SYSTEMS, SCIENCE AND SOFTWARE

SSS-R-77-3093

PASSIVE SEISMIC TECHNIQUES

Quarterly Technical Progress Report
For Period September 1, 1976 - November 30, 1976

J. M. Savino
T. H. Jordan
D. G. Lambert
R. C. Goff

Systems, Science and Software
P. O. Box 1620
La Jolla, California 92038

December, 1976

PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Under Contract No. E(04-3)-1313

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

see letter dtd Dec. 20, 1976 1313/8-2

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SYSTEMS, SCIENCE AND SOFTWARE

SSS-R-77-3093

PASSIVE SEISMIC TECHNIQUES

**Quarterly Technical Progress Report
For Period September 1, 1976 - November 30, 1976**

**J. M. Savino
T. H. Jordan
D. G. Lambert
R. C. Goff**

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**Systems, Science and Software
P. O. Box 1620
La Jolla, California 92038**

December, 1976

**PREPARED FOR THE UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION**

Under Contract No. E(04-3)-1313

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *EP*

TABLE OF CONTENTS

	Page
I. PROGRAM SUMMARY	1
II. TECHNICAL DISCUSSION	3
2.1 INTRODUCTION	3
2.2 TELESEISMIC TRAVEL TIMES	3
2.3 OPERATIONAL STATISTICS OF THE IVA	9
2.4 PROGRAM DEVELOPMENT	14
III. FUTURE PLANS	26
IV. REFERENCES	27

LIST OF ILLUSTRATIONS

No.		Page
2.1	Locations of the 16 seismograph stations that comprise the IVA (solid triangles). The station GLA (open triangle) is operated by Caltech.	4
2.2a	Tracings of seismograms from the 16 stations in the IVA showing the direct P waves from an earthquake at an epicentral distance (Δ) of 89.8° with respect to the center of the IVA . .	6
2.2b	Tracings of seismograms from 14 of the 16 stations in the IVA showing the direct P waves from a deep focus earthquake at an epicentral distance (Δ) of 75° with respect to the center of the IVA	7
2.2c	Selected tracing of a seismogram from Figure 2.2b illustrating various travel-time measurements	8
2.3	Histogram showing the recording statistics of the 16 IVA stations during the time period April 17, 1973-July 4, 1976.	10
2.4	Station location map with percentage of teleseismic events recorded in parentheses. This figure gives an indication of the areal coverage obtained to date for the Imperial Valley. .	12
2.5	Histogram depicting the azimuthal distribution of teleseismic events analyzed. The origin of the map is centered on the IVA. . . .	13
2.6	Block diagram of forward-inverse modeling code.	15
2.7	Block diagram of travel time pre-processing code.	17
2.8	Flowchart of subroutine GRID.	19
2.9	Flowchart of subroutine TGEN.	21
2.10	Flowchart of subroutine BISRCH.	23
2.11	Flowchart of subroutine INTERP.	24

I. PROGRAM SUMMARY

The overall objective of the subject program is to develop geophysical methods into useful cost-effective tools for geothermal reservoir delineation and evaluation. More specifically, the program involves the development and application of generalized inverse techniques to combined seismic (teleseismic and refraction) and gravity data sets for obtaining the three-dimensional velocity and density structure of a geothermal region. These techniques will be tested on data from the Imperial Valley, California.

The major thrust of our work during the first three months of this program involved the acquisition, generation and analysis of a teleseismic data base for the Imperial Valley. To date we have generated travel-time data for 176 earthquakes at widely different azimuths and epicentral distances with respect to the 16 seismic stations in the Imperial Valley array (IVA). Several programs for pre-processing this data base, including error analysis routines, were written and applied to the teleseismic travel-time data.

Arrangements have been made with Professor Shawn Biehler of the University of California at Riverside for obtaining the gravity data for the Imperial Valley. Professor Biehler has agreed to supply complete Bouguer anomaly data for the region bounded by 32° - 34° N, 114° - 117° W. Interpolated Bouguer data for all available areas within this general region at various map scales will also be provided for analysis.

The general program structure for the forward and inverse modeling procedures to be applied to the teleseismic and gravity observations has been developed. Computer programs for generating teleseismic travel-time and gravity

data vectors, and inputting these data vectors to the main modeling program have been written and tested with sub-sets of the main teleseismic data base.

II. TECHNICAL DISCUSSION

2.1 INTRODUCTION

The objective of this program is to develop and apply an inverse modeling procedure for determining three-dimensional variations in near-surface seismic velocities and densities based on surface observations of teleseismic travel times and pulse shapes, and gravity anomalies, respectively. The approach that we have adopted toward a solution to this problem is a parallel development of the observational data bases and modeling procedure. This section of the report describes the results obtained to date employing this approach.

