UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

User's Guide to HYPOINVERSE, a program for VAX computers to Solve for Earthquake Locations and Magnitudes

by
Fred W. Klein

U. S. Geological Survey
345 Middlefield Rd.
Menlo Park CA 94025

Open File Report 89-314

6/89 version

TABLE OF CONTENTS

INTRODUCTION

HYPOINVERSE was originally written for the Eclipse minicomputer in 1978, and that version is documented in USGS Open File Report 78-694. A revised version for VAX and Pro-350 computers is documented in Open File Report 85-515. This report supercedes the earlier documents and serves as a detailed user's guide to the current version running on the VAX computers in Menlo Park.

HYPOINVERSE will locate any number of events in an input file, which can be in several different formats. Any or all of printout, summary or archive output may be produced.

HYPOINVERSE is driven by user commands. The various commands define input and output files, set adjustable parameters, and locate a file of earthquake data using the parameters and files currently set. It is both interactive and "batch" in that commands may be executed either from the keyboard or from a file. The user may either supply parameters on the command line, or omit them and be prompted interactively. The current parameter values are displayed and may be taken as defaults by pressing just the RETURN key after the prompt. This makes the program very easy to use. Combining commands with and without their required parameters into a command file permits a variety of customized procedures such as automatic input of crustal model and station data, but prompting for a different phase file each time.

All commands are 3 letters long and most require one or more parameters or file names. If they appear on a line with a command, character strings such as filenames must be enclosed in apostrophes. The appendix gives this and other free-format rules for supplying parameters. When several parameters are required following a command, any of them may be omitted by replacing them with null fields (see appendix). A null field leaves that parameter unchanged from its current or default value. When you start HYPOINVERSE, default values are in effect for all parameters except file names.

If a file called "HYPINST." is in your current directory, it is read as a startup command file by HYPOINVERSE. It may be used to set your own default values, read station or crust model files that you always use, etc. You may then enter commands directly or transfer control to other command files to do specific jobs.

If you are running HYPOINVERSE on the Menlo Park VAX 11/785, put the following line in your LOGIN.COM file:

```
$ HYP :== RUN WE:[KLEIN.HYP]HYP.EXE
```

and run the program anytime by typing HYP.

To find out the maximum sizes of the various arrays the program uses for stations, phases etc. use the MAX command. If there are too many stations ("phase cards") in an event and archive output is being generated, the excess phase data is copied to the output file without any processing and with the calculated fields left blank. Another version of the program called HYPBIG and located in the same directory is identical to HYP but has larger arrays for station and phase data. The larger version may run more slowly on a busy or small computer and should only be used when needed.

The current maxima (array limits) of various data types are:

	HYP	HYPBIG
Number of stations in station file	1000	2200
Number of stations (phase cards) per event	500	700
Number of phases (P or S) per event	520	720
Number of homogeneous layer crustal models	24	
Number of linear gradient crustal models	24	
Number of layers per crustal model	20	
Number of nodes for model regionalization	55	
Characters in input shadow records	92	
Summary shadow records in input archive format	4	
Number of unknown (fictitious) stations:		
Number of 4-letter codes allowed in a run	10	
Number of 5-letter codes per event	25	

SPECIFYING CRUSTAL VELOCITY MODELS

The simplest case HYPOINVERSE handles is one crustal model and set of station delays used for all epicenters and all stations. HYPOINVERSE also allows considerable complexity of multiple velocity models. In any model, velocity varies only with depth. Many (see above) models may be used, each assigned to epicenters in different areas. Smooth transitions between adjacent models is accomplished by defining transition regions within which weighted averages of travel times, travel time derivatives and station delays for 2 or 3 different models are used. A weighted average of emergence angles is also calculated, but not used in the hypocenter solution.

The geometry of assigning models to different areas consists of a list "nodes" or points on a map. Each node is assigned to a model along with the radius of a circle within which that model is used. Several nodes may be assigned to the same model, and if so the circles may overlap. It is thus possible to define an irregularly shaped region as the union of several circles.

If an epicenter lies within the inner circle surrounding any node, that model is used exclusively. An outer circle must also be defined for each node which describes how far out its influence extends. If an epicenter lies between inner and outer circles, it receives a partial "weight" for that model. The weight is a smooth cosine taper between inner circle (weight 1) and outer circle (weight 0). Each node is tested to see if the epicenter lies within its outer circle, but testing stops when the epicenter is found inside 3 outer circles. If the weights total more than 1.0, they are normalized to 1.0. If they total less than 1.0, the difference is made up using the default model (model number 1) such that the weights always total 1.0. If the epicenter lies outside all circles, the default model is used exclusively. The mix of models is determined on each iteration and the epicenter may migrate from one model to another.

Each crustal model is read separately with a CRH or CRT command. This associates each model with a number and a 3-letter code (the beginning of the model name). This 3-letter code labels the model in all of the output files. Each model has its own set of station delays. The DEL command reads a file containing station codes and the set of delays on the same line as the station code. The user must be certain the delays for each model are in order and correspond to the model number assigned when the crustal files are read. Aside from this step, models are labeled by 3-letter codes and not their number. Each node is defined by a NOD command. The MUL command is used to select either single model or multiple model modes and to define the default model.

HYPOINVERSE also has an alternate model capability permitting the use of different models by different stations for the same hypocenter. To use this feature, read in two models using any two model numbers. Then use the ALT command to designate the numbers of the primary and alternate models. The station file must designate which stations use the alternate model. Alternate models may be used with or without the multiple model feature. If you use both together, be sure to designate the primary and not the alternate model number in the NOD commands. Several different models may have alternates, but the same set of stations must use alternate models in all cases.

Models may be of two different types which are stored and calculated differently. The simplest is the homogeneous layer model, which calculates travel times directly from the velocity structure. The second model type uses layers with linear velocity gradients, but requires that a travel time table be generated by the program TTGEN. The table need be generated only once, and HYPOINVERSE uses it very efficiently by merely interpolating from it to get all travel times and derivatives. Tests on the VAX computer show that using a travel time table requires about 60% of the CPU time used with layer models. Use the CRH command to read homogeneous layer models and CRT for reading gradient (travel time table) models. The two model types may be used simultaneously.

Homogeneous layer models

Each model may consist of up to 20 homogeneous layers including the halfspace. Velocity must increase with depth. Use the CRH command to specify the model number and the name of the file containing the homogeneous layer model. The CRH command also reads the model into memory. For example:

CRH 2 'CRUST2.CRH'

The format of the crust model file (CRUST2.CRH in the example) is:

Line 1:	(A30)	Model name.
Lines 2 and later:	(2F5.2)	Velocity of layer and depth to its top.

The first 3 letters of the model name are used as the model code that appears in the print, summary and archive outputs. Use one line per layer, top layer first. The depth to the top of first layer must be 0.0, and the last layer is the halfspace.

Linear gradient models using a travel time table

An alternative and more computationally efficient way to compute travel times is by interpolation within a table generated prior to running HYPOINVERSE. Use of a table permits more complex travel time calculations, such as linear velocity gradients within layers and capacity for a buried low-velocity zone. The travel time table must be calculated and written to a file prior to locating earthquakes using the program TTGEN. For instructions on using TTGEN, see the appendix.

A travel-time table may be calculated for a velocity-depth function consisting of from 2 to 10 points at which the velocity and depth are specified. The velocity is then assumed to be linear between points, ie., with a uniform gradient within layers. Several restrictions apply to the possible models (see also the 1978 HYPOINVERSE report). (1) No two velocity-depth points may be at the same depth (a sharp velocity discontinuity is not allowed). Discontinuities may be modeled using thin layers with high gradients, but the transition layer should be thick enough that one or two rays used to generate the travel time table will bottom within the layer and define a reverse branch of the travel time curve. (2) The depth of the first point must be 0.0, and other points must be given in increasing order of depth. (3) The last (deepest) point sets the velocity of the homogeneous half space assumed to underlie the model. (4) The halfspace velocity must be the greatest of any specified to insure that rays can be refracted along the top of the halfspace. (5) One buried low-velocity zone is permitted in each model, ie. velocity may not decrease with depth except for one group of adjacent layers. (6) Homogeneous layers may be specified by assigning the same velocity to two adjacent points.

Use the CRT command to specify the model number and the file name containing the travel time table to be assigned to that model. The CRT command also reads the model into memory. The first 3 letters of the model name (as originally assigned before running TTGEN) are used as the model code for labelling output. For example:

CRT 1 'MODEL1.CRT'

Reading crust model files is more efficient if they are read in binary instead of ASCII. You may create a binary crust model file after reading in all crust model data including the multiple model parameters. Use the WCR command to write a snapshot of the crust model arrays to a binary file. Read the file back in with the RCR command. The RCR command replaces the CRH, CRT, MUL, ALT and NOD commands. Tests on the VAX show that binary reads using the RCR command are at least five times faster than equivalent ASCII reads.

