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SEISMIC SOURCE IDENTIFICATION TECHNIQUES

1 May 1966 - 28 Feb. 1971

ARI BEN-MENAHEM

DEPARTMENT OF APPLIED MATHEMATICS
THE WEIZMANN INSTITUTE OF SCIENCE
REHOVOT , ISRAEL

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(1) The preparation of a comprehensive library of computer programs for various fields of endeavor in theoretical and experimental seismology.

(2) The establishment of a modern geophysical observatory near Eilat, Israel, which includes strainmeters, tiltmeters and high-gain displacement-meters.

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INTRODUCTION

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3. LIST OF PUBLICATIONS

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1. Large Scale Processing of Seismic Data in Search of Regional and Global Stress Patterns, A. Ben-Menahem, H. Jarosch and M. Rosenman, Bull. Seism. Soc. Am., Vol. 58, pp. 1899-1932, 1968.

2. Fast Evaluation of Source Parameters from Isolated Surface-Wave Signals, A. Ben-Menahem and D.G. Harkrider, Bull. Seism. Soc. Am., Vol. 60, No. 4, pp. 1337-1387, Aug. 1970.

3. Tectonic Patterns in the Northern Red-Sea Region, A. Ben-Menahem and E. Aboodi, J. Geophys. Res., Vol. 76, No. 11, pp. 2674-2689, Apr. 1971.

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5. Towards a Unified Notation of Source Parameters, H. Jarosch and E. Aboodi, Geophys. J.R. astr. Soc., Vol. 21, pp. 513-529, 1970.

6. The Force System of the Chilean Earthquake of May 22, 1960, A. Ben-Menahem, May 1971 (in press).

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IV STRUCTURE OF THE EARTH INTERIOR.

16. The P-SV Decoupling Condition and Its Bearing on the Structure of the Earth, A. Ben-Menahem and M. Weinstein, Geophys. J.R. astr. Soc., Vol. 21, pp. 131-135, 1970.

V THEORY OF ELASTIC WAVE PROPAGATION.

17. On the Summation of Certain Legendre Series, S.J. Singh and A. Ben-Menahem, J. Eng. Math., Vol. 2, pp. 275-282, 1968.

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VI EARTHQUAKE-EXPLOSION RECOGNITION CRITERIA.

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VIII INSTRUMENTATION.

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I KINEMATIC PARAMETERS OF EARTHQUAKE FOCI

The ultimate objective of this study should be a dynamic theory of the focal processes based on assumptions justified by solid state physics. This, unfortunately, is far beyond the capability of geophysics today. A prerequisite, however, is the achievement of a basic understanding of the huge forces continually distorting the earth and the determination of the origin of the stresses that give rise to earthquakes.

The advent of high-speed computers and modern ultra-sensitive instrumentation makes it possible to derive definitive information from which we can reconstruct a kinematic picture of the seismic source from its far radiation-field.

The primary source of information is the instrumental recording of the ground motion due to a seismic event (e.g., earthquake, volcanic eruption, nuclear explosion, meteor impact). It is the result of the processes taking place at the source and of the subsequent distortion of elastic waves in the earth's mantle and crust and, finally, of the response of the seismograph to the ground motion. Therefore, for source studies, the seismogram must be cleared of the perturbing influence of the recording instruments and the earth's body. These effects are eliminated numerically from the spectrums of the recorded wave-trains after a calculation of these influences. After all the appropriate signals (recorded from the same event at a world-wide network of stations) have been equalized in phase and amplitude, their residuals are compared with those calculated from theoretical source models. An elaborate search program is then set up to find the best theoretical fit to the data. This procedure is carefully adjusted to fit the different type of signals that are known to be recorded. Seismic body-waves traverse the earth along least-time ray-paths. Surface-waves have their energy-flux vector mostly parallel to the earth's surface. On the other hand, obtaining source information from free-oscillation data and residual static deformation requires certain refinements of the above technique. All in all, the method of spectral equalization proved itself to be useful for all periods above 10 seconds.

