sent? What part of the received message is signal, and what part noise? What is the nature of the signal (is it a longitudinal wave, as we assume, or does it contain contributions from other wave types that are also informative?) What is the nature of noise? We know it can be either random or systematic. If systematic, what are the physical conditions that cause it? What physical factors influence seismic wave transmission, and how are these related to geology? What is the physical and geologic nature of seismic velocity?

GRANT AND SUPPORT MECHANISMS

Research is carried on by a few of the major oil companies, notably Imperial Oil Limited, which has had a large research program for the past 12 years.

Grants in the form of tax deductions as a percentage of capital expenditure on research tend to encourage this work by large corporations. For the years 1962 to 1966 tax payers could deduct in addition to the amounts allowable for research, an additional 50% of the increase in research expenditures over those made in 1961. These incentive provisions will expire at the end of the 1966 taxation year. The budget speech of April 26, 1965 proposed a new incentive cash grant of 25% of the amount spent on research in the 1967 taxation year. No legislation has yet been enacted to put this proposal into law.

For this purpose "scientific research" means a systematic investigation by means of experimentation or analysis in a field of science

(a) to acquire new knowledge

(b) to devise and develop new products or processes

(c) to apply newly acquired knowledge in making improvements to existing products or processes.

Four incentive grants are presently available for Canadian students, offered by the Society of Exploration Geophysicists in the amount of $400 each for study in geophysics or a related field. One scholarship is offered by the C.S.E.G. to students resident in Alberta, Saskatchewan and British Columbia in the amount of $350.

Notable among the numerous supporting scholarships in science is the province of Alberta Assistance for Matriculants and undergraduates which includes fees plus $100 to $1250 based on academic standing and financial need.

The Canada Students Loan Plan provides for borrowing on the basis of financial need to a maximum of $1000 per annum and an aggregate of $5000.

DESIRABLE EDUCATIONAL QUALIFICATIONS

At least the following educational qualifications seem to be desirable in addition to a strong bachelor's degree in mathematics, physics, engineering or related fields:

(a) *Advanced Work in Applied Mathematics* including Modern Mathematics for Physical Applications, Statistics and Probability, Advanced theory of Potential, Communication Theory, Numerical Methods.

(b) *Advanced Work in Physics* including Theoretical Physics, Advanced Physical Optics, Advanced Geometrical Optics, Theory of Sound.

(c) *Fundamental Work in Geology* including Physical Geology, Laboratory Study of Rocks and Minerals, Historical Geology, Theory of Sedimentation.