SPECIFYING THE STATION LIST AND USE OF STATION DELAYS, ATTENUATION HISTORY AND MAGNITUDE CORRECTIONS

Specify the file containing names, coordinates and other station data using the STA command. For example:

STA '1984.STA'

The station data is read into memory as soon as this command is given, and is kept until another STA command is issued. The station file must contain one line per station. Use the H71 command to select either HYPOINVERSE or HYPO71 file format.

Reading station files is more efficient if they are read in binary instead of ASCII. You may create a binary station file after reading in all station data including the multiple model delays. Use the WST command to write a snapshot of the station arrays to a binary file. Read the file back in with the RST command. The RST command replaces the STA and DEL commands. The RST command does not replace the XMC or FMC commands to read magnitude corrections. If used, the XMC and FMC commands must be given after RST. The RST command does not replace the ATE command to manage attenuation histories. If read from the station card with the STA command, a calibration factor is written to and read from the binary file. The calibration history and expiration dates are not written to the binary file. If you are using attenuation histories, issue the ATE command after RST to read and dynamically update attenuations. Tests on the VAX show that binary reads using the RST command are several times faster than equivalent ASCII reads.

Station delay file

The HYPOINVERSE station file format holds two delays for models 1 and 2 (the HYPO71 format holds one delay). If you need more than the number of delays on the station card for use with multiple crustal models (see preceding section), you must read station delays from a separate delay file using the the DEL command. Each line of the delay file has the station code and a series of delays which must correspond to the crustal models read in with the CRH and CRT commands. The alternate model code for stations may either be in the station file or the delay file or both. A station becomes an alternate if so designated in either file. It is more sensible to tag alternate stations in the delay file so that it contains all of the model-dependent station data. To simplify the delay file without losing any generality, the delays for a model and its alternate should be the same.

The format of the delay file is:

Cols.	Format	Data
1-4	A4, 2X	First 4 letters of station code. The component (5th letter) is not used so that delays are matched to all components.
7	A1	Put an "A" here to use alternate models with this station.
8-	31F4.2	P delays for each model in order of model number.

You must read in the station list using the STA command before reading delays with the DEL command. The station file contains the ones you will use for locations and the STA command reads these into memory. The delay file may contain any set of stations: delays for stations already in memory will be used and those for a station not in the station file will be ignored. The delay file may thus be a master list containing all known delays and in any order. Delays for a station in the station file but not the delay file will have delays 3 and above set to zero.

The first 4 letters of the station codes are used to associate stations in the station and delay files. In USGS practice, the first 4 letters designate the site and the 5th is the component. The delay file thus needs only one entry per station site, and the DEL command will automatically associte the delay with all components at that site.

Station attenuation files

There are four options for specifying station gain information for use in calculating amplitude magnitudes or correcting coda magnitudes: 1) put the calibration factor in the station file to use for the whole location run; 2) specify the pre-amp attenuation in place of the station calibration factor on the station card (see the ATN command); 3) put calibration factors on the phase card to use only for that event and override that on the station card if present; or 4) read the attenuation history from a separate file and extract the data for any given date (see the ATE command).

Using a separate station attenuation file insures that the correct gain information will be used for each station on the date of the earthquake. Each attenuation has an associated expiration date. When an event is being processed whose date is after the attenuation's expiration date, HYPOINVERSE rereads the attenuation file and uses the updated attenuation. The attenuation file has one station per line. Unlike the delay file, 5-letter station codes are supported because the attenuation depends on the component (5th letter in USGS practice). The line consists of a station code followed by pairs of attenuations and their expiration dates. The last attenuation must have its expiration date left blank or set to zero to indicate that it applies into the future. A station may have at most 7 attenuations. If the attenuation for a station never changed, the line consists only of the station code and one attenuation. The attenuation is in db and is a multiple of 6 (0, 6, 12...60).

The relation between CAL factor and attenuation setting is

log(CAL) = -0.05*atten + 1.35

ATTEN:	0	6	12	18	24	30	36	42	48	56
CAL:	22.44	11.22	5.62	2.82	1.41	0.708	0.355	0.178	0.0891	0.0355

The format of the attenuation history file is:

Cols.	Format	Data
1-5	A5, 1X	Station code including component.
7-8	I2, 1X	First attenuation setting. Must be a multiple of 6 db.
10-19	5I2, 1X	Y, M, D, H, M expiration date of first attenuation. Leave the expiration of the last attenuation blank to indicate no expiration.
21-22	I2, 1X	Second attenuation.
24-33	5I2, 1X	Second expiration date.
		Format repeats: 7(I2, 1X, 5I2, 1X)

You use the ATE command to read the station attenuation file. The phase data file _must_ be in chronological order to insure getting correct attenuations. You _must_ read your station file (using the STA command) _before_ the attenuation file (with the ATE command) because HYPOINVERSE stores attenuations only for the stations already read into memory. This means that the attenuation file can contain the history of the entire network and only the data needed will consume space in HYPOINVERSE. The filename given with the ATE command is read both when the ATE command is given and as necessary to update an attenuation. The ATE command also asks for a date and time for which to load the initial attenuations. If you use the date of the first earthquake you wish to locate, HYPOINVERSE won't have to waste much time rereading the attenuation file. If you specify a year of 0, HYPOINVERSE loads the earliest attenuation for each station. This will require more updates from the attenuation file but will not require knowing the date of the first event.

Station magnitude correction files

HYPOINVERSE calculates independent coda and amplitude magnitudes and can use separate corrections for each. There are two options for specifying station magnitude corrections: 1) put the magnitude correction in the station file to use for the whole location run; or 2) read the magnitude corrections from a separate file and extract the data for stations already in memory. The amplitude magnitude corrections are fixed for all events in the location run. Duration magnitude corrections, however, may vary with time because some critical instrumentation changes may not be reflected in the attenuation history. The XMC command reads the amplitude magnitude corrections and FMC reads the duration magnitude corrections for a specified date.

The handling of duration magnitude corrections is very similar to that for station attenuations. Using a separate magnitude correction file insures that the correct information will be used for each station on the date of the earthquake. Each FMAG correction has an associated expiration date. When an event is being processed whose date is after the correction's expiration date, HYPOINVERSE rereads the file and uses the updated correction. Both FMAG and XMAG correction files have one station per line. Unlike the delay file, 5-letter station codes are supported because the magnitude correction depends on the component (5th letter in USGS practice).

The file consists of a station code followed by pairs of FMAG corrections and their expiration dates. The last FMAG correction must have its expiration date left blank or set to zero to indicate that it applies into the future. A station may have at most 6 FMAG corrections and one XMAG correction. If the FMAG correction for a station never changed, the line consists only of the station code and one correction. Use the FMC command to read the FMAG correction file. The phase data file <u>must</u> be in chronological order to insure getting correct FMAG corrections.

The format of the duration magnitude correction file is:

Cols.	Format	Data
1-5	A5, 1X	Station code including component.
7-11	F5.2, 1X	First FMAG correction.
13-22	5I2, 1X	Y, M, D, H, M expiration date of first FMAG correction. Leave the last one blank to indicate no expiration.
24-28	F5.2, 1X	Second FMAG correction.
30-39	5I2, 1X	Second expiration date. Format repeats: 6(F5.2, 1X, 5I2, 1X)

The amplitude magnitude correction file may have only one value per station. The value applies to all events in the location run. The file also contains the instrument type (USGS short period or Wood-Anderson). It is important to give the instrument type here because the value in the XMAG correction file overwrites the instrument type read from the station file. Leaving the instrument type blank is the same as specifying a Wood-Anderson (type 0). Use the XMC command to read the XMAG correction file.

The format of the amplitude magnitude correction file is:

Cols.	Format	Data
1-5	A5, 1X	Station code including component.
7	I1, 1X	Instrument type code. Overwrites code from col. 60 of station card.
9-13	F5.2	XMAG correction.

You <u>must</u> read your station file (using the STA command) <u>before</u> the magnitude correction files because HYPOINVERSE stores corrections only for the stations already read into memory. This means that the magnitude correction file can contain the history of the whole network and only the data needed will consume space in HYPOINVERSE. The filename given with the FMC command is read both when the FMC command is given and as necessary to update a correction. The FMC command also asks for a date and time for which to load the initial FMAG corrections. If you use the date of the first earthquake you wish to locate, HYPOINVERSE won't have to waste much time rereading the file. If you specify a year of 0, HYPOINVERSE loads the earliest FMAG correction for each station.

This will require more updates from the FMAG correction file but will not require knowing the date of the first event.