2.2 TELESEISMIC TRAVEL TIMES

The United States Geological Survey (USGS), in cooperation with the California Institute of Technology (Caltech), has been operating a 16-element array of seismic stations in the Imperial Valley, California since approximately April, 1973. The spatial configuration of the Imperial Valley array (IVA) is shown in Figure 2.1. Each station employs a short-period vertical component seismometer whose signal is continuously relayed to Caltech where all 16 station signals are simultaneously recorded on multichannel develocorder film. Although the IVA was originally designed to monitor local seismicity, its geometry and location make it suitable for testing the teleseismic method in an actual geothermal environment.

The application of the general linear inverse modeling procedure to the seismic problem requires the generation of a travel-time data vector. The elements of this data vector are to be in the form of travel-time residuals based on measurements of first arrivals of P waves recorded at the

Figure 2.1. Locations of the 16 seismograph stations that comprise the IVA (solid triangles). The station GLA (open triangle) is operated by Caltech.

16 IVA stations from a large population of events. In order to sample as much of the crust beneath the Imperial Valley, these events should be distributed over as large an epicentral distance and azimuthal range as possible.

During three trips (two to Caltech and one to the USGS at Menlo Park), the IVA developer seismograms for the time period 17 April, 1973 - 4 July, 1976, were searched for the recording of worldwide events. Listings of event origin times and expected arrival times for P waves at the IVA were used during the search. Copies (3M viewer-copier) of seismograms for more than 200 events were collected and returned to S³ for further analysis. Tracings of the seismograms for two fairly well-recorded earthquakes are shown in Figures 2.2a and b. Note in Figure 2.2b the absence of recordings for the IVA stations BCK and PLT and the apparent dead trace for COT. The operational capability of this array will be commented on in more detail later in this section.

As stated above, the datum that we are interested in for each event-station pair is the first arrival time of the direct P wave. However, it is obvious from an examination of the individual station seismograms in Figures 2.2a and b that this can often be an ill-defined quantity. This is particularly true in the case of the relatively low-gain recording stations (e.g., OBB, COK, ING, WLK, BCK, BON, SNR and SLU in Figure 2.2a) and is compounded when the first motions of the P-waves are emergent in character (i.e., compare high gain stations RUN and COA in Figures 2.2a and b).

In order to circumvent this problem, we have employed a travel-time measurement technique similar to that proposed by Steeples and Iyer [1976]. This technique is illustrated in Figure 2.2c with one of the seismograms from Figure 2.2b.

Santa Cruz Earthquake

9 June 1973

O.T. = 08:21:27.3Z

Lat. 10.35, Long. 161.4E

 $h = 70 \text{ km}$, $m_b = 6.3$

Figure 2.2a. Tracings of seismograms from the 16 stations in the IVA showing the direct P waves from an earthquake at an epicentral distance (Δ) of 89.8° with respect to the center of the IVA.

Fiji Isl. Earthquake

4 June 1974

O.T. = 04:14:15.9Z

Lat. 15.85, Long. 175.1W

h = 276 km, $m_b = 6.0$

Figure 2.2b. Tracings of seismograms from 14 of the 16 stations in the IVA showing the direct P waves from a deep focus earthquake at an epicentral distance (Δ) of 75° with respect to the center of the IVA.

Figure 2.2c. Selected tracing of a seismogram from Figure 2.2b illustrating various travel-time measurements.

Starting with an estimate of the first arrival, a series of time measurements are made at successive peaks, zero crossings and troughs. In the case of some events, as many as nine time measurements were made for each available station seismogram. To date we have analyzed 176 events with an average of six stations per event and five time measurements per station. Thus, our basic teleseismic travel time data base presently consists of more than 4000 time measurements. Various error analysis techniques have been applied to these data in order to isolate measurement and transcription errors. The successive time measurements will be combined to improve estimates of first arrivals.

2.3 OPERATIONAL STATISTICS OF THE IVA

Develocorder seismograms for more than 300 events, earthquakes and underground explosions, were searched for acceptable events for analysis. Criteria for inclusion of an event in the data base were as follows:

1. P-waves recorded at three or more stations.
2. The waveforms must correlate across the array.

As noted previously, to date 176 events that meet these criteria have been analyzed. Because of fairly extreme variations in the recording capabilities of the IVA stations, however, the number of events recorded at a particular station is quite variable.

