UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
National Center for Earthquake Research

HYPO71 (REVISED): A COMPUTER PROGRAM FOR DETERMINING HYPOCENTER, MAGNITUDE, AND FIRST MOTION PATTERN OF LOCAL EARTHQUAKES

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This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature

Menlo Park, California
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CONTENTS

1. INTRODUCTION

HYPO71 is a computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes. The original program was dated December 21, 1971, and a user's manual was released as an open-file report of the U.S. Geological Survey on March 30, 1972 (Lee and Lahr, 1972). In order to generalize HYPO71 for worldwide usage and to correct a few programming "bugs", the program HYPO71 was revised on November 25, 1973, and a note on "Revisions of HYPO71" was released on January 30, 1974. Now that all reprints of the original HYPO71 manual have been exhausted, we take this opportunity to release a revised and updated HYPO71 manual. For simplicity, HYPO71 (Revised) will be referred to as HYPO71.

Because this report is intended as a manual for HYPO71 users, emphasis has been placed upon how to use the program. Our experience indicates that locating local earthquakes accurately requires considerable efforts. One must have accurate station coordinates (better than ± 0.1 km if possible), a reasonable crustal structure model (from controlled explosions), and reliable P and S arrivals. Naturally no computer program will give correct answers if the input data contain errors, so careful checking is essential before HYPO71 is run. One should also remember that small residuals and standard errors are NOT sufficient to guarantee accurate hypocenter solution.

HYPO71 is designed to catch some common mistakes in the input data, but this should not be counted on to find all of the errors. HYPO71 also provides an assessment of the quality of the hypocenter solution (see p. 26) and much other information. Users are urged to study the output carefully. We wish to emphasize that values for "TEST VARIABLES" (see p. 7) must be carefully chosen for a given application because they influence how the program goes about locating the earthquakes. The standard values in the program were developed for the large and closely spaced network of seismic stations in central California (with over 100 stations and station separation usually less than 10 kilometers).

HYPO71 differs from HYPOLAYR (Eaton, 1969) and its revised version HYPOMAG in its scope and design, except that a similar subroutine is used to calculate traveltimes and their derivatives. Although major results of HYPOLAYR (or HYPOMAG) could be reproduced with HYPO71, several additional features are available in HYPO71 to streamline routine data processing. Several schemes of detecting errors in input data are used to prevent erroneous solutions and premature termination. Options to make first-motion plots, calculate duration magnitudes, map residual minima, and compute more realistic traveltimes are now available.

Comments and criticisms of HYPO71 from users are welcome so that further improvements can be made. Users are urged to write or call Willie Lee (415-323-8111, Ext. 2630) should any problem occur in using HYPO71.

2. HOW TO USE HYPO71

The HYPO71 program is available in two versions: one for the IBM 360 or 370 computer in EBCDIC punched code, and the other for the CDC 6600 or 7600 computer in BCD punched code. It is written in FORTRAN IV language and has been successfully executed under the FORTRAN H compiler for IBM computers or under the MNF (University of Minnesota FORTRAN) compiler for CDC computers. The program requires approximately 150,000 bytes (or 37,500 words) of core storage for execution. Section 2.4 will describe how to adapt HYPO71 to your computer, especially when the available core storage is less than what is required. A listing of HYPO71 is given in Appendix 1 (p.45-86).

If HYPO71 is to be used routinely, a load module should be created and stored on disk. Since compilation and link-editing are not needed to execute a load module, considerable savings in computer time is achieved (about 2 minutes per run on an IBM 360/65 computer). In the following two sections, a step-by-step description of how to use the load module of HYPO71 is presented. A listing of a test run for IBM 360 or 370 computers is illustrated in Appendix 2 (p.87-89).

2.1 Input Card Deck Setup.

To execute the load module of HYPO71 the following input card deck setup is required:

(1) Job card

(2) Job control cards

(3) Input data cards

(4) End card

Because "Input Data Cards" are independent of the computer facility, they will be treated in detail in Section 2.2. For NCER users, a load module of HYPO71 has been stored on (1) USGS Computer Center at Reston, (2) Stanford Computation Center at Stanford University, and (3) Computing Facility at Lawrence Berkeley Laboratory. The input card deck setup for the Reston computer is illustrated in Appendix 2 (p.87-89). The deck setup for the Stanford computer is as follows:

```
- - - - - JOB CARD FOR STANFORD IBM 360/67 COMPUTER - - - - -
//HYPO EXEC PGM=HYPO71
//STEPLIB DD DSN=C896.LEE,UNIT=2314,DISP=OLD,VOL=SER=SYS10
//FT06F001 DD SYSOUT=A
//FT07F001 DD SYSOUT=B
//FT05F001 DD *
- - - - - INPUT DATA CARDS FOR HYPO71 - - - - -
/*
```

The deck setup for the LBL computer (BKY) is as follows:

```
- - - - - JOB CARD FOR BKY CDC 7600 COMPUTER - - - - -
LIBCOPY(UPGEO,BIN/BR,RHP71)
LINK,B,F=BIN.
LGOB,LC=20000.      (NOTE: LC=MAXIMUM NUMBER OF OUTPUT LINES)
EXIT.
7/8/9 CARD       (NOTE: MULTIPLE PUNCH OF 7,8,& 9 AT COLUMN 1)
- - - - - INPUT DATA CARDS FOR HYPO71 - - - - -
6/7/8/9 CARD      (NOTE: THIS IS THE BKY END OF JOB CARD)
```

2.1-1. Job Card. This card must be prepared according to the computer facility used. One should normally allow 1 second computer time (IBM 360/65) and 100 lines printout for each earthquake. In addition, 5 seconds and 500 lines should be allowed for overhead. The actual computer time and printout depend, of course, on the options chosen and on the amount of data for each earthquake.

2.1-2. Job Control Cards. These cards depend on the computer facility used and how the load module is stored. Examples for IBM and CDC computers are shown in Section 2.1 above.

2.2. Input Data Cards.

These cards contain the input data for HYPO71, and are set up as described below. A quick reference guide for variable names and formats of the input data is given in Figure 1. To denote a blank punch in the text, we use $_\Delta$.

	Item	Maximum Number of cards	Remarks	Page
(1)	Heading card	1	optional	5
(2)	Reset list	13	optional	7
(3)	Selection card	1		9
(4)	Station list	150		9
(5)	Blank card	1	to signal end of (4)	12
(6)	Crustal model list	20		12
(7)	Blank card	1	to signal end of (6)	12
(8)	Control card	1		12
(9)	Phase list	100	repeated for each quake	15
(10)	Instruction card	1	repeated for each quake	17
(11)	Additional instruction list		optional	17
(12)	Recycle card		optional	18

2.2-1 Heading Card. This card is optional and is used to write a heading above each earthquake in the output. Punch HEAD in columns 1 to 4, and the heading in columns 26 to 74.

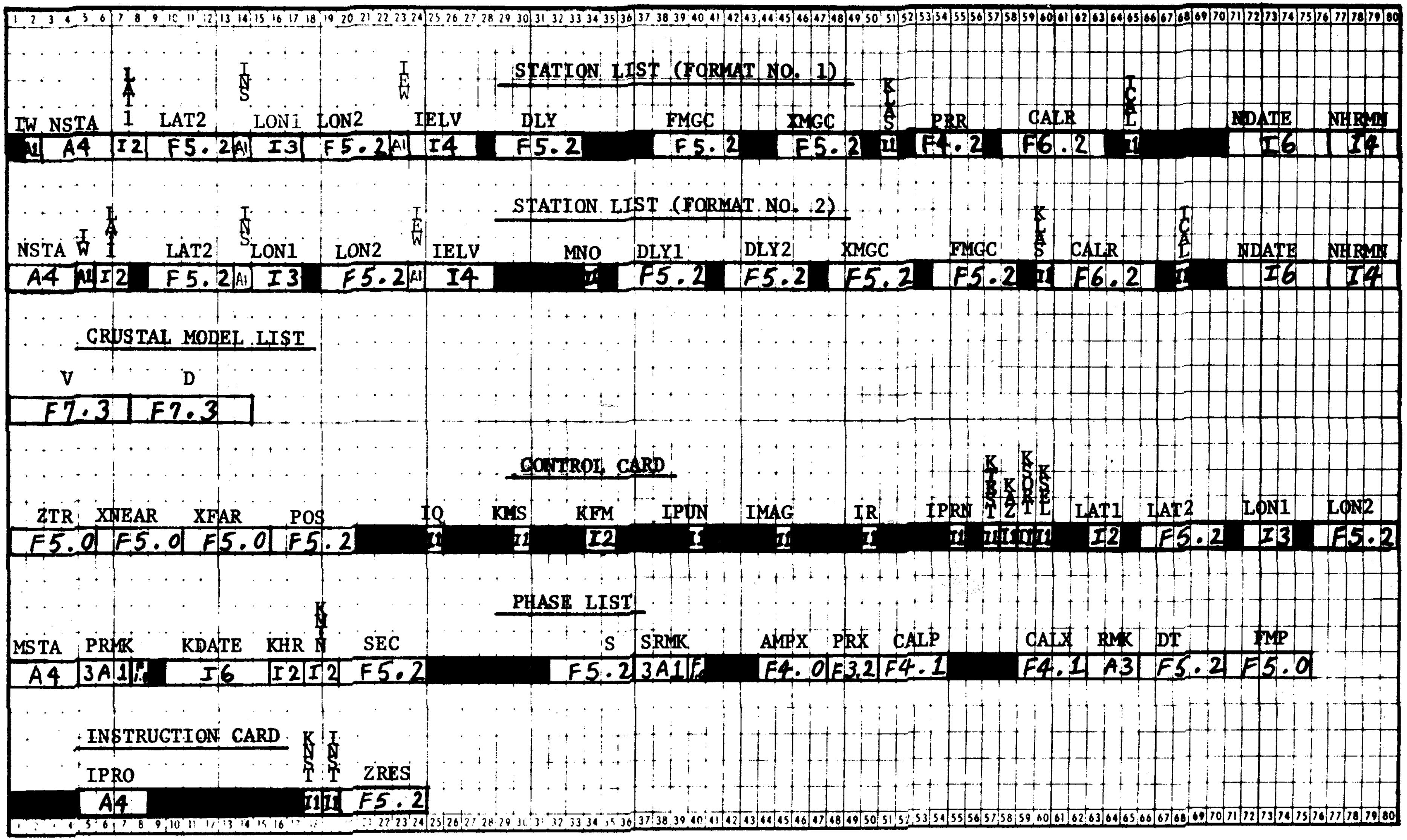


Figure 1. Variable Names and Formats of HYPO71 Input Data.

2.2-2 Reset List. This list is optional and may contain any number of cards up to a maximum of 13. The purpose of this list is to reset values of the test variables used in the program. The standard values (initiated by the program) are appropriate for earthquakes recorded by the USGS California Network of stations. Careful consideration should be given to their definitions and the values appropriate to a given set of data before this program is used.

An example of a reset card is:

RESET$_{\Delta}$TEST(06)=0.75 starting at column 1. The subscript of the test variable must be punched in columns 12 and 13, and the value of the test variable must be punched in F-format in columns 16 to 25. Definitions for the test variables are given as follows:

Test Variable	Standard Value	Definition
TEST(01)	0.1 sec	TEST(01) is the cutoff value for RMS below which Jeffreys' weighting of residuals is not used. It should be set to a value approximately equal to the overall timing accuracy of P-arrivals in seconds.*
TEST(02)	10 km	For each iteration step, if the epicentral adjustment $\geq$ TEST(02), this step is recalculated without focal-depth adjustment. TEST(02) should be set to a value approximately equal to station spacing in kilometers.
TEST(03)	2.	Critical F-value for the stepwise multiple regression (Draper and Smith, 1966). TEST(03) should be set according to the number and quality of P- and S-arrivals. A value between 0.5 and 2 is recommended. If TEST(03) $\leqq$ 0., a simple multiple regression is performed regardless of whether the matrix is ill-conditioned (p.32-33).