Other station comments

The relationships used in handling arrival times and delays are as follows:

TOBS = SEC + CCOR - OT
RES = TOBS - TCAL - DLY

where

SEC = observed arrival time
CCOR = clock correction
OT = origin time
TOBS = observed travel time
TCAL = calculated travel time
DLY = station delay
RES = travel time residual

To accomodate the new practice of 5-letter station codes, HYPOINVERSE now matches station and phase cards using either 4 or 5 letters. For information on 5-letter codes see Klein et al. (F.W. Klein, J.P. Eaton and F. Lester, Seismic station data for Northern California and surrounding areas, U.S.G.S. Open File Report 88-448, 1988). The 5th character (as used by Calnet) is the component (E, N, V etc.) and is in col. 9 of the phase card, col. 32 of the HYPOINVERSE station card, and col. 1 of the HYPO71 station card. See the format tables below. Select 5-letter codes by answering T to the ST5 command (the default). If you use 4-letter station codes, answer F to the ST5 command. Phase and station cards will then be matched using the first 4 letters of the station codes.

Use the H71 command to select either the HYPOINVERSE or HYPO71 station format. Some fields of the HYPOINVERSE format such as the second P delay, alternate crust model code and magnitude weights are not used in the HYPO71 format.

If a station is found in the phase but not the station file, an error message will normally go to the terminal and print file. This message may be suppressed for a certain list of stations. These could include fictitious "stations" such as those holding time code or other data. Use the UNK command to set the list of 4-letter codes (or the first 4 of the 5-letters) for which you want no error message. All phase data for unknown stations is saved in a separate area and will be archived at the end of the event in the output ARC file, but will not be listed in the print file.

The HYPOINVERSE station data format

Cols.	Format	Data
1-4	A4	Station name code. The first character may not be a number or the $ character. See also col. 32.
5	A1	Station weight code (in units of 0.1) by which the weights assigned each P & S phase are to be multiplied. Use the digits 0-9 for the weight in tenths; "*" or "0" for no weight; or any other character (including blank) for full weight.

6-7	I2, 1X	Latitude, degrees.
9-13	F5.2	Latitude, minutes.
14	A1	N or blank for north latitude, S for south.
15-17	I3, 1X	Longitude, degrees.
19-23	F5.2	Longitude, minutes.
24	A1	W or blank for west longitude, E for east.
25-28	4X	Reserved for elevation in m. Not used by HYPOINVERSE.
29-31	F3.1	Default period (in sec) at which the maximum amplitude will be read for this station. If period is given on phase card, it overrides this value.
32	A1, 1X	Optional 5th letter of station name code. Must match phase cards if used.
34	A1	Put a "2" or "A" here to designate this as an alternate crust model station. Both alternate and primary crustal models must be in use. Stations may also be tagged for use with an alternate model in the delay file.
35	A1	Optional station remark field to copy to print output.
36-40	F5.2, 1X	P delay (sec) for delay set 1.
42-46	F5.2, 1X	P delay (sec) for delay set 2.
48-52	F5.2	Amplitude magnitude correction. If in the range ± 2.4, the correction is included (by addition) in the amplitude magnitude, If you don't want a station's magnitude used in the event magnitude, use a correction of 5.0 plus the actual correction or assign a zero weight (see below).
53	A1	Amplitude magnitude weight code. Codes 0-9, "*" and blank are the same as the P & S weight codes. The actual weight used is the product of those on the station and phase cards.
54-58	F5.2	Duration magnitude correction (works the same as the amplitude magnitude correction).
59	A1	Duration magnitude weight code (works the same as the amplitude weight code).
60	I1	Instrument type code for this station used to select the appropriate response curve to derive an equivalent Wood Anderson amplitude. Must be either 0, 1 or 2: 0: Standard Wood-Anderson torsion seismograph. 1: USGS standard (1 HZ geophone, .7 critical damping.) 2: Hawaii-type Sprengnether seismometer.
61-66	F6.2	Calibration factor for amplitude magnitudes, equal to the peak-to-peak amplitude of a 10 microvolt RMS signal at 5 hz applied to the VCO and measured in mm on the Develocorder film viewer. For instrument types 0 and 2 this should generally be 1.0. A cal factor of 0.0 signifies an unknown response for which no amplitude magnitudes will be computed. If a cal factor is given on a phase card it overrides this value. The VCO attenuation

may be given in place of the cal factor (see the ATN command). An entire history of station attenuations with the dates of attenuation changes may be read from a separate file with the ATE command.

The HYPO71 station data format

Cols.	Format	Data
1	A1	Optional 5th letter of station name code. Must match phase cards if used.
2	A1	Station weight (in units of 0.1) by which the weights assigned each phase are to be multiplied. Use * or 0 for no weight, 1-9 for the partial weights 0.1 to 0.9, or leave blank for full (1.0) weight.
3-6	A4	4-letter station name code. The first character may not be a number. See also col. 1.
7-8	I2	Latitude, degrees.
9-13	F5.2	Latitude, minutes.
14	A1	N or blank for north latitude, S for south.
15-17	I3	Longitude, degrees.
18-22	F5.2	Longitude, minutes.
23	A1	W or blank for west longitude, E for east.
24-27	4X, 1X	Reserved for elevation in m. Not used by HYPOINVERSE.
29-33	F5.2, 1X	P delay (sec) for delay set 1.
35	A1, 2X	Optional station remark field to copy to print output.
38-42	F5.2, 2X	Duration magnitude correction. If in the range ±2.4, the correction is included (by addition) in the duration magnitude, and the result averaged with other stations to get the event magnitude. If you don't want a certain station's magnitude included in the average, use a correction of 5.0 plus the actual correction.
45-49	F5.2, 1X	Amplitude magnitude correction (see above for range etc.).
51	I1, 1X	Instrument type code for this station used to select the appropriate response curve to derive an equivalent Wood Anderson amplitude. Must be either 0, 1 or 2: 0: Standard Wood-Anderson torsion seismograph. 1: USGS standard (1 HZ geophone, .7 critical damping.) 2: Hawaii-type Sprengnether seismometer.
53-56	F4.2, 1X	Default period (in sec) at which the maximum amplitude will be read for this station. Must be in the range 0.1 to 1.9 inclusive. Specifying a period on the phase card overrides this value.
58-63	F6.2	Default calibration factor for amplitude magnitudes, equal to the peak-to-peak amplitude of a 10 microvolt RMS signal at 5 hz applied to the VCO and measured in mm on the Develocorder film viewer. For instrument types 0 and 2 this should generally be 1.0. A cal factor of 0.0 signifies an unknown response for which no amplitude magnitudes will be computed. The cal factor must be between 0 and 49.9 inclusive. Specifying a cal factor on

the phase card overrides this value.

PHASE DATA INPUT FORMATS

The name of the input phase data file is specified with the PHS command. The LOC command starts locating events. For example:

```
PHS '1983.PHS'
LOC
```

The file may contain any number of earthquakes. Phase data may be in one of several formats (see the COP command). All formats require a terminating line after each event. The terminating record may be all blank or may contain trial hypocenter data or an ID number. Each station may report any or all of (1) P time, (2) S time, (3) amplitude or (4) coda duration. An arrival time will not be recognized and processing will continue if any of the following are true:

1) The remark field ("IP" or "ES") is blank. (If the S remark is blank but the the S time is non-blank, the reading will be used.)
2) The station is not in the station file.
3) The phase line is incomprehensible or in a bad format.

In addition, data in traditional USGS format are rejected if:

4) The year, month & day do not agree with the first station read.
5) The P arrival time differs by more than 4 minutes from the first station (S times are not checked).

In addition to the traditional (full) and condensed phase formats, HYPOINVERSE archive output may optionally be read back in as input. Another option is the "shadow" format where <u>every</u> input line (phase, archive and terminator cards) are followed by a line with up to 90 bytes of data. The shadow record will carry data such as a series of coda amplitudes. The input shadow record will be copied to the archive output if shadow records are also selected for output. The summary headers in archive files may have from 1 to 4 shadow cards and each must begin with the $ character. CUSP input is not an ASCII format but invokes a series of database calls which read a binary "MEM" file. The format choices with the COP command are:

1 Traditional (full) phase format. (The default)
2 Condensed format (ASCII).
3 Archive format generated in an earlier HYPOINVERSE run.
4 Shadow phase format with a 1-line header and a record after each card.
  (This format is obsolete and is PHASEOUT's HYPO71 shadow option)
5 Archive format with shadow records.
  (This format is compatible with the PHASEOUT program's HYPOINVERSE option)
6 Locate one CUSP event, CUSP-ID number given with LOC command.
7 Locate several CUSP events, ID numbers given in a file.

The CAR archive output format command also supports shadow format. Shadow records on input and output may be selected independently of each other. If you select shadow output but not input, an empty record will appear after every output record. Note that COP 5 and CAR 3 are compatible formats. The CAR choices are:

1 Full archive format. (The default) (corresponds to COP 3 input format)
2 Condensed format. (corresponds to COP 2 input format)

3 Shadow format. (corresponds to COP 5 input format)

<u>The traditional USGS phase data input format</u>

Several data fields are read in places unused in the original HYPO71 format.