A few words should be said about the theoretical source-model that is tested against the data. In 1960, I put forward a new kinematic source model which predicted the existence of a seismic "Doppler-effect" in the far radiation-field. Furthermore, I outlined a method to extract from the data kinematic source parameters such as the length of the focus and the rupture speed. Many investigators have since shown this kinematic model to be a powerful tool to describe mathematically the main features of elastic waves radiated from extending sources.

In my work since 1965, I have advocated the necessity of a large-scale processing of seismic data in order to discover both regional and global stress patterns. I have shown that in order to obtain a fuller understanding of the nature of seismic sources it would be extremely helpful to study many earth-quakes from different regions, achieving through the resulting distribution a much firmer basis for drawing conclusions regarding the mechanism of seismic foci. Analysis of surface-waves from 6 major shocks and body-waves from 25 deep shocks disclosed the following traits:

(1) The spatial character of sources at a wide range of depths is that of a finite shear dislocation, the magnitude of which is scaled to its linear dimension, vertical extension and displacement.

(2) The temporal character of sources over a wide range of depths and magnitudes accords with that of the Heaviside step-function.

(3) The dip-slip orientation is dominant in deep shocks and great shallow North-Pacific earthquakes. This is in accord with the ideas of the new global tectonics.

(4) The seismic Doppler effect is substantiated by new data. Overwhelming evidence is presented which shows that the great Alaska shock of March 28, 1964, was indeed a propagating rupture with a speed of 3 to 3.5 km/sec over a total distance of 700 km.

Thus, in general, earthquake energy is released through a progressive rupture*. Fault lengths of shallow shocks with magnitude $8\frac{1}{4}$ - $8\frac{1}{2}$ on the Richter scale vary from 600-750 km. Shallow shocks with magnitudes $7\frac{3}{4}$ - 8 have fault-lengths of 200-400 km and shallow shocks with magnitudes $6\frac{3}{4}$ - $7\frac{1}{2}$ have fault-lengths from 50-100 km. The linear dimension of deep shocks in the magnitude range $6\frac{1}{2}$ - $6\frac{3}{4}$ seems to be of the order of 10-20 km.

A study of smaller shocks also revealed interesting results.

Seismological evidence for northern Red Sea tectonics followed from analysis of the March 31, 1969, earthquake. Source parameters were derived from polarities and amplitudes of P waves, spectral amplitudes of Rayleigh waves, and strain steps recorded at the Eilat Observatory. All the data over this wide spectral window point to a single solution that is consistent with known strike of faults in the epicentral region and the geotectonic hypothesis of the rotational movement of Arabia and Sinai relative to the African continent. The solution consists of a shear dislocation of 1 meter and fault area of 450 km^2 at a mean depth of 10 km, dipping about 45° to the east-northeast with a strike parallel to the Red Sea axis. The motion is normal sinistral with both dip-slip and strike-slip components. The trend of the motion is about 10° northeast. This implies an opening of the Red Sea at the source by some 50 cm along a front of 30 km, and yields a drift rate of the order of a few millimeters per year during this century. The direction of trend lines up with the axis of the Gulf of Eilat and the Jordan rift valley.

In order to facilitate future data reduction we have prepared detailed tables for spectral amplitudes of seismic surface waves.

Amplitude theory of seismic surface waves due to shear dislocations in multilayered isotropic elastic media has already been established. According to this theory surface-wave amplitudes and phases are given explicitly in terms of the source and path parameters. However, while the expressions for these spectral amplitudes depend on the source orientation parameters in a simple manner, the structural parameters and the source depth enter in a rather complicated way which necessitates lengthy computations. Thus, in order to facilitate the reduction and inversion of surface-wave amplitude and phase data, we have prepared detailed tables for various modes, periods, structures and source depth. It is hoped that the tables presented in the paper will indeed fulfill this need.