* Jeffreys' weighting is designed to catch large arrival-time errors. Therefore, it is useful to use it on preliminary runs. After arrival-time errors have been corrected, Jeffreys' weighting is not recommended. (i.e. Reset TEST(01) to a large value, such as 0.5, on your final run).

Test Variable	Standard Value	Definition
		This is not desirable because the hypocenter solution may be meaningless. On the other hand, if TEST(03) is set to 2 or greater, then Geiger's iteration may be terminated prematurely, before a good hypocenter is found.
TEST(04)	0.05 km	If the hypocentral adjustment is less than TEST(04), Geiger's iteration is terminated.
TEST(05)	5. km	If the focal-depth adjustment (DZ) is greater than TEST(05), DZ is reset to DZ / (K + 1), where K = DZ / TEST(05). TEST(05) should be set to a value approximately equal to half the range of focal depth expected. For example, most earthquakes have focal depths between 0 and 10 km in central California. Therefore, we use a value of 5 km for trial focal depth (p. 12), and TEST(05) = 5 km.
TEST(06)	4.	If no significant variable is found in the stepwise multiple regression, the critical F-value, TEST(03), is reduced to TEST(03)/TEST(06), and the regression is repeated. If TEST(06) $\leq$1., then the regression is repeated to find one variable, and the adjustment is made only if it is greater than TEST(06)* standard error. If TEST(03) is set to be less than 2, then TEST(06) should be set to 1.
TEST(07)	-0.87	Coefficients for calculating the duration magnitude (FMAG) (Lee, Bennett and Meagher, 1972): FMAG = -0.87 + 2 log(T) + 0.0035 D where T is signal duration in sec, and D is epicentral distance in km.
TEST(08)	2.00	
TEST(09)	0.0035	
TEST(10)	100 km	If the latitude or longitude adjustment (DX or DY) is greater than TEST(10), then DX is reset to DX/(J+1), and DY is reset to DY/(J+1), where J = D/TEST(10), D being the larger of DX or DY.

Test Variable	Standard Value	Definition
TEST(11)	8.	Maximum number of iterations in the hypocentral adjustment.
TEST(12)	0.5	If the focal-depth adjustment (DZ) would place the hypocenter in the air, then DZ is reset to DZ = -Z * TEST(12), where Z is the focal depth.
TEST(13)	1. km	Auxiliary RMS values are optionally calculated at ten points on a sphere of radius $\sqrt{3}$ * TEST(13) centered on the final solution. Eight of the ten points fall on the corners of a cube, with sides equal to 2 * TEST(13). If the solution converged to a minimum of RMS, then all nearby values of RMS will be greater. TEST(13) should be set to a value approximately equal to the standard error of hypocenter in kilometers. (See p. 30 for details).

2.2-3 Selection Card. In HYPO71, travel time from a trial hypocenter to a station is calculated from a given crustal model consisting of multiple horizontal layers. Each layer is specified by a P-velocity and the depth to the top of the layer. Additional complexity in crustal structure may be modeled in two ways:

a) Station Delay Model. The selection card is a blank, and the station delay is simply added to the calculated travel time for each station.

b) Variable First-Layer Model. The selection card has a 1 punched in Column 1. To account for different travel paths, the station delay at a given station is converted to an equivalent first-layer thickness. This then alters the crustal structure under this station. In other words, all stations have slightly different crustal structure: the P-velocities are the same, but the layer thickness of the first and second layers differ from station to station. In addition, two delays may be assigned to a given station corresponding to different earthquake source regions.

2.2-4 Station List. For each seismograph station, a station card must be punched. Use Station Format No. 1 for the Station Delay Model, and Station Format No. 2 for the Variable First-Layer Model. A maximum of 150 station cards is allowed in the program.

Station Format No. 1 (for Station Delay Model)

Column	Name	Format	Explanation	Examples
2	IW	A1	If IW = *, then this station has zero weight assighed to its P and/or S reading(s).	Normally blank
3-6	NSTA	A4	Station name	SBSM or $_{\Delta}$MOB
7-8	LAT1	I2	Degree portion of latitude	37
9-13	LAT2	F5.2	Minute portion of latitude	15.72
14	INS *	A1	Punch N or leave this column blank for stations in northerm hemisphere. Punch S for stations in southern hemisphere.	N or S
15-17	LON1	I3	Degree portion of longitude	121
18-22	LON2	F5.2	Minute portion of longitude	30.45
23	IEW *	A1	Punch E for eastern longitude. Punch W or leave this column blank for western longitude	E or W
24-27	IELV	I4	Elevation in meters. This data is not used in the program	1250 or $_{\Delta\Delta}$50
29-33	DLY	F5.2	Station delay in seconds	+0.20 or -0.08
38-42	FMGC	F5.2	Station correction for FMAG	+0.25 or -0.50
45-49	XMGC	F5.2	Station correction for XMAG	+0.25 or -0.50
51	KLAS	I1	System number is assigned for each station so that the frequency response curve of the seismometer and preamp is specified for the amplitude magnitude calculation (XMAG)	0 for Wood-Anderson 1 for NCER Standard 2 for EV-17 & Develco 3 for HS-10 & Teledyne 4 for HS-10 & Develco 5 for L-4C & Develco 6 for L-4C & Teledyne 7 for L-4C replacing HS-10 & Develco 8 for 10-day recorders

* INS and IEW <u>must</u> be the same for all stations.

Column	Name	Format	Explanation	Examples
53-56	PRR	F4.2	Standard period for XMAG	0.15 or blank
58-63	CALR	F6.2	Standard calibration for XMAG	$_{\Delta}$10.50 or blank
65	ICAL	I1	Calibration indicator: punch 1 if one always wants to use the standard calibration; otherwise leave it blank	1 or blank
71-76	NDATE	I6	Year, month, and day	710625 or blank
77-80	NHRMN	I4	Hour and minute	1224 or blank

Station Format No. 2 (for Variable First-Layer Model)

Column	Name	Format	Explanation	Examples
1-4	NSTA	A4	Station name	SBSM or $_{\Delta}$MOB
5	IW	A1	If IW=*, then this station has zero weight assigned to its P &/ S readings	normally blank
6-7	LAT1	I2	Degree portion of latitude	37
9-13	LAT2	F5.2	Minute portion of latitude	15.72
14	INS*	A1	Punch N or leave this column blank for stations in northern hemisphere. Punch S for stations in southern hemisphere	N or S
15-17	LON1	I3	Degree portion of longitude	121
19-23	LON2	F5.2	Minute portion of longitude	30.45
24	IEW*	A1	Punch E for eastern longitude. Punch W or leave this column blank for western longitude	E or W
25-28	IELV	I4	Elevation in meters. This data is not used in the program.	1250 or $_{\Delta\Delta}$50
34	MNO	I1	Preferred model number. If MNO=1 and this station is nearest to the earthquake, then model 1 is used.	1 or 2
36-40	DLY1	F5.2	Station delay for model 1 in seconds	+0.20 or -0.08
42-46	DLY2	F5.2	Station delay for model 2 in seconds	+0.20 or -0.08
48-52	XMGC	F5.2	Station correction for XMAG	+0.25 or -0.50
54-58	FMGC	F5.2	Station correction for FMAG	+0.25 or -0.50

* INS and IEW must be the same for all stations.

Station Format No. 2 (for Variable First-Layer Model)

Column	Name	Format	Explanation	Examples
60	KLAS	I2	System number (see explanation in Station Format No. 1).	
61-66	CALR	F6.2	Standard calibration for XMAG	Δ10.50 or blank
68	ICAL	I1	Calibration indicator: punch 1 if the standard calibration is to be used; otherwise leave it blank.	1 or blank
71-76	NDATE	I6	Year, month and day	710625 or blank
77-80	NHRMN	I4	Hour and minute	1224 or blank

2.2-5 Blank Card. Signals end of station list.

2.2-6 **Crustal Model List.** For each flat layer, a crustal model list card must be punched as follows:

Column	Name	Format	Explanation	Examples
1-7	V	F7.3	P-velocity in km/sec in a given layer	ΔΔ3.5ΔΔ
8-14	D	F7.3	Depth in km to the top of a given layer	ΔΔ0.00Δ for the first layer

2.2-7 Blank Card. Signals end of crustal model.

2.2-8 **Control Card.** This card selects some of the options in HYPO71 and must be punched as follows:

Column	Name	Format	Explanation	Examples
1-5	ZTR	F5.0	Trial focal depth in km	ΔΔΔ5.
6-10	XNEAR	F5.0	Distance in km from epicenter where the distance weighting is 1	ΔΔ50.
11-15	XFAR	F5.0	Distance in km from epicenter beyond which the distance weighting is 0	Δ200.

Column	Name	Format	Explanation	Examples
16-20	POS	F5.2	Ratio of P-velocity to S-velocity	$_{\Delta}$1.78 is recommended
25	IQ	I1	Quality class of earthquake to be included in the summary of residuals	1 for class A 2 for A and B 3 for A, B, and C 4 for all
30	KMS	I1	Indicator to check missing data	0 for NOT checking 1 for checking
34-35	KFM	I2	Minimum number of first motion readings required before it is plotted. Leave it blank if no first motion plot is needed.	15 or blank
40	IPUN	I1	Indicator for punched cards	0 for no punched cards 1 for punching summary cards 2 for punching summary and station cards 3 for punching summary cards and new station list with revised residuals 4 for punching summary cards and new station list with revised system number and standard calibration.
45	IMAG	I1	Method of selecting earthquake magnitude (MAG)	0 for MAG = XMAG 1 for MAG = FMAG 2 for $MAG = \frac{XMAG + FMAG}{2}$
50	IR	I1	Number of new system response curves to be read in. Normally leave it blank unless one wishes to override the NCER system response curves. See p. 57 (555-560), and p. 85-86.	blank

Column	Name	Format	Explanation	Examples
55	IPRN	I1	Indicator for printed output. We recommend IPRN = 1	0 for final solution and station residuals 1 for above plus one line each per iteration 2 for above plus station residuals per iteration 3 for above plus details from stepwise multiple regression
57	KTEST	I1	If KTEST = 1, then auxiliary RMS values are calculated at ten points on a sphere centered at the hypocenter. (See p.9). This option will help to determine if the solution is at the RMS minimum. (See p.30).	1 or blank
58 (CODE)	KAZ	I1	If KAZ = 1, then azimuthal weighting of stations is applied. See page 29.	1 or blank
59	KSORT	I1	If KSORT = 1, then the stations are sorted by distance in the output	1 or blank
60	KSEL	I1	If KSEL = 1, then printed output for each earthquake will start at a new page.	1 or blank
63-64	LAT1	I2	Degree portion of the trial-hypocenter latitude	
66-70	LAT2	F5.2	Minute portion of the trial-hypocenter latitude	
72-74	LON1	I3	Degree portion of the trial-hypocenter longitude	
76-80	LON2	F5.2	Minute portion of the trial-hypocenter longitude	

Note: If columns 63-80 are blank, then location of the nearest station is used as trial-hypocenter (with addition of 0.1 minute to both latitude and longitude to avoid "ARCTAN (0/0)" in calculating the azimuth between epicenter and station).

2.2-9 Phase list. For each seismographic station recording the earthquakes, a phase list card must be punched as follows. A maximum of 100 cards is allowed in the phase list. Examples of data forms for punching phase cards are shown in Appendix 5 (p. 111-113).

Column	Name	Format	Explanation	Examples
1-4	MSTA	A4	Station name	SBSM or $_{\Delta}$MOB
5	PRMK	A1	Description of onset of P-arrival	I denotes impulsive or sharp E denotes emergent or gradual
6	PRMK	A1	"P" to denote P-arrival	P or blank
7	PRMK	A1	First motion direction of P-arrival	U = Up = C = Compression D = Down = Dilatation + = poor U or C - = poor D N = Noisy blank = Not readable
8	PRMK	F1.0	Weight assigned to P-arrival	0 or blank = Full weight 1 = 3/4 weight 2 = 1/2 weight 3 = 1/4 weight 4 = No weight
10-15	KDATE	I6	Year, month, and day of P-arrival *	700105 for Jan. 5, 1970
16-17	KHR	I2	Hour of P-arrival*	18
18-19	KMIN	I2	Minute of P-arrival**	32
20-24	SEC	F5.2	Second of P-arrival	15.25
32-36	S	F5.2	Second of S-arrival	20.10

* 'KDATE' and 'KHR' must have the same values for P and S arrivals for a given earthquake. For arrival times where 'KHR' changes, the extra hour MUST be carried into 'KMIN'.