Cols.	Format	Data
1-4	A4	4-letter station name code. See also column 9. Must agree exactly (upper/lower case, position of blanks, etc.) with name in station file. May not be all blank, and may not begin with a number.
5-6	A2	P remark such as "IP". If blank, any P time is ignored.
7	A1	P first motion such as U, D, +, -, C, D. The number of non blank fields in an event are counted and output.
8	I1	Assigned P weight code: 0 or blank = full weight, 1= 3/4 weight, 2= half weight, 3= 1/4 weight, 4-9 = no weight.
9	A1	Optional 5th letter of station name. Must match 5th letter on station card if 5-letter names were selected with the ST5 command.
10-19	5I2	Year, month, day, hour and minute.
20-24	F5.2	Second of P arrival.
25	A1	Any non-blank character here gives P & S times zero weight
26-31	6X	Reserved remark field. (Calnet uses 26-28 for data source and 29-31 for recording device). This field is not copied to the archive output file.
32-36	F5.2	Second of S arrival. The S time will be used if this field is non-blank.
37-38	A2, 1X	S remark such as "ES".
40	I1	Assigned weight code for S. See P weight codes.
41	A1, 3X	Data source code. This is copied to the archive output.
45-47	F3.0	Peak-to-peak amplitude in mm on Develocorder viewer screen or paper record.
48-50	F3.2	Optional period in seconds where amplitude is read on the seismogram. If blank, the standard period on the station card is used.
51	I1	Amplitude magnitude weight code. Same codes as P & S.
52-54	3X	Amplitude magnitude remark (presently unused).
55-58	I4	Optional event sequence or ID number. This number may be replaced by an ID number on the terminator card, but is not output to the summary file.
59-62	F4.1	Optional calibration factor to use for amplitude magnitudes. If blank, the standard cal factor on the station card is used.
63-65	A3	Optional event remark. Two 1-letter event remarks may be derived from this 3-letter remark and output to the summary file. The first two 3-letter remarks in the input

		series of phases will, if they match one on a preset list, be abbreviated to the two final event remarks. In the following _ is a blank and # is any character. The preset remark list now consists of: "FLT" & "F__" (becomes F, felt); "TRM" & "T__" (becomes T, tremor associated); "LP#" (becomes L, long period); "BLS" (becomes B, quarry blast); "Q##" or "*##" (becomes Q, quarry blast); or "NTS" (becomes N, NTS shot).
66-70	F5.2	Clock correction to be added to both P and S times.
71	A1	Station remark. Unused except as a label on output.
72-75	F4.0	Coda duration in seconds. Negative or zero values are interpreted as no data.
76	I1	Duration magnitude weight code: 0 or blank = full weight, 1= 3/4 weight, 2= half weight, 3= 1/4 weight, 4-9 = no weight. The actual weight is the product of those on the station and phase cards. (Note that ignoring weight codes is an option with the MAG command).
77	1X	Reserved.

Condensed phase data input format

The condensed format is requested with the command "COP 2". Like the traditional format, the condensed format requires one line per station and a normally blank terminator line. Unlike the traditional format, a header giving the date & time is required, and a separate station line is required for each P time, S time, and amplitude. The coda duration may be on any line, and is right after the time or amplitude. Thus multiple lines with the same station name may be present. If you group all the entries for the same station together, the data will be attributed to one station as if entered on a single line in traditional format. This uses memory most efficiently.

HYPOINVERSE may optionally produce archive output in condensed format (see the ARC and CAR commands). The condensed archive format may also be read as condensed phase format. Since input phase and output archive formats are set independently, HYPOINVERSE may be used to condense phase data.

The first line of each event in condensed format must be a header containing date and time. The rule is that the P and S times at individual stations are added to the reference time on the header to get actual arrival times. Thus if the reference seconds field is blank (zero), the individual times refer to seconds within the reference minute. If the reference second is the event origin time, the individual times are actually observed travel time residuals. A HYPOINVERSE summary record is an acceptable header in which only the date and time fields are read. The format of the header is:

Cols.	Format	Data
1-10	5I2	Reference year, month, day, hour and minute.
11-14	F4.2	Reference second (optional). If blank, second is 0.0.

The format of each station line is:

Cols.	Format	Data
1-4	A4	Station name. Must agree exactly (upper/lower case, position of blanks, etc.) with name in station file. May not be all blank, and may not begin with a number.

14-17	F4.0	Optional coda duration in seconds.

The format of cols 5-13 depends on the letter (P, S, or A) in col 6:

<u>P time:</u>

5-6	A2	P remark such as "IP". An uppercase P must be present in col 6.
7	A1	P first motion such as U, D, +, -, C, D. The number of non blank fields in an event are counted and output.
8	I1	Assigned P weight code: 0 or blank = full weight, 1= 3/4 weight, 2= half weight, 3= 1/4 weight, 4-9 = no weight.
9-13	F5.2	Second of P arrival relative to reference time (the observed travel time if the reference second is the origin time).

<u>S time:</u>

5-6	A2, 1X	S remark such as "ES". An uppercase S must be present in col 6.
8	I1	Assigned S weight code.
9-13	F5.2	Second of S arrival relative to reference time.

<u>Amplitude:</u>

6	A1	Must be the uppercase letter A.
9-13	F5.2	Peak-to-peak amplitude in mm on Develocorder viewer screen or paper record. Use the form "XXXX." to input a large integer.

<u>The terminator line (all ASCII formats)</u>

One terminator line must follow each event. If the line is blank, a standard trial hypocenter is used: it is at the standard trial depth beneath the station with the earliest time, at an origin time two seconds before the earliest time. Trial values for any or all of depth, latitude, longitude or origin time may be specified on the terminator line. If a trial value is absent, the standard value is used. To specify a trial origin time, you must give hour, minute and second. To specify a trial latitude or longitude, you must give degrees and minutes. A terminator which is a HYPO71-style instruction card and is blank except for columns 18-19 is a valid terminator, but the instruction parameter will have no effect. To fix the depth for one event only, make the trial depth negative. To fix the depth for all events, set the default trial depth negative.

You may also use the hypocenter on the event header as a trial if you are reading the archive or shadow formats (COP 3, 4, or 5). You do this by choosing terminator format 3 with the H71 command. COP formats 3 and 5 expect the header in HYPOINVERSE format, format 4 expects the header in HYPO71 format. Using the previous location as a trial hypocenter may not reduce the number of iterations required or shorten the location run. That is because several iterations may be required before distance and residual weighting are invoked. As iteration proceeds, you may thus find that the hypocenter starts at its trial location, iterates away, then returns to the trial location after all weighting takes the same effect it had to produce the earlier location.

An optional 10-digit ID number may be supplied in columns 63-72 (a right justified integer) of the terminator card. It will appear in the print and archive outputs, but not the summary output. In Menlo Park, the PHASEOUT program puts the CUSP-ID number here.

Terminator (trial hypocenter) format

Columns 1-4 must be blank. Use the H71 command to select either HYPOINVERSE or HYPO71 terminator formats, or to get the trial hypocenter from the header if reading either archive or shadow format. If all terminator lines are blank, it does not matter which format is used. Either format may be used to enter a trial depth or to fix depth, but only the HYPOINVERSE format allows a trial epicenter or origin time on the terminator card.

HYPOINVERSE Terminator format

Cols.	Format	Data
1-4		Must be blank.
7-10	2I2	Trial hour and minute.
11-14	F4.2	Trial second.
15-16	F2.0, 1X	Trial latitude (deg).
18-21	F4.2	Trial latitude (min).
22-24	F3.0, 1X	Trial longitude (deg).
26-29	F4.2	Trial longitude (min).
30-34	F5.2	Trial depth (a negative value fixes depth).
63-72	I10	Optional ID number.

HYPO71 terminator format

Cols.	Format	Data
1-4		Must be blank.
19	I1	To fix depth, either put a 1 here or make trial depth negative.
20-24	F5.2	Trial depth.
63-72	I10	Optional ID number.

Reading earthquakes directly from CUSP "MEM" files

HYPOINVERSE now locates earthquakes directly from CUSP "MEM" files. There is one MEM file per event whose name contains the CUSP-ID number (i.e. X100229.MEM). You need not be in a CUSP environment or be on a computer supporting CUSP, but you must define one name before running HYPOINVERSE: on the Menlo Park VAX 785 type DEFINE EVENT_DDL "WE:[KLEIN.HYP.CUSP]EVENT.DDL" and on the 750 type DEFINE EVENT_DDL "DRAO:[CUSP.DBMS]EVENT.DDL".