High background noise levels in the Imperial Valley generated primarily by local agricultural activity [Iyer, 1974] require that stations on the valley floor be operated at relatively low magnifications (20,000 to 40,000 at 10 Hz). In contrast, the operating magnifications of stations located on or near bedrocks at the perimeter of the network range from 100,000 to 2,000,000 at 10 Hz [Hill, et al., 1975]. These differences in operating magnification are consistent with the station statistics shown in Figure 2.3. In

Figure 2.3. Histogram showing the recording statistics of the 16 IVA stations during the time period April 17, 1973-July 4, 1976. The dashed line indicates the total number of events (176) analyzed. The actual number of events and the percentage of the total are given at the top of each station column.

this figure the dashed line near the top indicates the total number of events analyzed, 176. A column is given for each station, the height of which represents the number of events recorded at that particular station (i.e., 104 or 59.1 percent of the total number of events at AMS).

As is obvious from Figure 2.3, the main IVA can be divided into two subarrays. One subarray consists of stations AMS, COA, CRR, PLT, RUN, SGL and SUP, all of which recorded more than 50 percent of the total number of events. The other subarray consists of the nine remaining stations that recorded approximately 34 percent or less. The relationship between station location with respect to the sediment pile in the Imperial Valley and percentage of events recorded is seen more clearly in Figure 2.4. Note how, in general, the high percentage recording stations are located near the edges of the Valley.

This lack of data from key stations in the center of the valley may be overcome to some extent by the addition of more observations based on seismograms that have been accumulating since July of this year. An estimated cut-off data for additional data is approximately 31 May 1977, which means that 11 months of seismograms will be available for study. Based on past experience, this could amount to an additional 75 to 100 events in the data base.

Just as important as the total number of events comprising the data base is their azimuthal and epicentral distribution. These two characteristics of the data are shown in Figure 2.5 where the number of events included in this study that occurred within 10° azimuthal ranges with respect to the center the IVA are plotted in the form of a histogram. As can be seen, several different circum-Pacific source regions, all within 100° of the IVA, account for most of the events analyzed. Proceeding clockwise around the Pacific the most active source regions are Central and South America, the Fiji-Tonga Islands, Japan, Kuril-Kamchatka, and

Figure 2.4. Station location map with percentage of teleseismic events recorded in parentheses. This figure gives an indication of the areal coverage obtained to date for the Imperial Valley.

Figure 2.5. Histogram depicting the azimuthal distribution of teleseismic events analyzed. The origin of this map is centered on the IVA. The numbers arranged in a circle denote the number of events that occurred within a 10° range in azimuth (e.g., 20 events between 130° and 140°). Representative source regions and their epicentral distance ranges are also indicated.

the Aleutian Islands and Alaska. We will be looking to fill in, as much as possible, the azimuthal ranges 10° - 90° and 150° - 220° with the IVA data that have been recorded since July, 1976.

2.4 PROGRAM DEVELOPMENT

Several of the computer programs necessary for the forward and inverse modeling phases of this project have been developed and tested with sub-sets of the data base. The data processed by the main program "TGVERT" (Figure 2.6) is provided by two pre-processing codes "TPREP", for travel time data, and "GPREP", for gravity data. The pre-processing proceeds along quite different lines but the end results for each data base can be handled in a parallel manner by the main code.

Referring to Figure 2.6, "TGVERT" first calls "INDATA" which reads pre-processing data from mass storage. "INPUT" is next entered and all card data for problem initialization is read. This routine in turn calls "GRID" which specifies all grid geometry, initializes velocity and gravity profile of structure, and uses subroutine "LOCATE" to calculate the location of recording stations in grid coordinates.

The matrix generation phase is now begun by calling subprogram "MATGEN". This routine uses "BISRCH", a binary search routine and calls "TKERN" and "GKERN" to calculate travel time kernels and gravity kernels which are the elements of the matrix. Travel time kernels are found by tracing rays backward from recording stations and calculating the path lengths traversed in each cell of the grid. Gravity kernels are calculated by use of Nagy's [1966] formula for right rectangular prisms. The matrix is written to mass storage as each row is generated.

Figure 2.6. Block diagram of forward-inverse modeling code.

"SURCOR" is next entered to apply surface corrections which are derived by using a fine grid to model the effects of near surface geology such as sediment thickness. "TKERN" and "GKERN" are again employed in this process.

The main inversion loop phase is now entered by calling "INVLP". This subprogram loops through calls to three basic routines, "VMULT", "FIT" and "EIGEN". "EIGEN" is first called to produce the first estimation of model parameters. "VMULT" forms the dot product of the kernels with the model vector to produce a data vector which can be compared by decision making routine "FIT" to see if an acceptable approximation has been obtained for the model. If further updating of the model is required "EIGEN" is again entered to generate eigen values for this purpose. The loop is continued until an acceptable fit is produced.