** For arrival times where 'KMIN' changes, 'KMIN' may be punched as it is, or if the same 'KMIN' is punched, carry the extra minute into 'SEC' & 'S'.

2.2-9 Phase list. -- Continued

Column	Name	Format	Explanation	Examples
37	SRMK	A1	Description of onset of S-arrival	I or E or blank
38		A1	"S" to denote S-arrival	S or blank
39		A1	First motion direction	U, or D, or +, or -, or N, or blank
40		F1.0	Weight assigned to S-arrival	Same as that for P-arrival at Column 8
44-47	AMPX	F4.0	Maximum peak-to-peak amplitude in mm	$_\Delta$24. or $_{\Delta\Delta}$24
48-50	PRX	F3.2	Period of the maximum amplitude in sec. Standard period (PRR) for this station as specified in the station list will be used if this field is blank.	.15
51-54	CALP	F4.1	Normally not used except as noted in next item.	
59-62	CALX	F4.1	Peak-to-peak amplitude of 10 μv calibration signal in mm. If this field is blank, then CALX = CALP. If again CALX is blank, then the standard calibration (CALR) for this station as specified in the station list will be used. If ICAL = 1 (in the station list for this station), then CALX will always be replaced by CALR.	$_\Delta$5.4
63-65	RMK	A3	Remark for this phase card. Any three characters (except CAL) may be used.	Q05 or blank
66-70	DT	F5.2	Time correction in sec. Normally not used for telemetered stations, so leave it blank.	blank

2.2-9 Phase list. -- Continued

Column	Name	Format	Explanation	Examples
71-75	FMP	F5.0	F-P time in sec. This is the duration time of earthquake. In NCER practice, one measures the time between the first P-arrival and that where the peak-to-peak amplitude of the seismic trace drops below 1 cm.	$_{\Delta\Delta}$15.

2.2-10 Instruction Card. At the end of the phase list for each earthquake, one instruction card must be punched as follows. For routine runs, one usually chooses free solution (i.e. let the program decide what is the best solution), so that the instruction card is simply a blank card.

Column	Name	Format	Explanation	Examples
5-8	IPRO	A4	Normally IPRO = blank. If IPRO = $_{\Delta}$**$_{\Delta}$, additional instruction card will follow	blank or $_{\Delta}$**$_{\Delta}$
18	KNST	I1	KNST = 0 implies do not use S Data KNST = 1 Use S Data Add 5 if First motion plot is desired	0, 1, 5, or 6
19	INST	I1	INST = 0 implies don't fix depth INST = 1 fix depth INST = 9 fix lat, lon, and depth. See 2.3-1 below	0, 1, or 9
20-24	ZRES	F5.2	Trial focal-depth. Normally this field is left blank unless one wishes to replace ZTR (in the control card) by ZRES for this earthquake.	blank

2.2-11 Additional Instruction List. Additional instruction cards may be optionally added to obtain other solutions for the same earthquake data. They are punched as follows:

Column	Name	Format	Explanation
5-8	IPRO	A4	If this is the last card in the instruction list, IPRO = blank. If more instruction cards follow, IPRO = $_{\Delta}**_{\Delta}$.
18	KNST	I1	Same as that described in section 2.3-10 (p. 17).
19	INST	I1	
20-24	ZRES	F5.2	
28-29	LAT1	I2	Degree portion of trial-hypocenter latitude
31-35	LAT2	F5.2	Minute portion of trial-hypocenter latitude
37-39	LON1	I3	Degree portion of trial-hypocenter longitude
41-45	LON2	F5.2	Minute portion of trial-hypocenter longitude

2.3-12 Recycle Card. Previous items may be repeated by using a recycle card to be punched on columns 2 to 4

Columns (2 to 4)	Remarks
***	Repeat (1) to (12) by returning to (1)
$$$	Repeat (6) to (12) by returning to (6)
¢¢¢	Repeat (8) to (12) by returning to (8)

2.3 Additional Options.

Several additional options are available in HYPO71, as follows:

2.3-1. All Fixed Solution. This option may be used to calculate the travel times to various stations for a known origin time and hypocenter (e.g. nuclear explosions or quarry blasts). This is achieved by specifying INST = 9, and an additional card must then be punched as follows:

Column	Name	Format	Explanation	Examples
1-5	ORG1	F5.0	Minute portion of origin time	ΔΔ15.
6-10	ORG2	F5.2	Second portion of origin time	10.05
11-15	LAT1	I5	Degree portion of latitude of hypocenter	ΔΔΔ37
16-20	LAT2	F5.2	Minute portion of latitude of hypocenter.	15.50
21-25	LON1	I5	Degree portion of longitude of hypocenter	ΔΔ121
26-30	LON2	F5.2	Minute portion of longitude of hypocenter	32.45
31-35	Z	F5.2	Focal depth of hypocenter in km	Δ0.00

2.3-2 Use of S-Arrivals. Whether or not S-arrivals are used in the hypocenter solution, they will appear on the output if they are punched on phase cards. To use S-arrivals in the solution, set KNST = 1 on the instruction card (p. 17 & 18).

2.3-3 Use of S-P Intervals. If the same time base is not available for some stations, it is still possible to include the recorded S-P intervals in the hypocentral solution. This is very useful when there are few available stations. The phase cards of the S-P interval data are punched as usual (see P.15). However, the weight assigned to the P-arrival (column 8) must be 9, and the weight assigned to S-arrival (column 40) is that desired for the S-P interval.

2.3-4 Calibration Changes. The system number (KLAS), and/or standard calibration (CALR) for any station may be changed from time to time by inserting a calibration card like an earthquake event. In this case, the phase list and instruction card are replaced by one card punched as follows:

Column	Name	Format	Explanation	Examples
1-4	MSTA	A4	Station name	SBSM or ΔMOB
10-15	KDATE	I6	Year, month, and day of new calibration	700215
16-17	KHR	I2	Hour of new calibration	21
18-19	KMIN	I2	Minute of new calibration	54
22	KLAS	I1	New system number	1
59-62	CALX	F4.1	New station calibration value (10 μv signal in mm)	13.2
63-65	RMK	A3	Must be "CAL"	CAL only

This option therefore allows an automatic updating of instrumental changes so that correct magnitudes based on amplitude data will be computed.

2.4 Adapting HYPO71 for Your Computer. The EBCDIC punched code of the HYPO71 program is written for an IBM 360 or 370 computer. A listing is given in Appendix 1 (p.45-86), where the number in the right hand side is the FORTRAN card sequence number. If you have an IBM 360 or 370 computer, adapting HYPO71 for your computer will be easy, except perhaps the error handling facility of your FORTRAN compiler and the amount of core storage available. If your FORTRAN compiler does not have ERRSET subroutines, you must delete HYPO71 cards numbered from 22 to 27 (see p.46). If the amount of core storage available to you is less than 150,000 bytes, you may reduce the dimension of the arrays and/or delete some non-critical subroutines.

The length of various HYPO71 components as compiled by FORTH on an IBM 360/65 computer is as follows:

HYPO71 Components	Card Sequence Number	Length (bytes)
MAIN	1 - 98	1,588
ANSWER	99 - 133	1,520
AZWTOS	134 - 211	1,836
BLOCK DATA	212 - 248	7,676
FMPLOT	249 - 361	13,568
INPUT1	362 - 562	5,766
INPUT2	563 - 676	2,574
MISING	677 - 737	1,218
OUTPUT	738 - 1021	7,604
SINGLE	1022 - 1499	9,028
SORT	1500 - 1526	560
SUMOUT	1527 - 1652	9,048
SWMREG	1653 - 1857	5,730
TRVDRV	1858 - 2024	4,344
XFMAGS	2025 - 2123	2,502
COMMON BLOCKS		47,318
FORTRAN LIBRARY		24,096
	Total	145,976 bytes

To execute HYPO71, however, one must add several thousand bytes to this total for buffers (this depends on the computer facility). Therefore, we suggest a core storage requirement of 150,000 bytes, although the program length is less than 146,000 bytes.

HYPO71 is dimensioned for a maximum of 150 station cards (NMAX = 151), and 100 phase cards (MMAX = 101). If not needed, the core storage may be reduced by redimensioning arrays that have been dimensioned for NMAX = 151 and MMAX = 101. In addition the statement (card number 245) which defines the values of NMAX and MMAX must be modified to the new values chosen. Savings of up to about 25,000 bytes may be realized.

Another way to reduce the core storage requirement is to remove non-critical subroutines and statements that call them:

Subroutine	Card Sequence Number	Cards Calling the Subroutine
ANSWER	99 - 133	1793, 1821
AZWTOS	134 - 211	1174
FMPLOT	249 - 361	1451
MISING	677 - 737	1450
SUMOUT	1527 - 1652	91

Up to about 30,000 bytes may be saved in this manner.

The BCD punched code for HYPO71 is a modification of the IBM version for CDC computers. It is essentially identical except for the following:

(1) Because CDC allows 131 characters per line (vs 132 characters for IBM), "SDFM" reads "SDF", and only one '*' follows large S-residuals instead of two '*'. This difference has no effect on your result.

(2) Because CDC only recognizes BCD punched codes, please avoid using characters such as "+", "#", "¢", "%".

(3) You <u>can</u> use "+" for your first P-motion, but not elsewhere. This restriction is not damaging, because you do not need to use "+" anywhere else.

(4) "¢" in the IBM version (and HYPO71 manual) has been replaced by "=" in the CDC version.

If you do not have either an IBM or CDC computer, adapting HYPO71 for your computer will depend on how similar your computer is to the IBM 360 or 370 computers. We suggest that you consult your computer center staff before undertaking this work.

Finally, to facilitate your adaption, a deck of test data (see p.87-89) always accompanies a request for the HYPO71 program. You should reproduce the results (within 1 or 2 counts of the last significant figures) shown on p. 90-96.

3. OUTPUTS OF HYPO71

Most outputs of HYPO71 are printed by the line-printer. Cards are punched only when the data must be read back into the computer for subsequent running of other computer programs. The printer outputs are generally self-explanatory; the following explanations may be helpful to the users. Results of the test run (listed in Appendix 2) is given in Appendix 3 (p. 90-96).

3.1 Iteration Output (optional).

If IPRN = 1 on the control card, a one-line output appears for each iteration. This information shows what happened in each adjustment from the trial hypocenter to the final hypocenter.

Heading	Explanation
I	Iteration step number. If a particular step is repeated, I is also repeated.
ORIG	Origin time in sec. Date, hour and minute are given in HYPOCENTER OUTPUT (Section 3.2).
LAT LONG Depth	Hypocenter location at Step I. See Section 3.2 for details.
DM	Epicentral distance in km to the nearest station.
RMS	Root mean square error of time residuals in sec. corrected for average P & S residual (AVRPS).
SKD	For S and D explanation, see Section 3.2. K denotes the status of the critical F-value (CF) in the iteration step. See Section 4 for more details. For K = 0, CF = TEST(03). For K = 1, CF = TEST(03)/TEST(06). For K = 2, F-test is skipped in order to calculate error estimates. For K = 3, On this step no variable met the F-test entrance criterion and termination will occur. For K = 4, F-test is skipped, and the most significant variable is found. This step is taken only if the adjustment is greater than TEST(06) times its standard error.