HYPOINVERSE locates events given their CUSP-ID numbers which are supplied in one of two ways: (1) type in the CUSP-ID numbers and locate events one at a time; or (2) provide a file listing the CUSP-ID numbers of the events to locate. You may use the latter to locate all the MEM files in a directory by making a directory listing to a file before running HYPOINVERSE (see below). There is now a substantial list of limitations to the CUSP capability which should improve in the future:

- Coda durations are presently not read and no magnitudes result.

- Station data must be read from an external file as before (using STA).

- Hypocenters and other calculated data cannot be put back into CUSP files.

- HYPOINVERSE cannot presently get instructions from the CUSP scheduler.

- HYPOINVERSE must be run in the directory containing the MEM files. As before, however, all other input and output files set in HYPOINVERSE may contain pathnames to other directories.

- At present, locating events from MEM files is noticably slower than reading ASCII phase files. Some speed gains within HYPOINVERSE will be possible, but the overhead in making database calls and sifting through unwanted information may always be more than reading ASCII files.

- CUSP MEM files are several times larger than an equivalent ASCII phase file because they contain seismogram data and entries for traces which were not picked. Of course you need not have your own copy of each MEM file.

CUSP data is treated like another input format selected with the COP command. Use COP 6 to locate one event at a time by CUSP-ID number. In this mode the number is supplied with the LOC command (i.e. LOC 100229). If you just type LOC, you will be prompted for the ID number. You must have read in a station and crust model file, and define other parameters as before. In this single event mode, any phase file specified will be ignored.

You may process a series of events by supplying a file listing their CUSP-ID numbers. Select this CUSP list option with the COP 7 command and specify the file containing the list with the PHS command. The file may only have one CUSP-ID per line, but HYPOINVERSE will ignore any lines containing a blank field or spurious text. The number should be right-justified. Use the new FID command to specify the format for reading the list file (the default is FID '(I10)'). If you want to locate all of the MEM files in a directory, type DIR/COL=1/OUT=CUSPLIST. *.MEM before running HYPOINVERSE. In HYPOINVERSE, use the commands COP 7, PHS 'CUSPLIST.' and FID. If all of the CUSP-ID's are 6 digits, use FID '(1X,I6)'. If you have a mixture of 5 and 6 digit numbers, you will have to edit the file to get a field with only right-justified numbers in it. Locate all the events with the LOC command.

<u>Input of new phase data from the keyboard</u>

If you do not have files of phase data, HYPOINVERSE has a utility to input arrival time data from the keyboard and write a condensed phase file in condensed format which can subsequently be located. The phase data may come from a reading sheet or other external source. The phase data input utility is invoked with the INP command (no arguments). You must be prepared with a small file containing a list of up to 100 station names (see below). You will be prompted for data from these stations, and will not have to enter station names. The input utility is mostly self-explanatory and prompts for the data and decisions it needs. A description of its operation follows.

The input utility first asks for the filename to which phase data will be written. If an existing file is named, any data there is appended to. If a file called "STALIST." is present in the current directory, it is read for the list of station names to prompt for on each event. If the file "STALIST." is not present, another filename is requested and must be given. The prompting list of stations is a convenience: data for other stations may be entered, but the unlisted station name must be given along with each datum. Also, data need not be entered for every station in the prompting list. Responding with just a RETURN goes on to the next station in the list. Stations reporting data for most events should therefore be listed for the most efficient operation. The "STALIST." file also controls whether S-times, amplitudes and durations are routinely requested for certain stations in addition to the P-times for all stations.

The format of the station prompting file is:

Cols.	Format	Data
1-4	A4	Station name. A P-time will be requested for all stations.
5	A1	If non-blank, prompt for an S-time for this station.
6	A1	If non-blank, prompt for an amplitude for this station.
7	A1	If non-blank, prompt for a duration for this station.

Next, the phase data input utility asks whether you want to input full arrival time remarks, first motion and weight ("IPU1", "ES_3", etc.). Pressing RETURN to either this initial question or a remark prompt for an individual station (if you answered "Y" to the initial question) simply produces a remark of "_P__" or "_S__" with full weights.

The following prompts and entries are made for each event you wish to input: (1) Enter the event date and time. For the second and later events, pressing RETURN to a prompt for year, month, day, hour or minute gets the default, which is that of the prior event. (2) Prompts will be made for each station on the prompt list. The P-time is entered first, followed by duration, S-time, and amplitude if you requested prompts for them. If you chose to enter full remarks and weights, prompts for these will precede those for each P and S time. (3) When the preset station list is complete, you will be asked if you want to enter another P or S time. If yes, you must enter station name, full remark (which will determine whether this a P or an S) and weight, and the time. The minimum remark you may enter is either "_P" or "_S". (4) You will then be asked for a duration and amplitude for the previous station. Enter zero if there is none, and input a positive value if there is. (5) When the event is complete, you will be asked whether you want to stop entering data and return to command level. If you answer anything but "Y" or "YES", you will be asked for the date and time of another event which you must complete.

IMPORTANT NOTES: (1) All station names are four letters long. If your station file uses three letter names and right-justifies them, you must include a leading blank in station names you enter. (2) All data identifiers such as P, S, A or C must be uppercase. The case (upper or lower) of station names must agree with that in your station files. (3) All numeric data may be entered in free-format (whole numbers may omit a decimal point, leading zeros are optional, etc.). Alphameric input such as station names and remarks, however, is used exactly as entered. (4) Once you press RETURN, the only way to correct mistakes is by leaving HYPOINVERSE, editing the phase file, and returning to locate the corrected file.

INTERACTIVE EARTHQUAKE PROCESSING

HYPOINVERSE can locate a set of events interactively. You can alter the input data and relocate several times until you are satisfied with an event. HYPOINVERSE does this by stepping automatically through a preset list of events you wish to process. The data for each event must be in separate files, and therefore the computer file system does the necessary updating of files and retrieval of the correct events. The two HYPOINVERSE commands which accomplish this are BAS to establish the file naming you will use and PRO to actually process (locate and edit) the set of events.

The first step requires putting each event you wish to locate in a separate file. The filenames must consist of a base name of 1-20 characters and a suffix of 1-8 characters for each input and output file type. The same base name is used for each input and output file type associated with an event, and each event must have a unique base name. The base names are read as a text string from a file listing all events to be processed. For example, a base name might be 840502133045 and a set of suffixes might be .ARC (input), .ARC (output archive), .PRT (output print) and .SUM (output summary). The filename to read for this event is then 840502133045.ARC. The minimum suffixes required are the input and print files.

A good way to build event files is as follows. First, locate an entire set (a month say) so that you have summary and archive files to work with. Then select the events you want to reprocess. You can use the SELECT program to get a summary file or type the date and time fields (in summary format) into a file. Then run the program EXOCET (similar to EXTRACT) to put each selected event into a separate file. The filenames will be of the form YYMMDDHHMMSS.ARC (like the example above). After reprocessing, these files will be replaced by their revised versions and can be reassembled into one file (in chronological order) using the VAX COPY command. Note that if the origin time of the event changes from the original one during reprocessing, the filenames will always be based on the original origin time. There are two ways to handle the events that will not be reprocessed: If you have a MERGE program, get a file of "rejected" (good) events when you run EXOCET. Later merge the good and repaired files together, and there will be no duplicated events. If you will not use a MERGE program, run EXOCET with "NONE" for a summary file. This will make an individual file for every event. HYPOINVERSE will reprocess only the selected events, and all events can be reassembled with the COPY command. The latter case is more cumbersome because many more files are involved.

The HYPOINVERSE BAS command defines the filenames to be processed interactively. First specify the file containing base file names of events to process. This may either be a summary file or a list of files produced with a VAX command like DIR/COL=1/OUT=filename *.ARC. Also give the number of characters in the base name and format (like A12) for reading the base name. Any blank spaces in the base names will be filled with zeros. Any line beginning with * or blank lines will be skipped. Any lines with an invalid filename will generate an error message but will be skipped over.

The BAS command also requests the filename extensions for the input, archive, summary and print files. If you don't want summary or archive files, specify "NONE" for those names. If your input and archive filenames are the same (my preference), HYPOINVERSE will read back the file it just wrote during interactive processing and all of your edits will be cumulative and saved. If the names are different, you might lose some changes unless they were explicitly made to the input file.

One of the processing steps is the examination of the print output file using the EDT editor. It is best to use a terminal with 132 columns to see all of the file. You can browse through the file and change the P, S and coda weights for the next location try. Any other types of changes must be made to the input file directly. If you choose to locate the event again, the print file will be read <u>after</u> the input file so that any changed weights will override the original ones. Note that weights changed in the print file will be carried to the output archive file. If this file is then read as input (input and archive file suffixes the same), the weight changes will be carried along and not lost.