II STATIC DEFORMATION OF THE EARTH BY SEISMIC EVENTS

A permanent deformation at the seismic source must in principle cause a permanent deformation field everywhere on the earth's surface. This was recently confirmed by observation of strain records from a number of earthquakes. The recent Red Sea earthquake of March 31, 1969 indeed produced an abrupt D.C. strain-change of magnitude 5×10^{-9} at our Eilat observatory. It seems that within the next decade there will be a sufficient number of sensitive strainmeters and tiltmeters capable of sensing abrupt D.C. changes of the order of 10^{-10}. To meet the needs of forthcoming measurements of this kind we have set out to solve the theoretical problem of the deformation of a sphere due to finite internal dislocation. This was done in the following stages: a) Green's tensor for the Naviér equation was expressed as an infinite sum of dyadic eigenvector-products; b) The Volterra-relation was applied to the expanded Green's dyadic to obtain the deformation field in the sphere due to various dislocation types; c) The ensuing expressions for the deformation field were recast in a form of a rapidly convergent series for arbitrary values of the Poisson ratio and the source parameters; d) Surface displacements and strains were computed for various sources for an average earth model. Numerical results were tabulated and mapped in a convenient form; e) Calculations were extended to dislocations of finite length and depth; f) This theory was then applied to strain observations from two seismic events; (i) A comparison was made between observed strain-steps (recorded at Hawaii, California and Colorado) from the Alaska earthquake of March 28, 1964, and the calculated values. It was shown that the theoretical values are within an order of magnitude of the observed values and are of the right sign. (ii) Our strain meters at the Eilat observatory have recorded very clear strain-steps from the Red Sea shock (magnitude 6.7). We have calculated theoretical strain-changes for a model based on observed initial motions of P-waves. Calculated strains fairly agree with the observed.

An interesting application of the above theory is the mechanism of the Chandler Wobble.

The 14-month precessional motion of the earth's instantaneous axis of rotation about its axis of figure is known today as the Chandler Wobble. Spectral analyses of latitude time-series disclosed that the motion is damped with a 'Q' value between 30 and 40. The wobble must therefore be maintained by a certain source of energy. Opinions differ as to the possible driving mechanisms. Some geophysicists claim that irregular variations of the atmosphere are the most likely cause of the wobble. Recently, some evidence has been presented in support of the hypothesis that earthquakes may excite the wobble and produce the observed polar shift. The idea behind the latter alternative is that great earthquakes produce permanent displacement fields throughout the earth (see I-4). Since these fields are generated in a time interval that is relatively small as compared to the wobble period, a first order perturbation occurs in the elements of the inertia tensor of the rotating earth. This in turn causes a vectorial change in the instantaneous angular velocity. Considering the earth as a symmetric top with moments of inertia $A = B \neq C$ referred to the principal axes, an approximate solution to the Liouville equation of motion is obtained. The solution expresses the perturbation of the angular velocity vector in terms of the perturbation of the elements of the inertia tensor. These in turn are calculable in terms of the deformation field caused by the seismic event.

The answer to the question whether earthquakes (or great volcano eruptions) may maintain the wobble forever, will depend on three factors: (1) The perturbing effect of a single event occurring at a given location in the earth. (2) The rate of occurrence of the appropriate seismic events. (3) The dissipation rate of the wobble. I have obtained an explicit solution for (1) in a form that is easily calculable. (3) is taken from the literature and (2) is estimated on the basis of known earthquake statistics. The final conclusion is that seismic events may at most account for 30 percent of the observed secular polar shift. It seems therefore that the wobble is maintained by "cooperation" of more then a single mechanism.

III FREE-OSCILLATION AMPLITUDES FOR REALISTIC EARTH AND SOURCE MODELS

During the last decade seismologists have discussed the free oscillations of the earth and have computed its eigen-periods for various standard models. It is important, however, for the identification of the spectral lines, as well as for the studies of the seismic source itself, to know the relative amplitudes of various modes of vibrations excited by a given source.

We have used the eigenvector-expansion of the Green's tensor in conjunction with the Volterra-relation to obtain the final expressions for spectral line-amplitudes of toroidal and spheroidal motion in terms of the source constants and the radial dependence of the density, rigidity and the Poisson ratio. Eigenfunctions and eigenvalues can be calculated by the well-known Runge-Kutta integration routine. Once these entities are calculated for a given earth model, the amplitudes of the spectral lines follow with relative ease.

Universal tables for spectral line amplitudes of surface displacements and strains of a gravitating radially-heterogeneous earth, have been prepared. Given a structural model and a dislocation source of arbitrary orientation and depth, spheroidal and toroidal line-amplitudes are calculable for $\ell < 100$, $n < 4$ everywhere on the earth's surface. Using the existing observations in the literature from 1961-1971, we have shown:

(1) The combination of realistic earth models (such as the

Jeffreys-Bullen model or the Gutenberg-Bullard model) together with finite dislocation source models, produce theoretical displacements and strains that match the observations.