3.1 Iteration Output (optional). -- Continued

Heading	Explanation
CF	Critical F-value. Its value is controlled by K as described above.
ADJUSTMENTS (km)	Under these three columns, adjustments in km for the latitude (DLAT), longitude (DLON), and focal depth (DZ) from the multiple regression analysis are given.
PARTIAL F-VALUES	Under these three columns, the partial F-values for the hypocentral adjustments are given. Values not calculated are set equal to -1.00.
STANDARD ERRORS	Under these three columns, the standard errors for the hypocenter adjustments are given in km.
ADJUSTMENTS TAKEN	Under these three columns, the actual adjustments taken to reach the next trial hypocenter are given in km.

3.2 Hypocenter Output.

Heading	Example	Explanation
DATE	700630	Date of earthquake: Year, month, and day. In this case, it is June 30, 1970.
ORIGIN	1659 24.05	Origin time: hour, minute, and second (Greenwich civil time). In this case, it is 16 hr, 59 mn, and 24.05 sec.
LAT	37-48.64	Latitude of epicenter in degrees and minutes: 37° 48.64'.
LONG	121-57.59	Longitude of epicenter in degrees and minutes: 121° 57.59'
DEPTH	3.62	Focal depth in km: 3.62 km. A '*' may follow the DEPTH to indicate a fixed focal depth solution.
MAG	1.35	Magnitude of the earthquake. User specifies its choice from XMAG and/or FMAG.
NO	15	Number of station readings used in locating the earthquake. P and S arrivals for the same station are regarded as 2 readings. If NO = 3, a fixed depth solution is given. If NO<3, no solution is given.

Heading	Example	Explanation
DM	2	Epicentral distance in km to the nearest station.
GAP	110	Largest azimuthal separation in degrees between stations.
M	1	Crustal model number. M is used for the Variable First-Layer Model only.
RMS	0.09	Root mean square error of time residuals in sec. $RMS = \sqrt{\Sigma R_i^2/NO}$, where R_i is the time residual for the i^{th} station.
ERH	0.4	Standard error of the epicenter in km.* $ERH = \sqrt{SDX^2 + SDY^2}$, where SDX and SDY are the standard errors in latitude and longitude, respectively, of the epicenter. If ERH = blank, this means that ERH cannot be computed because of insufficient data.
ERZ	1.2	Standard error of the focal depth in km.* If ERZ is blank, this means that ERZ cannot be computed either because focal depth is fixed in the solution or because of insufficient data.
Q	B	Solution quality of the hypocenter. This measure is intended to indicate the general reliability of the solution:

Q	Epicenter	Focal Depth
A	Excellent	good
B	good	fair
C	fair	poor
D	poor	poor

Q is taken as the average of QS and QD (defined below). For example, an A and a C yield a B, and two B's yield a B. When QS and QD are only one level apart, the lower one is used, i.e., an A and a B yield a B.

SQD	A|B	QS and QD rating, In this case, QS = A, and QD = B. QS is rated by the statistical measure of the solution as follows:

* Statistical interpretation of standard errors involves assumptions which may not be met in earthquake locations. Therefore the standard errors may not represent actual error limits.

QS	RMS (sec)	ERH (km)	ERZ (km)
A	< 0.15	≤ 1.0	≤ 2.0
B	< 0.30	≤ 2.5	≤ 5.0
C	< 0.50	≤ 5.0	
D	Others		

QD is rated according to the station distribution as follows:

QD	NO	GAP	DMIN
A	≥ 6	≤ 90°	≤ DEPTH or 5 km
B	≥ 6	≤ 135°	≤ 2x DEPTH or 10 km
C	≥ 6	≤ 180°	≤ 50 km
D	Others		

Heading	Example	Explanation
ADJ	0.0	Last adjustment of hypocenter in km. Normally this is 0 or less than 0.05.
IN	0	Instruction code (KNST and INST in input)
NR	17	Number of station readings available. This includes readings which are not used in determining hypocenter.
AVR	0.00	Average of time residuals in sec. $AVR \equiv \sum_i R_i/NO$. Normally this is 0.
AAR	0.07	Average of the absolute time residuals in sec. $AAR \equiv \sum_i \lvert R_i \rvert /NO$.
NM	5	Number of station readings available for computing maximum amplitude magnitude (XMAG).
AVXM	1.4	Average of XMAG of available stations.
SDXM	0.1	Standard deviation of XMAG of available stations.
NF	3	Number of station readings available for computing F-P magnitude (FMAG).
AVFM	1.3	Average of FMAG of available stations.
SDFM	0.2	Standard deviation of FMAG of available stations.
I	4	Number of iterations to reach the final hypocenter.

Items from DATE to Q inclusive are repeated at the head of every first-motion plot. If summary cards are punched, these items occupy from column 1 to 80.* However, order for M, GAP, and DMIN are changed. A heading card is punched preceding the summary cards, if IPUN ≥ 1 on the control card.

3.3 Station Output.

After each hypocenter output of 2 lines, station output follows for each station.

Heading	Example	Explanation
STN	BOL	Station name.
DIST	1.3	Epicentral distance in km.
AZM	202	Azimuthal angle between epicenter to station measured from north in degrees.
AIN	94	Angle of incidence measured with respect to downward vertical.
PRMK	IPUO	This is PRMK from input data.
HRMN	1659	Hour and minute of arrival time from input data.
P-SEC	25.30	The second's portion of P-arrival time from input data.
TPOBS	1.25	Observed P-travel time in sec. TPOBS ≡ T + DT - ORG where T is the P-arrival time, ORG is the origin time, and DT is the time correction from input data.
TPCAL	1.09	Calculated travel time in sec.
DLY/H1	0.05 or 3.12	If the Station Delay Model is used, then DLY means the station delay in sec from the input station list. If the Variable First-Layer Model is used, then H1 means the thickness of the first-layer in km at this station.
P-RES	0.16	Residual of P-arrival in sec. If the Station Delay Model is used, then P-RES ≡ TPOBS - (TPCAL + DLY). If '**' follows P-RES, it means that in the Jeffreys' weighting, this P-arrival is not reliable. If the Variable First-Layer Model is used, then P-RES ≡ TPOBS - TPCAL.

* The punch format is given on p.61 (773-775) & is used on p.64 (934-935).

Heading	Example	Explanation
P-WT	1.06	Weight used in hypocenter solution for P-arrival. This weight is a combination of quality weight specified in the data and other selected weightings. WT's are always normalized so that the sum is equal to NO. Normalization is necessary so as to avoid distortion in computing standard errors.
AMX	15.0	Maximum amplitude in mm from input data.
PRX	0.10	Period of maximum amplitude in sec. from input data. If PRX is not given on the phase card, then PRR from the corresponding station card is used in the computation of XMAG, but is not printed here.
CALX	2.20	Calibration in mm used in computing XMAG. If CALX is blank in the phase card, then CALR from the corresponding station card is used and is printed here as CALX.
K	5	System number for the station from input data.
XMAG	1.60	Maximum amplitude magnitude computed from AMX, PRX, CALX and K. A * follows XMAG if XMAG - AVXM $\geq$ 0.5.
RMK	Q05	Remark from input data.
FMP	10.0	F-P in sec from input data.
FMAG	1.02	F-P magnitude computed from F-P and DIST. A * follows FMAG if FMAG - AVFM $\geq$ 0.5.
SRMK	ES$_\Delta$2	This is SRMK from input data.
S-SEC	26.50	The second's portion of S-arrival time from input data.
TSOBS	2.45	Observed S-travel time in sec. TSOBS $\equiv$ T + DT - ORG, where T is the S-arrival time, ORG is the origin time, and DT is the time correction from input data.
S-RES	-0.22	Residual of S-arrival in sec. If the Station Delay Model is used, then S-RES $\equiv$ TSOBS - POS* (TPCAL + DLY). If the Variable First-Layer Model is used, then S-RES $\equiv$ TSOBS - POS*TPCAL.
S-WT	0.5	Weight used in hypocenter solution for S-arrival. See explanation of P-WT for additional information.
DT	blank	Station time correction in sec. from input data. DT is used to correct all stations to the same time base.

If S-P interval data are used, the meanings of some of the above headings are changed as follows.

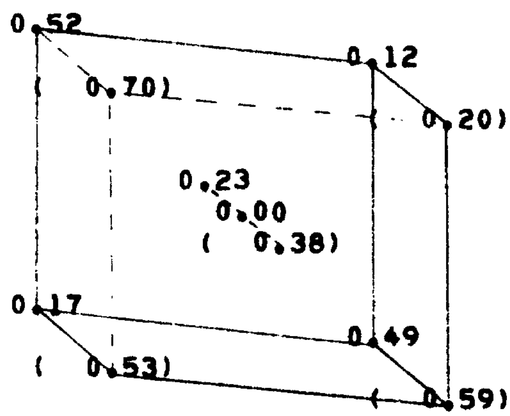
Heading	Explanation
P-RES	S-P residual in sec. It is defined by P-RES ≡ TSOBS - TPOBS - (POS - 1) (DLY + TPCAL) for the Station Delay Model. DLY is multiplied by zero for computing P-RES as above for the Variable First-Layer Model.
S-RES	Same as P-RES
P-WT	Weight used in hypocenter solution for S-P interval data.
S-WT	Will always be **** to denote S-P interval data.
TSOBS	Observed S-P interval in sec.

3.4 Map of Auxiliary RMS Values.

This is an optional output for which KTEST is set to 1 on the Control Card (see p. 14). RMS values are computed at 10 points on a sphere centered on the final hypocenter. Each RMS value corresponds to an origin time which has been corrected for the average residual of the P and S arrivals (AVRPS) given at that point. A 3-dimensional view of the auxiliary RMS value minus the final hypocenter RMS value is printed (DRMS). An example is shown below; the view is looking down to the northwest. It is necessary by NOT sufficient for all DRMS values to be positive for a good solution. If any DRMS value is negative, then the solution has not converged to a minimum. It is important to set the radius of the sphere appropriately for a given application (see p.9, TEST(13)).

LAT	LON	Z	AVRPS	RMS
8.17	14.76	0.0	-0.39	0.63
8.17	8.02	0.0	-1.42	0.23
8.17	14.76	9.62	-0.31	0.81
8.17	8.02	9.62	-1.19	0.30
5.47	11.39	0.0	-0.26	0.34
				0.11
5.47	11.39	13.28	-0.56	0.48
2.77	14.76	0.0	0.50	0.27
2.77	8.02	0.0	-0.88	0.60
2.77	14.76	9.62	0.37	0.63
2.77	8.02	9.62	-0.74	0.70

DRMS



4. COMPUTATIONAL PROCEDURES IN HYPO71

The program HYPO71 consists of a main program and 14 subroutines: ANSWER, AZWTOS, BLOCK DATA, FMPLOT, INPUT1, INPUT2, MISING, OUTPUT, SINGLE, SORT, SUMOUT, SWMREG, TRVDRV, and XFMAGS. A complete listing of the program (with a fair amount of comments) is given in Appendix 1. Before we give some program notes, a brief outline is given of Geiger's method (Geiger, 1912) of determining the hypocenter of local earthquakes.

4.1 Geiger's Method.

Let the coordinates of the i^{th} station be (x_i, y_i, z_i), and the observed arrival time be τ_i. Let t_i be the computed arrival time based on a trial solution [i.e., an assumed origin time (t), and hypocenter (x, y, z)]. If the time residual

$$R_i \equiv \tau_i - t_i \tag{1}$$

is small, Taylor expansion of it will give:

$$R_i = dt + \frac{\partial t_i}{\partial x} dx + \frac{\partial t_i}{\partial y} dy + \frac{\partial t_i}{\partial z} dz + e_i \tag{2}$$

Since the travel time and derivatives can be computed from the given crustal model, we may obtain the adjustment vector (dt, dx, dy, dz) by least squares, i.e., demanding that the error e_i be such that:

$$\Sigma\, e_i^2 = \text{a minimum} \tag{3}$$

where Σ denotes summation over all stations, i.e., $i = 1$ to $i = n$. This is accomplished by solving the following normal equations which are derived from applying condition (3) to equation (2):

$$ndt + \Sigma a_i dx + \Sigma b_i dy + \Sigma c_i dz = \Sigma R_i$$

$$\Sigma a_i dt + \Sigma a_i^2 dx + \Sigma a_i b_i dy + \Sigma a_i c_i dz = \Sigma a_i R_i$$

$$\Sigma b_i dt + \Sigma a_i b_i dx + \Sigma b_i^2 dy + \Sigma b_i c_i dz = \Sigma b_i R_i \tag{4}$$

$$\Sigma c_i dt + \Sigma a_i c_i dx + \Sigma b_i c_i dy + \Sigma c_i^2 dz = \Sigma c_i R_i$$

where

$$a_i \equiv \frac{\partial t_i}{\partial x} \; ; \; b_i \equiv \frac{\partial t_i}{\partial y} \; ; \; c_i \equiv \frac{\partial t_i}{\partial z} \tag{5}$$

The improved origin time and hypocenter then becomes:

$$t + dt, \text{ and } (x + dx,\ y + dy,\ z + dz) \tag{6}$$

Now (6) may be taken as the next trial solution, and the same procedure is repeated until some cutoff criteria are met.