How to change weights in the print file

(1) Make the change on the line showing the station you wish to change. In identifying stations marked in the print file, HYPOINVERSE uses both the 5-letter code and data source code (in case there are multiple sources for the same station). If the station code is blank on the line you change (as for multiple readings from the same station), it will be inferred from the non-blank line above.

(2) To change a P weight, put a new weight code in column 1.
To change an S weight, put a new weight code in column 8.
To change a coda weight, put a new weight code in column 6.

This example shows the columns read for new weight codes:

```
column:  12345678
              c
              o
weight        d
code:    P    a S
         |    | |
station  V    V V
line:     BCSM VB
```

(3) These are the weight codes currently recognized:

0-9 New 1-digit weight code to replace old one.
- Remove reading by adding 5 to weight code.
+ Restore reading by subtracting 5 from weight code. Partial weight codes (1-3) will be converted to full weight (0).

Flow of steps in interactive processing

(1) Read the base name for a new event and form the input and output filenames. When no base names remain in the file you are done.

(2) Open the event files, locate the event, then close the files. If you have the REP command set to report events to the terminal, you will see a list of the previous tries for this event with the most recent at the bottom so you can compare them and (hopefully) note improvements.

(3) You will then be put in EDT editing the print output file. You may examine the file and change only the P, S and coda weights by putting codes in certain columns. The history of successive location tries is also written to the print file.

(4) If you are satisfied with the event, you can QUIT the editor without saving changesto the print file. If you change weights, you must EXIT the editor to save changes.

(5) You will then get a prompt from the primary branch point within the processing loop. The possibilities and their actions are:

return. This event is OK, go on to next event (step 1 above).
T Relocate the current event. Go to step 6 below.
ZXZ Delete the current event, including all versions of all input and output files. Then return to step 5.

Any other response typed to this prompt will be interpreted as a VAX (DCL) command. You may do any special operation such as delete the most recent version of the archive file to cancel changes you just made (DELETE 800101120030.ARC;0). If you want to stop processing, issue a ctrl-Y at this point.

(6) Relocate the current event. HYPOINVERSE first asks whether you want to edit the input file. This is where you can make any change, such as deleting stations, changing data, flagging quarry shots, etc. When the event is relocated, the input file is read first, then the print file for new weights. Weight changes in the print file thus override those in the input file. Go to step 2 above.

When you finish processing a set of events, delete all of the print files and purge the old versions of the input, archive and summary files because they will not be needed. If you interrupted the processing session without finishing, you can edit the file listing the base names to either remove or comment out the events already processed.

FIXING DEPTH OR HYPOCENTER

HYPOINVERSE offers a few limited options for fixing hypocentral parameters. One option is fixing the depth while solving for epicenter and origin time. This can be done for all events in a run by making the trial depth (set with the ZTR command) negative. Fixing depth can also be done on an individual event basis by using a negative trial depth on the terminator card. To specify a trial depth on the terminator you can't use the condensed phase format or be reading CUSP MEM files directly (use only COP 1, 3, 4, or 5).

You can fix the hypocenter by preventing iterations away from the "trial" hypocenter. You do this by setting the maximum number of iterations ITRLIM to zero with the CON command. Be sure to specify a trial hypocenter and origin time when using 0 iterations. Also be sure to invoke distance and residual weighting on iteration 0 (DIS and RMS commands) because HYPOINVERSE will always iterate until distance and residual weighting begin. All calculations including travel times will apply to your hypocenter. The origin time may shift slightly from your trial value: HYPOINVERSE removes the weighted average station residual from the trial origin time. This minimizes the RMS residual and solves for an origin time and is useful for finding the origin times of known quarry shots, for example. Thus you can never actually fix the origin time in HYPOINVERSE. The calculated travel times are of course independent of the origin time.

Here is a command file fragment to fix hypocenters:

```
CON 0 /          Set ITRLIM to 0
DIS 0 /          Begin distance weighting immediately
RMS 0 /          Begin residual weighting immediately
COP 5            Read shadow format with a summary header
H71 1 3 1        Get the trial hypocenter from the header
```

DURATION (CODA) MAGNITUDES

HYPOINVERSE offers a choice between the traditional duration (F-P) magnitude Md and the recently-derived lapse time (tau) magnitude Mt (C.A. Michaelson, Coda duration magnitudes in Central California, U.S.G.S. Open File Report 87-___, 1987). Both use the same duration, coda, or (F-P) values in columns 72-75 of the phase card. The USGS practice is to determine the end of the coda or "F phase" when the coda decays to 10 mm peak-to-peak on the Develocorder viewer. The lapse-time magnitude adds the P travel time to the duration to get tau. Hypoinverse uses the calculated rather than observed P travel time so that durations can be specified without P times. Tau magnitudes also account for station gain if known. Gain may be expressed on the station card as either a calibration factor or as attenuation in db (positive numbers like 12, 18, etc. See the ATN command). All magnitudes are calculated and output to the print file and magnitude file (see the MFL command) to a precision of 0.01. Magnitudes output to the summary and archive files are to the nearest 0.1.

Choose between magnitude types with the MAG command. You may calculate either type of coda magnitude but not both. Use the DUR command to set the coefficients in the duration magnitude expression for Md. Use the TAU command for defining the lapse-time magnitude coefficients.

The traditional duration magnitude expression is:

Md(fmp) = FMA + FMB*log(fmp) + FMD*D + FMZ*Z + STACOR

where: fmp is the F-P time or duration,
D is the epicentral distance,
Z is the (positive) depth, and
STACOR is the "dur" mag correction from the station card.

HYPOINVERSE adds to the above expression the optional gain correction term:

FMGN * 0.5 * log(4.19/ CAL factor)

FMGN is normally 0 or 1 and controls whether this term is used. A CAL of 0 (representing an unknown value) also omits the term. Not using a gain correction is equivalent to assuming an attenuation of 15 db for all stations.

The magnitude relation may be bi-linear in log(fmp): HYPOINVERSE uses the values FMA1, FMB1, FMD1 and FMZ1 when fmp is less than FMBRK and FMA2, FMB2, FMD2 and FMZ2 when fmp is more than FMBRK. The USGS currently uses the values FMA1=-0.87, FMB1=2.0, FMZ1=0.0, FMD1=0.0035, and FMBRK=9000 (or some large number so that FMA2, FMB2, FMZ2 and FMD2 are never used).

The lapse-time (tau) magnitude expression is:

Mt(tau) = DMA0 + DMA1*log(tau) + DMA2*log2(tau) + DMLIN*tau + DMZ*Z
+ DMGN*G + STACOR

where: tau is the lapse time (P travel time + coda duration fmp),
Z is the (positive) depth,
STACOR is the "dur" mag correction from the station card, and
G is the gain correction = 0.025*atten - 0.375 (atten = 12, 18 etc)
Also G = -0.5*log(CAL factor) + 0.3 and
log(CAL) = -0.05*atten + 1.35

The coefficients DM-- are set by the TAU command. The defaults are: DMA0=-1.312, DMA1=2.329, DMA2=0, DMLIN=0.00197, DMZ=0, and DMGN=1. If you do not know the station attenuations or CAL factors, you should probably assume an "average" attenuation of 15 db. You may do this in several ways: (1) Use a CAL factor of 3.98 and select the CAL factor option with the ATN command. (2) Leave the CAL factor unknown by using 0 or blank on the station card and select the CAL factor option. (3) Do not use an attenuation correction by setting DMGN=0 with the TAU command.

AMPLITUDE (LOCAL) MAGNITUDES

All magnitudes are calculated and output to the print file and magnitude data file to a precision of 0.01. Magnitudes output to the summary and archive files are to the nearest 0.1.

The method for calculating local magnitudes assumes that maximum peak to peak amplitudes are read from a standard Wood-Anderson torsion seismograph. If amplitude is read from another instrument, it is corrected to an equivalent Wood-Anderson response using Jerry Eaton's XMAG formulation. Richter's original magnitude formula is:

$$ML = \log(A/2) - \log(Ao) + G$$

where A is the maximum amplitude, -log Ao is a tabulated function of distance and G is the station magnitude correction. The implementation of this formula in HYPOINVERSE is:

$$XMAG = \log(AMP / (2 \times CAL \times R(PER))) + F(D) + XCOR$$

where: AMP is the peak-to-peak amplitude in mm. CAL is the calibration factor of the instrument, defined as the peak-to-peak amplitude in mm of a 10 microvolt RMS signal at 5 HZ applied to the VCO. For a Wood-Anderson instrument, CAL should be 1.0. R(PER) is the response of the instrument at standard gain as a function of period PER relative to the Wood-Anderson. The program assumes that the relative response is completely specified by CALxR(PER). For a Wood-Anderson instrument, HYPOINVERSE uses R=1. F is the distance correction given by Bakun and Joyner (The ML scale in central California, BSSA, v74, p1827, 1984):

$$F = \log(D/100) + .00301\,(D-100) + 3$$

where D is the hypocentral distance in km. XCOR is the station correction. CAL, PER and XCOR are input on the station card and a value of PER for an individual reading may be entered on the phase card. AMP is input on the phase card.