(2) The theoretical calculations of the spectral line amplitudes can be used as an additional tool for the investigation of earthquake source-mechanism and the infra-structure of the earth's interior.

As an example of the use of our program for the inversion of source data we have derived the force system at the source of the colossal Chilean earthquake of 1960. A unique solution is found indicating a dip-slip motion on a fault dipping 45° to the east with the oceanside downthrown. Likewise, using amplitude data of the Alaskan earthquake of 1964, in conjunction with other surface wave data, a dip-slip motion on a nearly vertical fault is obtained.

IV STRUCTURE OF THE EARTH'S INTERIOR

One may show that in principle the earth's density distribution can be surmised from the decoupling conditions of seismic body waves. That is to say: The decoupling conditions of longitudinal and shear waves in the earth's interior impose certain differential relations between the density and the Lamé parameters. Thus, assuming that decoupling exists, it is possible to test the high-frequency decoupling hypothesis against the known distributions of density and rigidity in the earth. Also, given the distributions for the Lamé parameters with depth, the density function can be found as a solution of an ordinary differential equation. This has been done for a real earth model.

V THEORY OF ELASTIC WAVE PROPAGATION IN THE EARTH

Long-range and high frequency ray-theoretical approximations are used extensively in almost all phases of the environmental sciences, especially in acoustics, earthquake seismology and exploration geophysics. In spite of the usefulness of many of these approximations the conditions for their validity and the accuracy that they imply are not known. A few attempts have been made to bridge the gap between wave and ray theory for elastic wave propagation in a radially heterogeneous earth but a fundamental theory has been lacking. For this reason I have decided to launch a basic study, starting *ab initio* from the field equations.

First, the potential representation of the elastic vector fields was employed to effect decoupling of longitudinal and shear motions. Two types of decoupling were considered: decoupling for all values of the frequency and decoupling for high frequencies. It was found that the three constitutive parameters of the medium (density plus the two Lamé constants) should satisfy three simultaneous non-linear differential equations. Next, the high frequency decoupling condition was tested against the known distributions of ρ, λ and μ in the earth. It was found that this condition is satisfied by the "J-B" earth model to within 5 percent. Following this result, an asymptotic theory was developed for the decoupled potential equations, using a special coordinate system suitable for the development of the asymptotic theory. The final results were cast into a form of a series in which the first term is the known 'geometrical-optics' term. The theory was applied to a shear dislocation of arbitrary orientation and a center of explosion in radially heterogeneous media.

Various aspects of elastic wave propagation in a spherically symmetric, non-gravitating, isotropic, inhomogeneous medium are considered. It is shown through a simple example that the high frequency decoupling conditions of the vector wave equation may be approximately satisfied by real Earth models. An asymptotic theory is developed for the decoupled potential equations. This theory is applied to the case of a shear dislocation and to that of a center of compression in a radially heterogeneous medium. Explicit expressions are obtained for the ray-theoretical displacements.

Recently the use of amplitudes in seismic studies has increased. Theoretical amplitudes can be obtained from travel times or from the structure of the Earth. It we had an 'exact' structure we could derive the amplitude distance relationship directly from it, but nothing would really be lost if we first computed a travel-time table and used it to obtain the amplitudes. In reality no exact structure is known, so if we have a good travel-time table it may serve as the source for an amplitude table. The present work deals with one aspect of obtaining theoretical amplitude tables for the various body-wave phases.

The amplitude is the result of various factors, among them geometric spreading, inelastic attenuation, the radiation pattern, etc. In addition, for phases which are reflected at boundaries (e.g., PcP, PS), the reflection factor has also to be considered. We are dealing with all these factors in a more general work; here we only want to report on a technique we use for obtaining the divergence caused by geometric spreading.

By using a cubic spline interpolation method a representation of seismological travel-time tables is achieved which is highly continuous. Divergence coefficients for seismic phases computed from this representation are free from non-essential discontinuities and are thus more meaningful than those obtained using other methods of interpolation. Results are compared with those obtained by others. For six phases results are given in graphs and tables.