In the case of S-P interval data, τ_i and t_i become the observed and calculated S-P intervals respectively. Because there is no dependance on the origin time, equation (2) becomes

$$R_i = \frac{\partial t_i}{\partial x} dx + \frac{\partial t_i}{\partial y} dy + \frac{\partial t_i}{\partial z} dz + e_i \tag{7}$$

and the normal equations (4) are modified accordingly.

Since the normal equations (4) are a set of 4 simultaneous linear equations for four unknowns: dt, dx, dy, dz, they may be solved by the usual method of matrix inversion. In practice, however, this matrix is often ill-conditioned, and computational difficulties arise. In HYPO71 a new method of finding the adjustment vector is introduced. Instead of carrying out the traditional procedure (which is equivalent to a simple multiple regression), a step-wise multiple regression is used. Equation (2) defines the time residual R_i as a function of dt, dx, dy, and dz. A statistical analysis is first performed to see which independent variable should be included in the regression and the normal equations are then set up for only those significant variables. Therefore, the adjustment vector is obtained by solving a matrix which is never ill-conditioned. Furthermore, convergence to a final hypocenter solution is also more rapid.

4.2 Program Notes.

These notes serve as extended comments on HYPO71, and are given in the order of the program listing (see Appendix 1).

(1) MAIN: The main program controls the flow of data processing by initializations and calls to various subroutines.

(2) ANSWER: It prints the intermediate results of the regression analysis (SWMREG), and is used only for tracing the computation of a given earthquake.

(3) AZWTOS: It performs the azimuthal weighting of stations by quadrants. Each occupied quadrant is given an equal weight. The quadrants are set up so as to minimize the number of quadrants without stations.

(4) BLOCK DATA: Initialize values for short-distance calculation, and for various constants used in the program.

(5) FMPLOT: Plot first-motion pattern of the lower focal hemisphere in an equal area projection. It is modified from subroutine PPROJ (NCER PROGRAM LIBRARY No. S007) written by M. S. Hamilton. For each observation, we have the azimuth α, the angle of incidence β, and a symbol SYM, where $0° \le \alpha \le 360°$, $0° \le \beta \le 180°$, and SYM = C (or +) for compression, or D (or -) for dilatation.

If $\beta > 90°$, we let $\alpha = 180° + \alpha$ and $\beta = 180° - \beta$ so that all points plotted are in the lower focal hemisphere. The observation is transformed into polar coordinates (r,θ) in an equal area projection by the formulas:

$$r = \sqrt{2}\,\sin(\beta/2)$$

$$\theta = \alpha$$

A symbol is plotted on the graph at the point (r,θ). The symbol to be plotted is determined by the following rules:

If SYM = C, then plot one of the following:

- C If no other observation occupies the position (r,θ).
- B If one 'C' already occupies (r,θ).
- A If two or more 'C' already occupy (r,θ).
- X If at least one 'D' already occupies (r,θ).

If SYM = D, then plot one of the following:

- D If no other observation occupies the position (r,θ).
- E If one 'D' already occupies (r,θ).
- F If two or more 'D' already occupy (r,θ).
- X If at least one 'C' already occupies (r,θ).

If SYM = + or −, it is plotted only if the position (r,θ) is not occupied.

(6) INPUT1: Read in heading card, reset test-variable list, station list, crustal model, and control card. If any array dimension is exceeded, an error message will be printed out and the program will then stop.

(7) INPUT2: Read in phase list and instruction card. If 'CAL' is encountered in RMK columns, system number and standard calibration are revised.

(8) MISING: This subroutine checks if any station in the station list which should record the earthquake is missing from the input data. A "missing" station will be printed if its epicentral distance is less than the nearest

station, or if it would reduce the azimuthal gap between its two neighboring stations (EX-GAP) by not less than 30°. The latter check applies only to a radius of $25*(MAG)^2$ km (100 km if MAG is not given of the final epicenter), where MAG is the earthquake magnitude. The amount by which the missing station would reduce the EX-GAP is given by RD-GAP.

(9) OUTPUT: See Section 3

(10) SINGLE: This routine processes one earthquake at a time, and involves the following steps.

a. Set up a trial hypocenter: The first trial epicenter is normally set to be the latitude and longitude of the station with the earliest P-arrival. 0.1' is added to the latitude and longitude of the trial epicenter to avoid difficulties in computing azimuthal angle. The first trial focal-depth is set equal to that given in the control card, unless specified on the instruction card. The first trial origin-time is set so that the average residual of P and S-arrivals is zero.

b. Geiger's adjustments: A maximum of TEST(11) (p.9) iterations are allowed in this DO loop to adjust the trial hypocenter to the final one. Latitude-longitude coordinates are converted to x-y coordinates using a short distances' calculation by Richter (1958, p. 701-705). Epicentral distance is then computed and distance weighting is combined with quality weighting. Other weightings (azimuthal and Jeffreys') are also included if chosen. Subroutine TRVDRV (see Appendix 4, p.97ff. for details) is called to compute travel time and derivatives. S-arrivals are treated like P-arrivals by multiplying the calculated P travel time by the ratio of P-velocity/S-velocity. S-P interval data are treated analogously. Subroutine SWMREG is called to carry out a stepwise multiple regression of the time residuals and obtain the adjustment vector (dx, dy, dz, dt) and its standard errors. If the horizontal adjustment, $\sqrt{dx^2 + dy^2}$, is greater than 10 km (TEST(02)), the adjustment vector is re-computed with fixed focal-depth. Focal-depth adjustment is restricted so that the hypocenter will not be placed in the air (see TEST(12)) and it must also not exceed 5 km (TEST(05)) in any one adjustment. These are accomplished by changing dz by the necessary amount, and any modification of dz is compensated by a change in dt. If the hypocentral adjustment, $\sqrt{dx^2 + dy^2 + dz^2}$, is less than 0.05 km (TEST(04)), then the iteration is terminated.

During the iteration process, if the RMS value increases, then the trial hypocenter is moved back by 1/5 of the previous adjustment, and the iteration step-number is not incremented. This procedure is repeated until the RMS value decreases or for a maximum of 4 times. The variable accounting for the largest portion of the adjustment is then deleted in the next multiple regression step.

c. Compute error estimates: Standard errors of adjustments dx, dy, and dz are computed by forcing subroutine SWMREG to make a simple multiple regression analysis. These errors correspond to the uncertainties involved if the final hypocenter were to be adjusted in all co-ordinates (x, y, z) once more.

(11) SORT: This is a utility subroutine to sort X_i, i = 1, . . ., N by increasing value.

(12) SUMOUT: This subroutine prints a table of the number and percentage of earthquakes in each quality class, Q, (see P. 26). It also prints a summary of travel time, X-magnitude, and F-magnitude residuals by station.

(13) SWMREG: This subroutine computes the Geiger adjustment vector (and its standard errors) by a step-wise multiple regression of travel time residuals. The method used here is that given in Draper and Smith (1966, p. 178-195), and will be briefly summarized as follows:

Equation (2) of Section 4.1 may be written more compactly as

$$e_i = Y_i - B_o - \sum_{j=1}^{3} B_j X_{j,i} \quad \text{for } i=1,\ldots,n$$

If there are stations with only S-P intervals then this equation is modified to the form:

$$e_i = Y_i - X_{o,i} B_o - \sum_{j=1}^{3} B_j X_{j,i} \quad \text{for } i = 1,\ldots,n$$

where $Y_i = R_i$

$$B_o = dt;\ B_1 = dx;\ B_2 = dy;\ B_3 = dz$$

$$X_{1,i} = \partial t_i/\partial x;\ X_{2,i} = \partial t_i/\partial y;\ X_{3,i} = \partial t_i/\partial z$$

$$X_{o,1} = \begin{cases} 1 \text{ for P or S data} \\ 0 \text{ for S-P interval data} \end{cases}$$

let $$Q = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (Y_i - X_{o,i} B_o - \sum_{j=1}^{3} B_j X_{j,i})^2$$

By minimizing the sum of the squares, Q, the maximum likelihood estimates of B_o, B_1, B_2, and B_3 will be obtained.

Setting $\frac{\partial Q}{\partial B_i} = 0$ yields these four equations. In the following 3 pages, repeated indices i imply summation over i = 1, . . . , n.

$$X_{o,i}\, X_{o,i}\, B_o + \sum_{j=1}^{3} B_j\, X_{o,i}\, X_{j,i} = X_{o,i}\, Y_i$$

$$X_{1,i}\, X_{o,i}\, B_o + \sum_{j=1}^{3} B_j\, X_{1,i}\, X_{j,i} = X_{1,i}\, Y_i$$

$$X_{2,i}\, X_{o,i}\, B_o + \sum_{J=1}^{3} B_j\, X_{2,i}\, X_{j,i} = X_{2,i}\, Y_i$$

$$X_{3,i}\, X_{o,i}\, B_o + \sum_{j=1}^{3} B_j\, X_{3,i}\, X_{j,i} = X_{3,i}\, Y_i$$

We can solve the first of these four equations for B_o.

Of the n original equations let q be the number based upon S-P interval data. Then set $m = n - q$.

$$X_{o,i}\, X_{o,i} = m$$

Define $\tilde{V}_j = \frac{1}{m} \sum_{i=1}^{n} X_{o,i}\, V_{j,i}$

Then:

$$B_o = \tilde{Y} - \sum_{j=1}^{3} B_j\, \tilde{X}_j$$

Use this value of B_o in the other three equations. Kth equation (k may equal 1, 2, or 3) becomes

$$X_{k,i}\, X_{o,i}\, \tilde{Y} + \sum_{j=1}^{3} (B_j\, X_{k,i}\, X_{j,i} - B_j\, X_{k,i}\, X_{o,i}\, \tilde{X}_j) = X_{k,i} Y_i\ ,$$

or

$$\sum_{j=1}^{3} X_{k,i}\, (X_{j,i} - X_{o,i}\, \tilde{X}_j)\, B_j = X_{k,i}\, (Y_i - X_{o,i}\, \tilde{Y}).$$

But note that:

$$(X_{k,i} - X_{o,i}\tilde{X}_k)(X_{j,i} - X_{o,i}\tilde{X}_j) = X_{k,i}(X_{j,i} - X_{o,i}\tilde{X}_j) + X_{o,i}X_{o,i}\tilde{X}_j\tilde{X}_k - X_{o,i}X_{j,i}\tilde{X}_k$$

$$= X_{k,i}(X_{j,i} - X_{o,i}\tilde{X}_j) + m\tilde{X}_j\tilde{X}_k - m\tilde{X}_j\tilde{X}_k$$

The K^{th} equation can then be written:

$$\sum_{j=1}^{3}(X_{k,i} - X_{o,i}\tilde{X}_k)(X_{j,i} - X_{o,i}\tilde{X}_j)B_j = (X_{k,i} - X_{o,i}\tilde{X}_k)(Y_i - X_{o,i}\tilde{Y})$$

for k = 1, 2, or 3

These are a set of 3 simultaneous linear algebraic equations in the B_j and are known as the normal equations. They can be solved by a number of methods. Here we choose the abbreviated Doolittle method which is a variation of the usual Gaussian elimination. At each stage in the elimination, we make a decision as to what variable shall next be included in the regression.