Two instrument types in addition to the Wood-Anderson are presently available:

type code	Instrument
0	Wood-Anderson torsion seismograph.
1	1 HZ velocity transducer with 0.8 critical damping (standard)
2	Hawaii type Sprengnether seismometer with Develco VCO.

For type 1, HYPOINVERSE uses interpolation within a digitized response curve to find R:

RESPONSE CURVE OF THE USGS STANDARD HIGH GAIN (L4C 1 SEC.) RELATIVE TO W.A.

FREQUENCY	.16	.20	.25	.32	.40	.50	.63	.79	1.00
LOG FREQ	-.8	-.7	-.6	-.5	-.4	-.3	-.2	-.1	0.0
RESPONSE	.159	.303	.432	.550	.660	.762	.855	.937	1.010

FREQUENCY	1.26	1.59	2.00	2.51	3.16	3.98	5.01	6.31	7.94
LOG FREQ	.1	.2	.3	.4	.5	.6	.7	.8	.9
RESPONSE	1.077	1.149	1.229	1.318	1.413	1.512	1.613	1.717	1.821

FREQUENCY	10.0	12.6	15.9	20.0	25.1	31.6	39.8	50.1
LOG FREQ	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7
RESPONSE	1.921	1.998	2.010	1.918	1.740	1.502	1.196	0.789

In the period range 0.1 to 1.9 second, R is approximately a linear function of the logarithms of period and R:

for type 1: log (1/R) = -1.3 -.95 log (0.2/PER) (sperceded by above array)
for type 2: log (1/R) = .41 -.56 log (0.2/PER)

If the calibration factor CAL is found equal to 0, no magnitude will be computed for that station. The useful range of XCOR is ±2.4. If you want to compute a magnitude for a station but exclude the result from the event magnitude, either give it a zero weight or use a value of XCOR equal to 5.0 plus the actual correction. See the sections on station and phase input for more information.

If you are calculating amplitude magnitudes from vertical instruments, you should correct magnitudes to account for the lower amplitudes on verticals than on horizontals for which the ML scale was originally defined. The amplitude magnitude correction for vertical instruments in Central California is empirically about +.25. You can add this to all magnitude corrections of vertical stations in the station file. More easily, if you use 5-letter station codes with the component as the fifth letter (USGS practice), a global correction applied to all V and Z components may be set with the VER command.

<u>The weighting of duration and amplitude magnitudes</u>

The net duration or amplitude magnitude for an event (as reported in the event header and summary card) is the weighted median of the station magnitudes. The weighted median is the value for which half of the total weights are higher and half are lower. Amplitude and duration magnitudes are calculated and reported separately and are never mixed.

Separate amplitude and duration weights may be specified on both the station and phase cards. The weight used is the product of the two. The weight codes are the same as for individual P and S times: 0 or blank = full weight, 1= 3/4 weight, 2= 1/2 weight, 3= 1/4 weight, 4-9 = no weight. Specifying a magnitude correction larger than 2.5 also gives that station zero weight and the actual value minus 2.5 is used as a correction.

The print and summary outputs of HYPOINVERSE report the weighted median magnitude, the total of all weights (essentially the number of magnitudes used in the average), and the mean absolute difference (MAD error) for both amplitude and duration magnitudes. The magnitudes and final station weights are also listed for each station in the print and archive outputs.

WEIGHTING OF P & S TIMES

The actual weight given a P or S time is the product of several factors:

(1) The station weight. A code on the station card results in a weight factor between 1 and 0 in tenths for that station for the entire run.

(2) The global S weight. This number is set with the SWT command for an entire run and multiplies all S weights. For example, setting SWT to 0.5 gives all S times half the weight they are individually assigned.

(3) The weight assigned each phase. The weight codes 0-4 and blank yield weights in steps of 0.25. The codes 4-9 yield no weight.

(4) The weight-out code on each phase card. Putting a non-blank character in col 25 gives both P & S zero weight.

(5) Distance weight. Weight decreases from 1.0 to 0.0 with increasing distance.

(6) Residual weight. Weight decreases from 1.0 to 0.0 with increasing absolute value of travel time residual.

The individual P & S weight codes as originally assigned, the weight-out code and the final weight used (to two decimal places) are preserved in the archive output file.

SOME SIMPLE COMMAND SEQUENCES

Several examples of command sequences will illustrate the flexibility of HYPOINVERSE. The intent here is to point out some of the most useful commands and how they might be sequenced. The commands which set your default parameters or which read station and crustal model files can be placed in a file called "HYPINST." and will be executed on startup each time HYPOINVERSE is run in that directory.

Example 1.	The simplest possible run (keeps all defaults).
CRH 1 'MOD1.CRH'	Read layer model 1 from the file MOD1.CRH.
STA 'ALL.STA'	Read station list from file ALL.STA.
PRT 'RUN1.PRT'	Send printer output to the file RUN1.PRT.
PHS 'SET1.PHS'	Define the phase file as SET1.PHS.
LOC	Locate the events.

Example 2:	Generates additional output files.
CRT 1 'MOD1.CRT'	Read gradient model 1 from the file MOD1.CRT.
STA 'ALL.STA'	Read station list from file ALL.STA.
PRT 'RUN1.PRT'	Send printer output to the file RUN1.PRT.
SUM 'SET1.SUM'	Write HYPOINVERSE summary data to the file SET1.SUM.
ARC 'ARC1.ARC'	Write archive data to the file ARC1.ARC.
PHS 'SET1.PHS'	Define the phase file as SET1.PHS.
LOC	Locate the events.

Example 3:	Read condensed phase data, write a compact print file, and use HYPO71 format summary output.
CRH 1 'MOD1.CRH'	Read layer model 1 from the file MOD1.CRH.
STA 'ALL.STA'	Read station list from file ALL.STA.
PRT 'RUN1.PRT'	Send printer output to the file RUN1.PRT.
LST 0	Don't list available stations or crust model in printout.
KPR 1	List only final solution & station data on printout for each event.
TOP F	Don't begin each new event at the top of a page.
SUM 'SET1.SUM'	Write summary data to SET1.SUM.
H71 2 2 2	Use HYPO71 summary, terminator & station formats.
PHS 'SET1.PHS'	Define the phase file as SET1.PHS.
LOC	Locate the events.

Example 4:	Locate a set of events with, then without S.
CRH 1 'MOD1.CRH'	Read layer model 1 from the file MOD1.CRH.
STA 'ALL.STA'	Read station list from file ALL.STA.
PRT 'RUN1.PRT'	Send printer output to the file RUN1.PRT.
SUM 'WITHS.SUM'	Put summary data with S in this file.
SWT 1.0	Set S weighting to 1.0 (full weight).
PHS 'SET1.PHS'	Define the phase file as SET1.PHS.
LOC	Locate the events.
SUM 'NOS.SUM'	Put summary data without S in this file.
SWT 0	Set S weighting to 0 (no weight).
PRT 'RUN2.PRT'	Send printer output for the second run to this file.
LOC	Locate the same events as before.

COMMANDS RECOGNIZED BY HYPOINVERSE

The parameters are listed below each command. The parameter defaults, if any, are listed in the examples. Commands will generate prompts for parameters and show you the current value if you do not supply them on the command line. If you want to keep the value, just press the RETURN key. Type HELP or HE2 for a listing of commands and a very brief description.

---- INPUT FILES --

CRT Read a linear gradient crustal model into a travel-time table.
- Model number (1-20).
- File name containing the travel-time table.

Example: CRT 2 'TTMOD2.CRT'

CRH Read a homogeneous layer crustal model.
- Model number (1-20).
- File name containing the layer depths and velocities.

Example: CRH 3 'LAYMOD3.CRH'

STA Read a station data file into memory.
- File name containing stations.

Example: STA '1983.STA'

PHS Set the phase data input filename.
- Phase filename.

Example: PHS 'PHASES.PHS'

---- BINARY FILES --

WCR Write a snapshot of all crustal models and multiple model definitions currently in memory to a file in binary form. You should have issued all CRT, CRH, NOD, ALT and MUL commands first.
- Supply the filename to write to.

Example: WCR 'WE:[KLEIN.MULT]MULTMOD.BIN'

RCR Read a binary file of all crustal models and multiple model definitions previously written with a WCR command. RCR replaces the CRT, CRH, NOD, ALT and MUL commands. Binary reads are several times faster than ASCII reads and worth the effort for frequently read files.
- Supply the filename to read from.