Seismologists have by now recognized that there is no hope to produce useful theoretical body wave seismograms in the next few years. Computers are simply too slow for this job. Ways and means must therefore be found to bypass the difficulty in order to be able to use the wealth of information present in the seismograms without spending thousands of computer hours in a crash program of summing millions of rays and/or normal modes.

I have given much thought to this problem because I am convinced that it is of major importance in seismology. If we restrict ourselves to a few strong phases that are recorded in each station, there is no need to reproduce the entire seismogram.

It is sufficient to have a machine program that will calculate the predicted spectral amplitude of a given arrival at a given station from a given source, and this can be done with relative ease. The amplitude of a certain arrival is a product of a number of factors: reflection coefficients at discontinuities, geometric divergence, physical attenuation along the ray-path, crustal distortion and the source radiation pattern.

Of these factors, the hardest to compute is the geometric divergence coefficient, since it depends on the second derivative of the travel-time function. Recently a suitable numerical procedure, known as the method of cubic spline interpolation, has been introduced with great success. Accordingly the J-B travel-time tables are approximated by cubic splines and the divergence factor is computed therefrom.

VI EARTHQUAKE-EXPLOSION RECOGNITION CRITERIA

Static displacements were calculated for an earth model which consists of a single layer of thickness H overlying a homogeneous half space. Localized sources simulating earthquake and explosion foci are placed at depths $h = \frac{H}{2}$ and $h = \frac{3}{2}H$. The ensuing surface deformation is evaluated as a function of the epicentral distance for a typical continental crust model.

A new technique is used for the quadrature of the displacement integrals. By this method one is able to calculate 1000 layer-integrals of the type

$$F_{mn}(x,t) = \int_0^\infty \frac{y^n e^{-xy} J_m(ty)\,dy}{1 + (A+By^2)e^{-2y} + De^{-4y}} ,$$

with an accuracy of 0.1 percent, in less than 2 minutes.

It is found that for epicentral distance $r > 20H$ the displacements decay like $(r/H)^{-\alpha}$ where $2 < \alpha < 5$. For compressional and strike-slip displacements at all depths and for a dip-slip source above the layer, $2 < \alpha < 3$. For a dip-slip source located below the layer, $3 < \alpha < 5$. Maximal displacements for w_r, u_r, u_x, u_y and u_z occur at approximately $r \simeq 0.8h$ and decay with source-depth like $h^{-3/2}$.

VII PROGRAMMING

In order to be able to process data both from our Eilat observatory and from other institutions and agencies, we have amassed a collection of complete programs for most of our needs. However, a considerable effort will still be required to complete some of the areas where we do not have programs. I would like to recommend that as much as possible a system of program-sharing be introduced for contractors on the lines of IBM's SHARE library of programs and subroutines. The following form our library of complete programs, and no attempt has been made to catalogue separately the subroutines used.

a) LOVAMP - This is a program for computing Love-wave amplitudes of a layered half-space based on Harkrider's program (required for SEARCH).

b) RAYAMP - This is a program for computing Rayleigh-wave amplitudes of a layered half-space based on Harkrider's program (required for SEARCH).

c) SEARCH - This is a program which uses a least-squares fit for matching amplitude spectra (already corrected for instrument and attenuation) with the calculated radiation pattern in order to find the source mechanism parameters, i.e. strike, dip and slip angles, fault-length and rupture velocity.

d) BODYWAVE - This program computes corrected spectral amplitudes from digitised bodywave data.

e) SURFWAVE - This program computes corrected spectral amplitudes from digitised surface-wave data and then goes on according to various options to compute directivity, attenuation coefficients, phase velocities and initial phases.

f) MAGNIFY - This is a program for the computation of the instrumental response (based on the report by Espinosa, Sutton and Miller).

g) TESTMEGA - Given station and epicenter coordinates and the origin time of an earthquake, this program computes the arrival time of 16 different bodywave phases.

h) DISTANCE - Given station and epicenter coordinates, this program computes and plots the epicentral distance in kilometers and degrees, azimuth, inverse azimuth and great circle distance. It also sorts the stations according to distance and azimuth.