The computational procedure is basically applying linear transformations to the augmented correlation matrix A:

$$A = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & 1 & 0 & 0 \\ R_{21} & R_{22} & R_{23} & R_{24} & 0 & 1 & 0 \\ R_{31} & R_{32} & R_{33} & R_{34} & 0 & 0 & 1 \\ R_{41} & R_{42} & R_{43} & R_{44} & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

where

$$R_{jk} = \frac{\sum_{i=1}^{n}(X_{j,i} - X_{o,i}\tilde{X}_j)(X_{k,i} - X_{o,i}\tilde{X}_k)}{\left[\Sigma(X_{j,i} - X_{o,i}\tilde{X}_j)^2 \ \Sigma(X_{k,i} - X_{o,i}\tilde{X}_k)^2\right]^{1/2}}$$

with the understanding that

$$X_{4,i} \equiv Y_i \text{ and } \tilde{X}_4 \equiv \tilde{Y}.$$

In the program, we use

$$S_{jk} = \sum_{i=i}^{n} (X_{j,i} - X_{o,i}\,\tilde{X}_j)\,(X_{k,i} - X_{o,i}\,\tilde{X}_k)$$

$$= X_{j,i}\,X_{k,i} - X_{o,i}\,X_{j,i}\tilde{X}_k + m\tilde{X}_j\,\tilde{X}_k - X_{o,i}\,X_{k,i}\,\tilde{X}_j$$

$$= X_{j,i}\,X_{k,i} - \frac{(X_{o,i}\,X_{j,i})\,(X_{o,i}\,X_{k,i})}{m} + m\tilde{X}_j\,\tilde{X}_k - m\tilde{X}_k\,\tilde{X}_j$$

and set $R_{jk} = \dfrac{S_{jk}}{\left[(S_{jj})\,(S_{kk})\right]^{1/2}}$

Matrix A is successively transformed whenever a variable (X_k) enters or leaves the regression. Whether a variable enters (or leaves) the regression depends only on whether the variance obtained by adding the variable to the regression is significant (or insignificant) at a specified F-level. This is accomplished by computing:

$$F_k = (\Phi - 1)\,V_k/(A_{44} - V_k)$$

where Φ is the degrees of freedom (n-1-number of variables in regression), and

$$V_k = A_{k4}A_{4k}/A_{kk}$$

If F_k exceeds the specified critical F-value (CF), then variable X_k enters the regression by transforming the elements of matrix A in two steps. First we compute

$$T_{kj} = A_{kj}/A_{kk} \quad \text{for } j=1,\ldots,7.$$

$$T_{ij}(i \neq k) = A_{ij} - A_{ik}A_{kj}/A_{kk} \text{ for } i=1,\ldots,7 \quad \text{and } j=1,\ldots,7.$$

We then replace elements of matrix A by that of matrix T just computed. Similarly to delete a variable from the regression we compute

$$F_k = \Phi A_{k4}^2 \;/\; (A_{44}A_{k+4,k+4})$$

If F_k is less than the specified critical F-value (CF), then variable X_k leaves the regression by transforming the elements of matrix A in two steps. First we compute

$$T_{kj} = A_{kj}/A_{k+4,k+4} \quad \text{for } j=1,\ldots,7.$$

$$T_{ij} \; (i \neq k, j \neq k) = A_{ij} - A_{i,k+4}A_{k+4,j}/A_{k+4,k+4}$$

$$T_{ik}(i \neq k) = A_{ik} - A_{i,k+4}/A_{k+4,k+4}$$

$$\text{for } i=1,\cdots,7 \quad \text{and } j=1,\cdots,7.$$

Then we replace elements of matrix A by that of matrix T just computed. After all variables are examined, we obtain the regression coefficients and their standard errors by

$$B_j = A_{j4} \sqrt{S_{44}/S_{jj}}$$

$$E_j = \sqrt{S_{44}A_{44}/\Phi} \quad \sqrt{A_{j+4,j+4}/S_{jj}}$$

where $S_{jk} = \Sigma (X_{ji}X_{ki}) - (\Sigma X_{ji}) (\Sigma X_{ki})/n$

for $j=1,\ldots,4$ and $k=1,\ldots,4$.

The regression constant is then obtained by

$$B_o = \tilde{Y} - \sum_{j=1}^{3} B_j \tilde{X}_j .$$

Because all indices are dummies, they are named differently in the program. Furthermore, a simple extension takes into account the weighting factors provided that they are normalized to equal the number of observations.

(14) TRVDRV: This subroutine is a modification of TRVDRV written by J. P. Eaton (Eaton, 1969). It computes the travel time and derivatives for a horizontal-layer model. Please see Appendix 4 (p.97ff.) for details.

(15) XFMAGS: This subroutine computes maximum amplitude magnitude (XMAG) and F-P magnitude (FMAG) for each station. The former is computed according to Eaton (1970). In brief:

$$XMAG = \log(A/2C) - R_{kf} - B_1 + B_2 \log(D^2) + G$$

where A = Maximum peak-to-peak amplitude in mm.
C = Calibration peak-to-peak amplitude in mm.
R_{kf} = Frequency response of system number k and frequency f ($f = 1/\tau$, where τ is the period in sec.)

$$\left.\begin{array}{l} B_1 = 0.15 \\ B_2 = 0.80 \end{array}\right\} \text{ for } 1 \text{ km} \leq D \leq 200 \text{ km}$$

$$\left.\begin{array}{l} B_1 = 3.38 \\ B_2 = 1.50 \end{array}\right\} \text{ for } 200 \text{ km} \leq D \leq 600 \text{ km}$$

$D = \sqrt{\Delta^2 + Z^2}$, where Δ is the epicentral distance and Z, the focal depth.

G = station XMAG correction.

FMAG is computed according to an empirical equation (Lee, Bennett and Meagher, 1972):

$$FMAG = C_1 + C_2 \log F + C_3 \Delta + \gamma$$

where

C_1 = -0.87, or TEST(07)

C_2 = 2.0, or TEST(08)

C_3 = 0.0035, or TEST(09)

F = F-P time in sec.

Δ = epicentral distance in km.

γ = station FMAG correction.

ACKNOWLEDGEMENTS

We wish to thank Jerry Eaton for permission to include a section of his report (Eaton, 1969, p.26-38) as Appendix 4 of this manual. We are grateful to Ray Buland of University of California at San Diego for pointing out two errors in the original HYPO71 program concerning the azimuthal weighting.

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NOTE

Appendix 1 (A listing of HYPO71), Appendix 2 (A listing of a test run of HYPO71), and Appendix 3 (Printed results of the HYP071 test run) are NOT reproduced here, because users can print the corresponding computer files (HYPO71.for, HYPO71.inp, and HYPO71.out) if needed.

This page replaces pages 45-96 of Lee and Lahr (1975)

APPENDIX 4

Calculation of Traveltimes, Derivatives, and Angle of Incidence

(by J. P. Eaton)

This section is taken from Eaton (1969, p. 26-38), and explains how traveltimes, derivatives, and angles of incidence are calculated in HYPO71.

Calculation of Traveltimes, Derivatives, and Angles of Incidence

(Subroutines TPAR and TRVDRV)

Program TRVDRV, on which these subroutines are based, was designed to calculate traveltimes and derivatives of traveltimes with respect to epicentral distance and focal depth for events in an "earth" consisting of N-1 flat layers above a homogeneous half space. The earth model is described by the depth to the top of layer L and the P-velocity in layer L; i.e., by D(L), V(L), L = 1, N, where the index N refers to the half space.

The course of the program can be outlined as follows:

1. Determine the layer, J, that contains the focus at depth, H.

2. Determine which of the several possible waves (direct, and refractions from successively lower horizons) is the first arrival at distance DELTA.

3. Calculate the traveltime and derivatives by an appropriate method: for refracted waves these calculations are straightforward, but for the direct waves a numerical solution must be employed.

Because the traveltime, derivative, and angle of incidence calculations are a critical central part of the hypocenter determination, these subroutines are treated more thoroughly than other subroutines in the program. This writeup describes a somewhat more elaborate version of the subroutine that constitutes a self-contained program as well as a test of the program on an actual earth model (the 3-layer "Hawaii B" structure). It is supplemented by an independent flow chart and a FORTRAN listing of the TRVDRV program. The variables used in the program and flow chart are identified in the accompanying list. The same notation will be used, generally, in the following section of the writeup, which outlines the mathematical formulation of the program and discusses some of the principal problems that must be solved. The notation used in this section is nearly identical (but not exactly) to that used in HYPOLAYR and its subroutines.

<u>Traveltime of Refracted Waves</u>

(See Sketch A)

The traveltime, to distance DELTA, of seismic waves from a focus in layer J that are refracted along the top of layer M can be written:

$$T = TINJ(M) + DELTA / V(M)$$

The intercept, $TINJ(M)$, can be written:

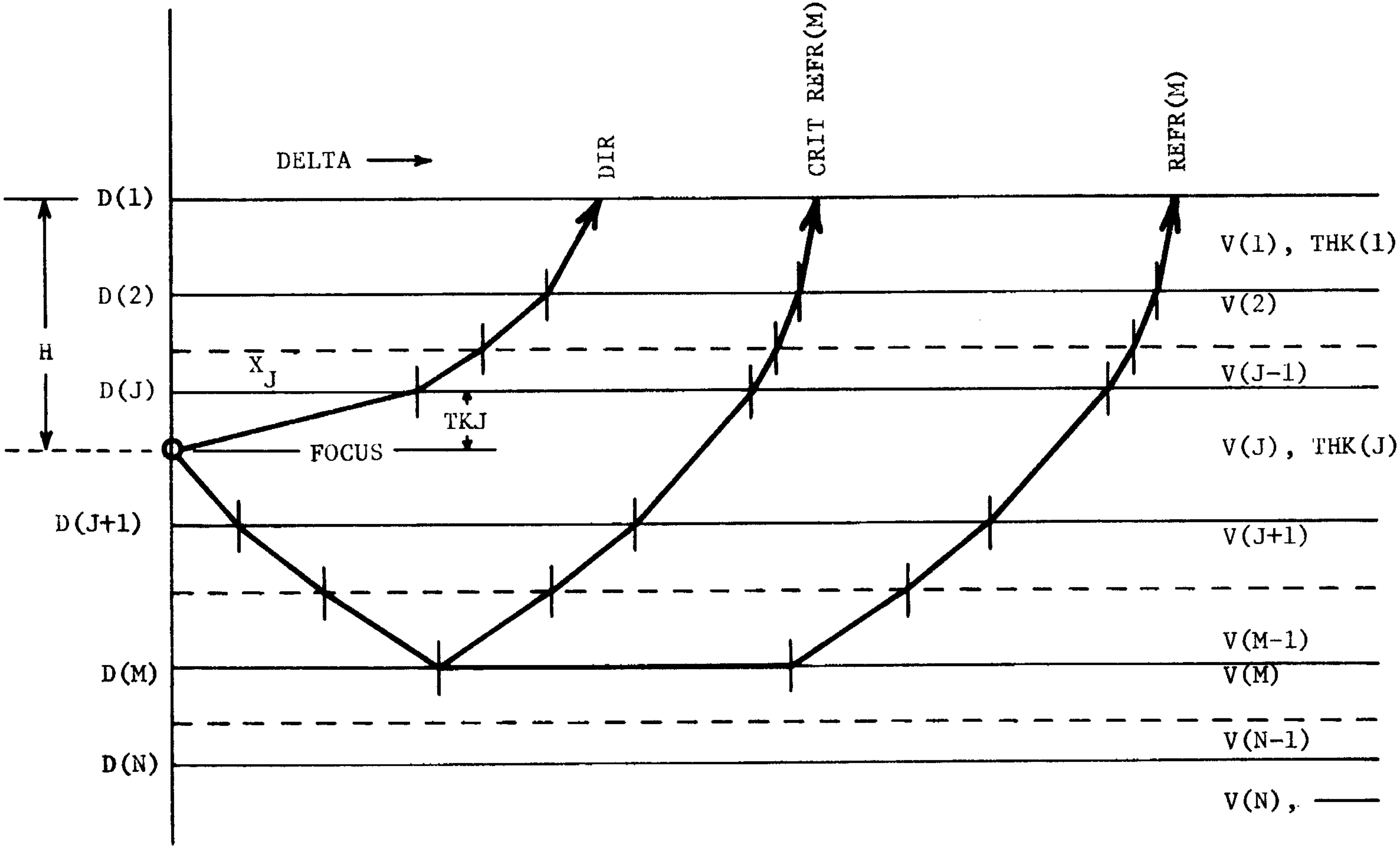
$$TINJ(M) = TID(J,M) - \frac{TKJ * \cos \theta_M^J}{V(J)}$$

where $TID(J,M)$ is the intercept of a wave with its focus at the top of layer J (at depth D(J)) that is refracted along the top of layer M (at depth D(M)).