Subprogram "EDIT" is finally called to produce a printed description of the results which are also saved on mass storage.

The travel time pre-processing code "TPREP" (Figure 2.7) is employed to apply baseline corrections to the station array, to apply weighting factors based on estimated reliability of data acquisition and to select that portion of the data base to be used and create the data vectors used by the main code. Four vectors are generated, (1) a travel time residual vector, (2) an angle of incidence vector, (3) a back azimuth vector and (4) an indexing vector. The process by which this is done is as follows.

"INCARD" is first called to read all card input except those control flags used to specify the data set. These cards are read in the processing loop of "TGEN". "INTGL" is used to read in the Herrin [1968] travel time tables, the angle of incidence tables [Pho and Behe, 1972] and the station location table from mass storage. Next "TGEN" is called to loop through the entire data base reading entries from

Figure 2.7. Block diagram of travel time pre-processing code.

mass storage and select the data set. For each station event pair "DISAZ" is used to calculate the distance, azimuth, and back azimuth from station to event. "INTERP" then loops over all station which are to be associated with a particular event and does the table lookup and interpolation required to obtain theoretical travel times and angles of incidence for each ray. For this purpose, "BISRCH", a binary search routine, and "YLGINT", a library Lagrangian interpolation routine are used. Subroutine "VCTRS" is finally called to organize the data vectors before writing them to mass storage. A printed description of the result may also be produced at this point.

Diagrams depicting the general flow in some representative routines which are mentioned above appear in Figures 2.8 through 2.11.

Check to see if X's were specified in incard (if not DX's, DY's, DZ's must be specified)

Loop to generate
 $DX(I) = X(I) - X(I-1)$
 $DY(J) = Y(J) - Y(J-1)$
 $DZ(K) = Z(K) - Z(K-1)$
 or
 $X(J) = X(I-1) + DX(I)$
 $Y(J) = Y(J-1) + DY(J)$
 $Z(K) = Z(K-1) + DZ(K)$

Print detailed description of main grid and surface grid geometry if desired including initial value of velocity or density specified for each layer

Figure 2.8. Flowchart of subroutine GRID.

Note total number of
zones in main and
surface grids and
print these numbers

Call distance azimuth
routine to calculate
coordinates of each
station relative to
origin of grid co-
ordinate system

Figure 2.8. (Concluded)

Figure 2.9. Flowchart of subroutine TGEN.

Figure 2.9. (Concluded)

Figure 2.10. Flowchart of subroutine BISRCH.

Calculate average delta from event to array

Locate index of delta in travel time table nearest Δ_{AVG}

Loop over sufficient number of deltas in table to span the array about Δ_{AVG}

Interpolate between table entries in depth direction for each delta in range

Loop over all stations in array which are to be associated with this event

Interpolate in delta direction on values found in 4 loop for delta associated with each station

Figure 2.11. Flowchart of subroutine INTERP.

Locate index of delta in angle
of incidence table nearest Δ_{AVG}
etc.

Follow identical procedures
for angle of incidence table
look up and interpolation as
was done for travel time
table

Figure 2.11. (Concluded)

III. FUTURE PLANS

All work under this project is proceeding according to schedule. During the next quarter our research efforts will focus more on the waveform analysis and modeling tasks of the project as the generation of the teleseismic and gravity data bases is finalized. We plan to apply the forward and inverse modeling programs to a test case consisting of a buried sphere in a homogeneous half space. In addition to verifying the computer programs, this test case should provide insight on the dependence of the resolving power of the teleseismic and gravity fields on model parameters.

IV. REFERENCES

- Herrin, E. [1968], "Introduction to 1968 Seismological Tables for P Phases," Bull. Seism. Soc. Amer., 58, pp. 1193-1242.
- Hill, D. P., P. Mowinckel and K. M. Lahr [1975], "Catalog of Earthquakes in the Imperial Valley, California, June 1973-May 1974," USGS Open-File Report 75-101.
- Iyer, H. M. [1974], "Search for Geothermal Seismic Noise in the East Mesa Area, Imperial Valley, California," USGS Open-File Report, p. 52.
- Nagy, D. [1966], "The Gravitational Attraction of a Right Rectangular Prism," Geophysics, 31, pp. 362-371.
- Pho, H. T. and L. Behe [1972], "Extended Distances and Angles of Incidence of P Waves," Bull. Seism. Soc. Amer., 62, pp. 885-902.
- Steeple, D. W. and H. M. Iyer [1976], "Low-Velocity Zone Under Long Valley as Determined from Teleseismic Events," J. Geophys. Res., 81, pp. 849-860.