i) SURFARR - This computes the arrival time of surface waves, according to given group velocities. It also prints the azimuth, inverse azimuth and great circle distance of subsequent arrivals.

j) HYPERMAP - This is based on R. Parker's program to plot world maps in 11 different projections, with options to add points or lines such as stations or great circles etc.

k) EXTRACT - This program uses the C & GS events tape and searches it for events according to various criteria, such as region or origin time, and makes up a subset of the data file which may then be sorted according to ascending magnitude or depth. It is also possible to find stations within a given range of distance. With this program comes UPDATE to continually update the data file, as new cards become available.

l) DEMULTI - This program demultiplexes data tapes from Eilat and assembles the data on cards or tape with or without a plot for further analysis.

m) TESTRAD - Similar to SEARCH for finding source mechanisms of body waves.

n) PIONEERA - This program computes the tangential displacements u_θ , u_ϕ for N = 1,20 for the Toroidal cases given the dimensions of the source and the strike direction for a range of dip and slip angles.

o) PIONEERB - This program computes the radial displacement u_r for N = 1,20 for the Spheroidal case, given the dimensions of the source and the strike direction for a range of dip and slip angles.

p) AMPA - For a given model and depth of the source, this program computes the eigenvalues and eigenfunctions for $N \geq 1$ for spheroidal oscillations. AMPB does a similar job for radial oscillations $N = 0$.

q) AMPC - Given the dimensions of the source and the strike direction, this program computes the displacements and strains for three cases for spheroidal oscillations:

(i) Vertical strike slip

(ii) Vertical dip slip

(iii) Dip slip on a 45° plane.

AMPD does a similar job for the toroidal case.

VIII INSTRUMENTATION OF THE EILAT GEOPHYSICAL OBSERVATORY

A seismic station has been set up near Eilat in a massif north of Eilat after performing noise studies in various alternative locations in Israel. Instrumentation at the observatory includes:

a) A triaxial seismograph system belonging to the WWNSS consisting of 3 short period and 3 long period instruments with photographic recording. The short-period magnification is 200,000 all the year round. The long-period magnification is 375 for strong earthquake recording (see also Paragraph f).

b) A triaxial magnetometer (Automation Forster, Inc Model MF-55-331) with simultaneous photographic and digital recording with a resolution of 0.1γ .

c) An infrasonic microbarograph system (Geotech Model 10560) with simultaneous digital and photographic recording of pressure changes over a wide frequency range.

d) A 30-meter 2 component mercury tiltmeter built and installed by the Massachusetts Institute of Technology. The output is in three distinct frequency ranges:

Surface wave (16-120 seconds) tilt sensitivity ~ 3×10^{-11} radians
Eigenperiod (32-7200 seconds) tilt sensitivity ~ 3×10^{-11} radians
Tidal (dc-300 seconds) tilt sensitivity < 1×10^{-11} radians

The surface wave output is recorded on heat-sensitive paper and photographic recording. The Eigenperiod is recorded on strip chart recorders and digital magnetic tape.

e) A 30-meter 2 component quartz-tube Strainmeter was installed by Professor Major with direct recording on strip chart recorders with a sensitivity of about 0.7×10^{-8} rad/inch. We are now engaged in adding a high-pass filter to remove the tidal component and then we shall have visible drum recording and simultaneous digital recording as well as the strip charts.

f) The latest addition to the observatory is the Lamont High Gain Long Period triaxial seismograph system. This has low gain photograph recording with a peak magnification of about 6,000. The velocity transducer output is also routed via a phototube amplifier for the high-gain output which is also recorded photographically. The peak amplification is at present about 60,000 but will be revised upwards shortly when the Lamont crew finish the final tuning. There is also a displacement transducer output. This and the high-gain are output on digital magnetic tape at 1 sample/second for the velocity transducers and is sampled every 5 seconds for the displacement transducers.

Thus it will be seen, that we have assembled a pretty complete set of instruments in order to be able to process seismic data in conjunction with magnetic and barometric data. The latter are todate still in the stage of running-in.

Sub. Contract AF61(052)-954

There have been no significant inventions conceived during the life of the subject contract.