Finally,

$$TID(J,M) = \sum_{L=J}^{M-1} \frac{THK(L) * \cos \theta_M^L}{V(L)} + \sum_{L=1}^{M-1} \frac{THK(L) * \cos \theta_M^L}{V(L)}$$

In these equations, θ_M^L is the angle of incidence in layer L of a wave that is refracted horizontally in layer M.



SKETCH A. Notation used to specify crustal model.

Critical Distance (Initial Point) of Refracted Waves

Analogous equations can be written for the distance to the initial point (distance of critical reflection) of the wave from a focus at depth H (in layer J) that is refracted along the top of layer M.

$$DIDJ(M) = DID(J,M) - TKJ * \tan\theta_M^J \quad , \text{ and}$$

$$DID(J,M) = \sum_{L=J}^{M-1} THK(L) * \tan\theta_M^J + \sum_{L=1}^{M-1} THK(L) * \tan\theta_M^J$$

where $DID(J,M)$ is the critical distance for a wave with a focus at the top of layer J (depth D(J)) that is reflected from the top of layer M (depth D(M)).

For waves that are refracted along or critically reflected from the top of layer M, the angle of incidence in layer M is $\pi/2$.

Critical Distance and Intercept Formulas in Terms of Layer Velocities and Thicknesses

From Snell's law $\quad \sin\theta_M^L = \dfrac{V(L)}{V(M)}$. Hence,

$$\cos\theta_M^L = \left(1 - V(L)^2/V(M)^2\right)^{1/2} = \frac{\sqrt{V(M)^2 - V(L)^2}}{V(M)} \quad , \text{ and}$$

$$\tan\theta_M^L = V(L) \Big/ \sqrt{V(M)^2 - V(L)^2} \quad .$$

The expressions for TID(J,M), DID(J,M) TINJ(M), and DIDJ(M) can be written:

$$TID(J,M) = \sum_{L=J}^{M-1} \frac{THK(L) * \sqrt{V(M)^2 - V(L)^2}}{V(M) * V(L)} + \sum_{L=1}^{M-1} \frac{THK(L) * \sqrt{V(M)^2 - V(L)^2}}{V(M) * V(L)}$$

$$DID(J,M)=\sum_{L=J}^{M-1}\frac{THK(L)*V(L)}{\sqrt{V(M)^2-V(L)^2}}+\sum_{L=1}^{M-1}\frac{THK(L)*V(L)}{\sqrt{V(M)^2-V(L)^2}}$$

$$TINJ(M)=TID(J,M)-TKJ*\frac{\sqrt{V(M)^2-V(J)^2}}{V(M)*V(J)}$$

$$DIDJ(M)=DID(J,M)-TKJ*\frac{TKJ*V(J)}{\sqrt{V(M)^2-V(J)^2}}$$

In these equations, TKJ is the depth of the focus below the top of layer J, ie., TKJ = H - D(J).

Traveltime of the Direct Wave

The traveltime of the direct wave to distance DELTA from a focus in the first layer is simply:

$$T=\sqrt{H^2+DELTA^2}\,/\,V(1)$$

For a focus in a deeper layer (J = 2, N) the expression for T as a function of DELTA is too complex to be useful, if it can be obtained at all. However, both T and DELTA are relatively simple functions of $\sin\theta_J$, where θ_J is the angle of incidence of the ray at the focus in layer J. In the program "DIRECT", a simple method for determining $\sin\theta_J$ and then calculating T for any specified DELTA was developed. This routine is employed in the present program to compute the traveltime of the direct ray to distance DELTA for $J > 1$.

Maximum Distance at Which the Direct Wave Can Be a First Arrival.

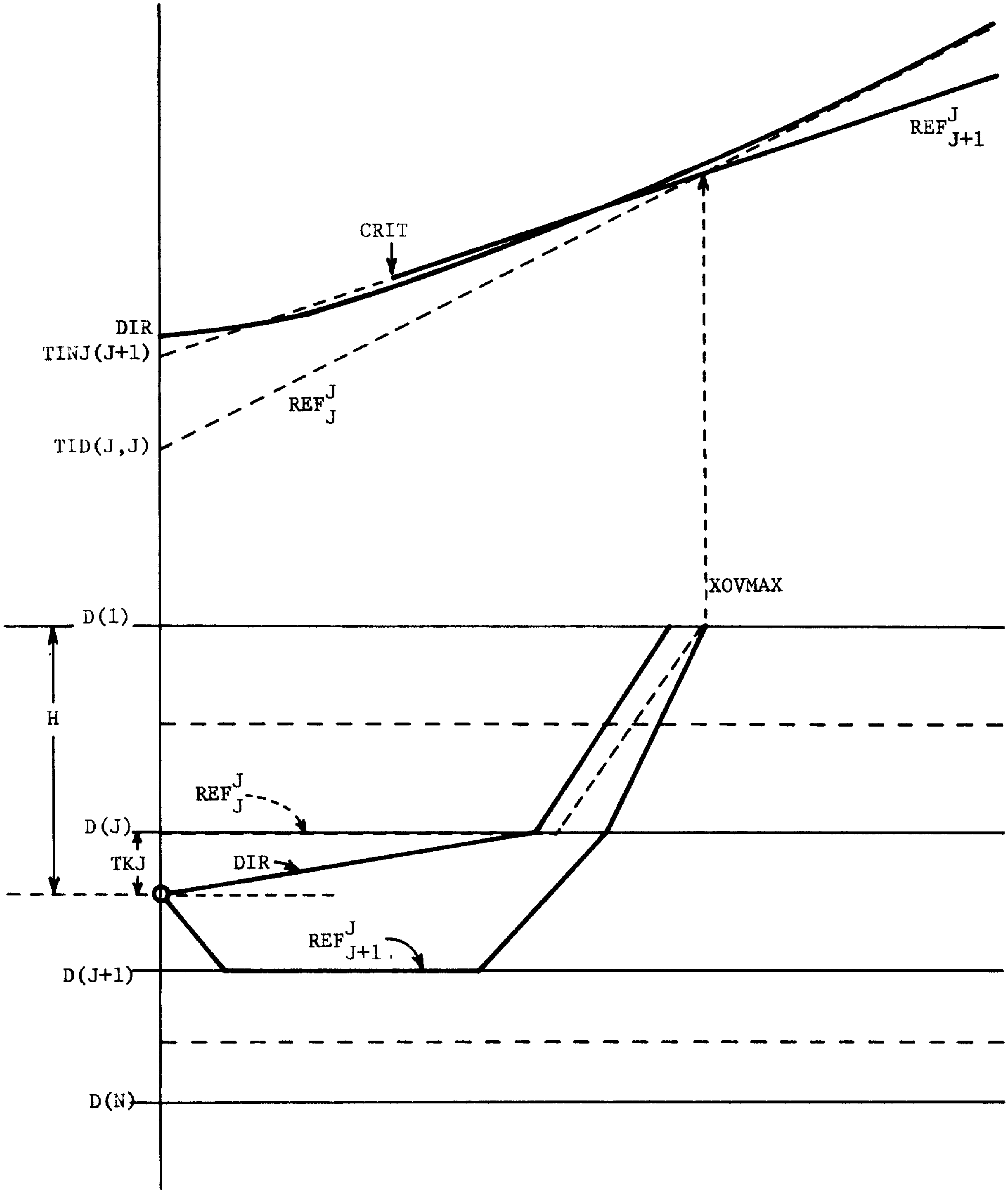
(See Sketch B)

Because the traveltime of the direct wave is more time-consuming to calculate than the traveltimes of refracted waves, a preliminary test is made to determine whether DELTA is beyond the range of possible direct-wave first arrivals. Consider a focus at depth H in layer J. At large DELTA the direct wave is asymptotic to the refraction line for a focus at the very top of layer J; but the direct wave is always later than the asymptote. Let the crossover distance between the wave refracted along the top of J from a focus at the top of J and the wave refracted along the top of J + I from a focus at depth H be XOVMAX. Then the crossover between the direct wave and the refracted wave from J + I will be smaller than XOVMAX, and the first arrival at DELTA larger than XOVMAX must be a refracted wave, if J $<$ N.

Because the initial point of the refraction from layer K + 1 is coincident with the critical reflection from the top of K + 1 (or the bottom of K) and because the reflection from the base of K must be later than the direct wave (if K = J) or a refracted wave from the top of K, the initial point of the K + 1 refraction curve must lie above the K-refraction curve (or the direct-wave curve if K = J). Hence, for DELTA greater than XOVMAX and J $<$ N the first arrival must be a refracted wave recorded beyond its initial point.

Determination of Which Wave Is the First Arrival at DELTA $<$ XOVMAX

For DELTA less than XOVMAX the first arrival may be the direct wave: so the traveltime of the direct wave must be computed and



SKETCH B. Sketch to illustrate discussion of XOVMAX, initial point, and critical distance.

compared with the traveltimes of possible refracted phases to establish which arrival is earliest. In this range of DELTA, however, it must be established that any prospective refracted first arrival actually exists at the specific value of DELTA considered; i.e., is DELTA beyond the initial point of the refracted wave?

Derivatives of Traveltime with Respect to Epicentral Distance and Focal Depth.--When the nature of the first arrival at distance DELTA has been established, the traveltime of that arrival is set equal to T and derivatives of the traveltime with respect to DELTA and H are computed by methods that are appropriate for the first-arrival wave type.

Derivatives of refracted-wave traveltimes with respect to DELTA and H.--For refracted waves, by differentiation of the equation for T as a function of DELTA and H:

$$\partial T / \partial DELTA = \frac{1}{V(M)}$$

$$\partial T / \partial H = \frac{-\sqrt{V(M)^2 - V(J)^2}}{V(M) * V(J)}$$

Derivatives of first-layer direct arrivals.--For the direct wave through layer 1:

$$\frac{\partial T}{\partial DELTA} = \frac{DELTA}{V(1) * \sqrt{H^2 + DELTA^2}}$$

$$\frac{\partial T}{\partial H} = \frac{H}{V(1) * \sqrt{H^2 + DELTA^2}}$$

Derivatives of direct-wave traveltimes: $J > 1$.--(See sketch C.)

Because both T and DELTA for the direct wave from layers below the first can be expressed in terms of the parameter $\sin\theta_J$

$$\frac{\partial T}{\partial \text{DELTA}} \quad \text{can be computed as} \quad \frac{\dfrac{\partial T}{\partial \sin\theta_J}}{\dfrac{\partial \text{DELTA}}{\partial \sin\theta_J}}$$

$$\frac{\partial T}{\partial \text{DELTA}} =$$

$$\frac{\text{TKJ}*U/\left(V(J)*(1.0-U^2)^{3/2}\right) + \sum_{L=1}^{J-1} \text{THK}(L)*V(J)*U/\left(V(L)^2*\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{3/2}\right)}{\text{TKJ}/(1.0-U^2)^{3/2} + \sum_{L=1}^{J-1} \text{THK}(L)*V(J)^2/\left(V(L)^2*\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{3/2}\right)}$$

where

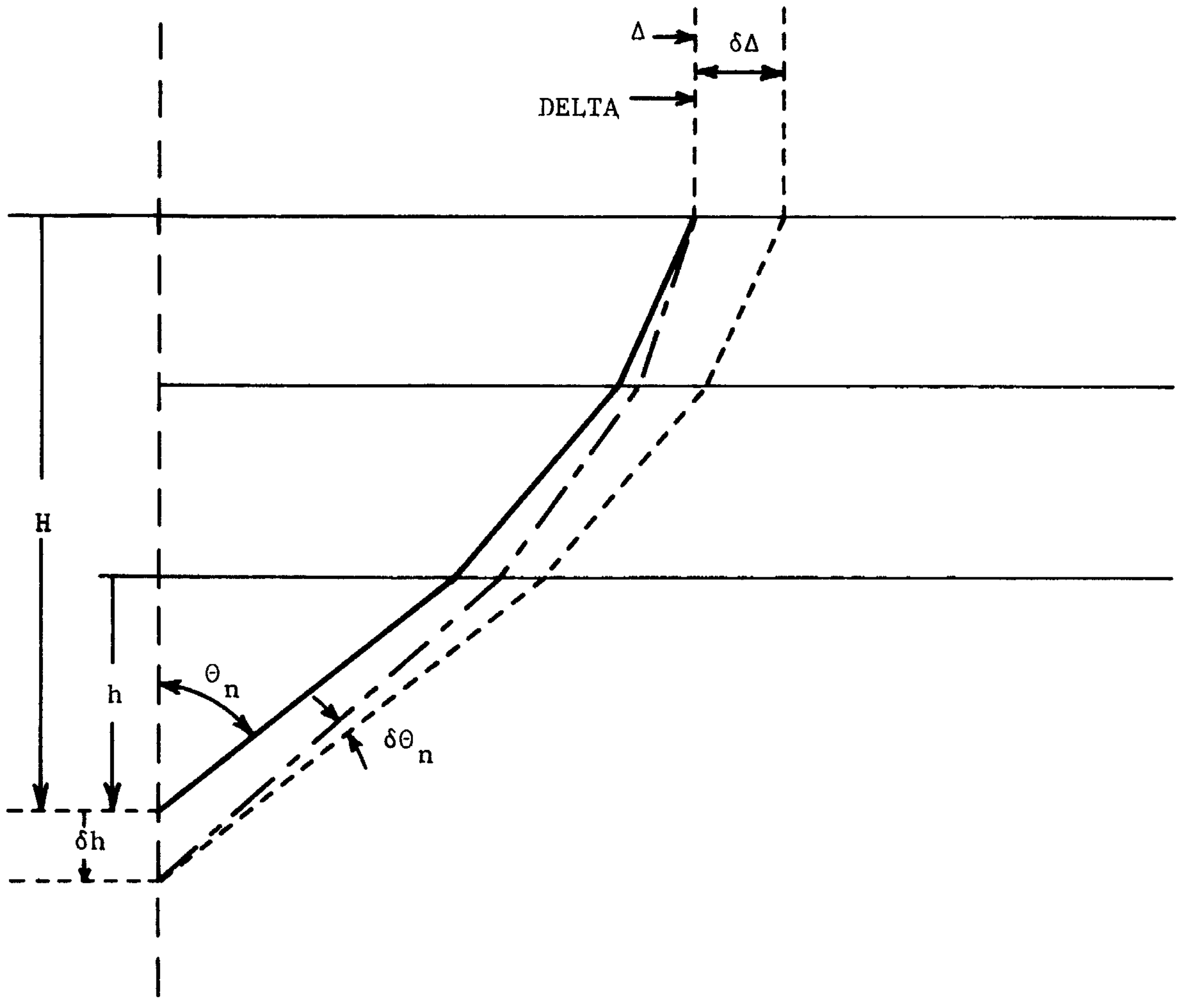
$$U = \sin\theta_J$$

Note: $\frac{\partial T}{\partial \text{DELTA}}$ *can be calculated more simply from elementary considerations.*

$$\left.\frac{\partial T}{\partial \Delta}\right|_h = \frac{\sin\theta_J}{V_J} = \frac{1}{\bar{V}}$$

, where $\bar{V}$ is the apparent surface velocity at distance Δ.

(Thanks to Rex Allen for catching this point. 6/10/75 JPE)



SKETCH C. Sketch to illustrate derivation of $\left.\frac{\partial T}{\partial h}\right|_{\Delta \mathrm{const}}$.

Next, we must calculate $\left.\frac{\partial T}{\partial H}\right|_{DELTA}$ for the direct arrival from layer J.

Letting U = $\sin\theta_J$, and h = TKJ = H - D(J), and DELTA = Δ,

$$T = \frac{h}{V(J)*\sqrt{1.0-U^2}} + \sum_{L=1}^{J-1} \frac{THK(L)*V(J)}{V(L)^2*\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{1/2}}$$

$$\Delta = \frac{h*U}{\sqrt{1.0-U^2}} + \sum_{L=1}^{J-1} \frac{THK(L)*U}{\left(\frac{V(J)^2}{V(L)^2}-U^2\right)^{1/2}}$$

Holding U = $\sin\theta_J$ = const, increase h by an amount δh. The corresponding changes in T and Δ are

$$\delta T_1 = \left.\frac{\partial T}{\partial h}\right|_U * \delta h$$

$$\delta \Delta_1 = \left.\frac{\partial \Delta}{\partial h}\right|_U * \delta h$$

Next, change U by an amount δU, holding h constant so that the change in Δ, $\delta\Delta_2$, is equal and opposite to that caused by the previous change in h.

$$\delta\Delta_2 = \left.\frac{\partial \Delta}{\partial U}\right|_h * \delta U = -\left.\frac{\partial \Delta}{\partial U}\right|_U * \delta h = -\delta\Delta_1$$

Thus, the required δu is:

$$\delta u = - \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h} * \delta h$$

The corresponding change in T is

$$\delta T_2 = \left.\frac{\partial T}{\partial u}\right|_h \delta u$$

Substituting the previous expression for δu

$$\delta T_2 = - \left.\frac{\partial T}{\partial u}\right|_h * \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h} * \delta h$$

The total change in Δ, i.e., $\delta \Delta_1 + \delta \Delta_2 = 0$, and the total change in T is

$$\delta T = \delta T_1 + \delta T_2 = \left.\frac{\partial T}{\partial h}\right|_u * \delta h - \left.\frac{\partial T}{\partial u}\right|_h * \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h} * \delta h$$

$$\left.\frac{\delta T}{\delta h}\right|_\Delta = \left.\frac{\partial T}{\partial h}\right|_u - \left.\frac{\partial T}{\partial u}\right|_h * \frac{\left.\frac{\partial \Delta}{\partial h}\right|_u}{\left.\frac{\partial \Delta}{\partial u}\right|_h}$$

We have previously calculated

$$\frac{\left.\frac{\partial T}{\partial u}\right|_h}{\left.\frac{\partial \Delta}{\partial u}\right|_h} = \left.\frac{\partial T}{\partial \Delta}\right|_h$$

Passing to the limit

$$\left.\frac{\partial T}{\partial h}\right|_\Delta = \left.\frac{\partial T}{\partial h}\right|_u - \left.\frac{\partial T}{\partial \Delta}\right|_h * \left.\frac{\partial \Delta}{\partial h}\right|_u .$$

But $\left.\frac{\partial T}{\partial h}\right|_u = \frac{1}{V(J)\sqrt{1.0-u^2}}$, $\left.\frac{\partial \Delta}{\partial h}\right|_u = \frac{u}{\sqrt{1.0-u^2}}$

and

$$\left.\frac{\partial T}{\partial h}\right|_{\Delta} = \frac{1.0}{V(J) * \sqrt{1.0 - u^2}} - \frac{u}{\sqrt{1.0-u^2}} * \left.\frac{\partial T}{\partial \Delta}\right|_{h}$$

Thus

$$\left.\frac{\partial T}{\partial h}\right|_{\Delta} = \frac{1.0 - V(J) * u * \left.\frac{\partial T}{\partial \Delta}\right|_{h}}{V(J) * \sqrt{1.0 - u^2}}$$

In the notation used in the FORTRAN program

$$DTDH = \frac{1.0 - V(J) * u * DTDD}{V(J) * \sqrt{1.0 - u^2}}$$

APPENDIX 5

Examples of Data Forms for Punching Phase Cards

In order to avoid errors in preparing the phase cards, it is useful to write the seismic data on a special form from which it is easily key-punched. *Users of HYPO71 are urged to prepare their data forms carefully.* Examples of data forms used at NCER are given in the following two pages.

Page 112 shows a typical data form used for processing seismic data from a large network of stations. The actual form is 8-1/2 x 13 inches, and only the top two-thirds are shown here. This form has space for data recorded on four develocorder films or nets. Each net has 16 stations, and station names are labelled in the form. Since S-arrivals are difficult to read on develocorder films, they are not routinely processed and are not included in the form. Space for two more nets and space for remarks are not shown here. In the upper left corner of the data form are abbreviations for some commonly used remarks to be punched in column "RK."

Page 113 shows a data form used for a small network where S-arrivals are routinely read and time corrections may be needed. Amplitude data are not processed and are left out in the form. An additional column for rise time is included although it is not used in the HYPO71 program. The actual form is 8-1/2 x 11 inches and fits nicely in a loose-leaf binder.

N = NOISY
Q = QUARRY
A = A BOMB
NE = NO ENERGY
REV. APR. 28, 1971

CF = CROSS-FEED
D = DEAD
E = EMERGENT

10 11	12 13	14 15	16 17	18 19
YR	MO	DY	HR	MN

P NET

STN (1–4)	i P u / e d (5–7)	W (8)	P (sec) (20–24)	AMX (mm) (44–47)	PRX (sec) (48–50)	RK (63–65)	FMP (sec) (71–75)
ANG	P		.		.		
BOL	P		.		.		
PAL	P		.		.		
SAL	P		.		.		
CYH	P		.		.		
WDS	P		.		.		
MOB	P		.		.		
SFT	P		.		.		
BGU	P		.		.		
LTW	P		.		.		
POR	P		.		.		
STV	P		.		.		
STJ	P		.		.		
BCR	P		.		.		
EGR	P		.		.		
PES	P		.		.		

B NET

STN (1–4)	i P u / e d (5–7)	W (8)	P (sec) (20–24)	AMX (mm) (44–47)	PRX (sec) (48–50)	RK (63–65)	FMP (sec) (71–75)
PMR	P		.		.		
CHR	P		.		.		
CAN	P		.		.		
PCL	P		.		.		
ANZ	P		.		.		
DIL	P		.		.		
OCR	P		.		.		
SJG	P		.		.		
LTR	P		.		.		
PKH	P		.		.		
FRP	P		.		.		
SRS	P		.		.		
PNC	P		.		.		
QSR	P		.		.		
CNR	P		.		.		
MON	P		.		.		

Date

Time by	______	______
Checked by	______	______
KP by	______	______

SAN LUIS RESERVOIR

10 11	12 13	14 15	16 17	18 19
YR	MO	DY	HR	MN

Feb. 27, 1974

	STN	i P u e d	P W	P (sec)	S (sec)	i S u e d	S W	RK	DT (sec)	FMP (sec)	RISE TIME (sec)
	1 2 3 4	5 6 7	8	20 21 22 23 24	32 33 34 35 36	37 38 39	40	63 64 65	66 67 68 69 70	71 72 73 74 75	76 77 78 79 80
1	SL1	P		.	.	S					.
2	SL2	P		.	.	S					.
3	SL3	P		.	.	S					.
4	SL4	P		.	.	S					.
5	SL5	P		.	.	S					.
6	SL6	P		.	.	S					.
7	SL7	P		.	.	S					.
8	SL8	P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.
9	ARN	P		.	.	S					.
10	SLD	P		.	.	S					.
11	PCL	P		.	.	S					.
12	FEL	P		.	.	S					.
13	LTR	P		.	.	S					.
14	QSR	P		.	.	S					.
15	EMM	P		.	.	S					.
16	RBM	P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.
		P		.	.	S					.