Example: RCR 'WE:[KLEIN.MULT]MULTMOD.BIN'

WST Write a snapshot of all station data and delays currently in memory to a file in binary form. You should have issued all STA and DEL commands first. Note that only one calibration factor and one of each magnitude correction are written (no histories or expiration dates) so the ATE, FMC and XMC commands must still be used.
- Supply the filename to write to.

Example: WST 'WE:[KLEIN.STAS]CUSPSTA.BIN'

RST Read a binary file of all station data and delays previously written with a WST command. RST replaces the STA and DEL commands. Binary reads are several times faster than ASCII reads and worth the effort for frequently read files.
- Supply the filename to read from.

Example: RST 'WE:[KLEIN.STAS]CUSPSTA.BIN'

---- READING ADDITIONAL STATION DATA -------------------------------------

The following four commands can't be given until a station file is read with the STA command. That is because these commands read station data and store it only for the stations already in memory. All data read by these commands may also be supplied in the station file, but some fields will be redefined by these commands. Data management is much easier with station locations (STA command), delays (DEL), attenuation (gain) settings (ATE), duration magnitude corrections (FMC) and amplitude magnitude corrections (XMC) in separate files. For example, the network delays may all be stored in one place and need not be incorporated into every station file. In addition, one file can have delays for every conceivable station but only those matching stations in the location file will use memory in HYPOINVERSE.

DEL Read in the station delays for all models from a file. The delay file, if used, <u>must</u> be read in <u>after</u> the station file because the stations with delays need not correspond to those in the station file. Note that the old DLY command no longer functions because this is a more flexible way of assigning delays. Also see the "multiple crustal models" sections.

- Specify the file name with the station delays.

Example: DEL 'ALLSTA.DEL' (There is no default).

ATE Read and use station attenuations from an attenuation history file. You must read your station file with the STA command before reading the station attenuation file. Once an attenuation file has been read, it is reread as needed during a location run to find a new CALibration factor after the expiration date of the previous one. See the section on specifying the station list. Also see the "event magnitudes and names" section.

- Supply the filename of the attenuation history file.
- Supply the date and time (2-digit year, month, day, hour) for which to load the initial station attenuations. Use a year of zero to load the earliest attenuations and let the earthquake dates update the the station attenuations as needed.

Example (there is no default): ATE 'ALL.ATN' 80 1 1 0

FMC Read and use station duration magnitude corrections from an FMC history file. You must read your station file with the STA command before reading the magnitude correction file. Once a file has been read, it is reread as needed during a location run to find a new magnitude correction after the expiration date of the previous one. See the section on specifying the station list.

- Supply the filename of the duration magnitude correction history file.
- Supply the date and time (2-digit year, month, day, hour) for which to load the initial station magnitude corrections. Use a year of zero to load the earliest corrections and let the earthquake dates update the the magnitude corrections as needed.

Example (there is no default): FMC 'ALL.FMC' 80 1 1 0

XMC Read and use station instrument types and amplitude magnitude corrections from an XMC file. You must read your station file with the STA command before reading the magnitude correction file. The magnitude corrections apply to all events in the location run, thus dates are not relevant. See the section on specifying the station list.

- Supply the filename of the amplitude magnitude correction file.

Example (there is no default): XMC 'ALL.XMC'

---- FILE FORMATS AND RELATED CONTROLS --

COP Set the input phase data format.
- Supply the format number as follows:

1 Traditional USGS (full) phase format.
2 Condensed format (codas on lines with P times).
3 HYPOINVERSE archive format (output from previous run).
4 Traditional phase format with shadow records (PHASEOUT HYPO71 shadow option).
5 Archive format with shadow records (PHASEOUT HYPOINVERSE shadow option).
6 One CUSP event (ID number with LOC command).
7 Many CUSP events (ID numbers read from a file; see FID command).

Example: COP 1 (the default)

CAR Set the archive file format. The condensed format contains only observed travel times, amplitudes, durations, assigned weights & first motions for each station, and the event location. The formats correspond to phase data input formats.
- Supply the format number as follows:

1 Full format with all data.
2 Condensed format.
3 Full format with shadow records after every line.

Example: CAR 1 (the default).

FID Set the format for reading CUSP ID numbers to locate (use with COP 7).
- Supply the format as a text string.

Example: FID '(I10)'

H71 Choose between HYPOINVERSE and HYPO71 formats where they differ.
- Set the summary format flag 1 for HYPOINVERSE, 2 for HYPO71.
- Set the terminator format flag 1 for HYPOINVERSE, 2 for HYPO71, or 3 for getting the trial hypocenter from the header record (COP formats 3, 4 or 5 only).

- Set the station format number 1 for HYPOINVERSE, 2 for HYPO71.

Example: H71 1 1 1 (the default)

ST5 Choose between 4- and 5-letter station codes.
- Set the flag T for 5-letter codes, F for 4-letter codes.

Example: ST5 T (the default)

UNK Set a list of 4-letter station codes (or the first 4 of 5 letters) that you expect to be in the phase but not station file. Stations in this list will not produce an "unknown station" error message but will be archived in the ARC file. Give the number of stations (maximum 10) and that many 4-letter codes. Stations will be recognized as "unknown" only by a match of the first 4 letters of their 5-letter code, but all 5 letters will be used when the data is written.

Example: UNK 0 (the default) or UNK 3 'ABCM' 'IRIG' 'WWVB'

---- OUTPUT FILES --

PRT Set the print output filename.
- Supply the filename. Use 'NONE' to omit a printout file.

Example: PRT 'NONE' (the default), or PRT 'PRTFIL.PRT'

SUM Set the HYPOINVERSE summary output filename.
- Supply the filename. Use 'NONE' to omit a HYPOINVERSE summary file.

Example: SUM 'NONE' (the default), or SUM 'OUT.SUM'

ARC Set the archive output filename. This file contains all the data calculated for each station.
- Supply the filename. Use 'NONE' to omit an archive file.

Example: ARC 'NONE' (the default), or ARC 'OUT.ARC'

MFL Set the magnitude data output filename. This file contains precise magnitudes and other data necessary to recalculate magnitudes or evaluate magnitude statistics.
- Supply the filename. Use 'NONE' to omit a magnitude file.

Example: MFL 'NONE' (the default), or MFL 'OUT.MFL'

ERF Error messages (for bad data, station names, etc.) are always written to the print file if one is specified. They may also be sent to the terminal to spot errors during a location run by turning them on. The most serious errors are always sent to the terminal.
- Supply a T to send error messages to the terminal, F otherwise.

Example: ERF F (the default).

APP Set the 3 logical flags that indicate whether an existing output file is appended to (T), or whether a new one is created (F).
- Supply 3 logical flags for: 1= printout file, 2= summary file, 3= archive file.

Example: APP F F F (the default), or APP F T F to append only to the summary file.

---- MULTIPLE CRUSTAL MODELS --

MUL Indicate whether region-dependent crustal models are to be used. If so, also give the number of the default model to use outside the explicit regions.
- Set a flag T to use multiple models or F to use one model.

Example: MUL F (the default) or MUL T 1

NOD Define a circle on a map (by its center and radius) within which all epicenters will use a particular crustal model and set of station delays. Presently 38 nodes or circles are allowed. Each NOD command issued defines a new node: you thus cannot reset a node once defined and will not have meaningful default values to examine. (The SNO command displays the current nodes on the terminal). The transition width defines a ring outside the inner circle within which the crustal model is used in combination with other models.

- Set the latitude of the circle center (degrees, positive north).
- Set the latitude of the circle center (minutes).
- Set the longitude of the circle center (degrees, positive west).
- Set the longitude of the circle center (minutes).
- Set the radius (km) of a circle where the model is used exclusively.
- Set the transition width outside the circle (km) for partial weighting.
- Set the crust model number for this node.

Example: (there are no defaults) NOD 37 10 122 5.4 30 10 2

(This node for model 2 is a 30 km radius circle with a 10 km-wide transition zone surrounding it).

SNO Show the nodes (circles) for various crustal models which have thusfar been defined by NOD commands.

Example: SNO

ALT Designate one crustal model as an alternate to another and use the alternate for stations so indicated in the station file. This feature allows using different models with different stations for the same earthquake, and may be used with or without the region-dependent model feature. Any number of models may have alternates.

- Specify the primary model number to have an alternate.
- Specify its alternate model number.

Example: (there are no defaults) ALT 2 3

(This says that if model 2 would normally be used for a particular epicenter, use model 3 with stations assigned to the alternate model).

---- PROCESS EVENTS IN A PHASE FILE --------------------------------

LOC Locate events. This is the command that actually locates earthquakes using the files and parameters set by previous commands.

Example: LOC

BUG Check phase file for format problems and station file for missing stations, and write error messages to the print file. Phase, station, and print files must have been specified before issuing the BUG command. Works only with ASCII input formats.

Example: BUG

PRO Interactively edit and relocate earthquakes in individual files, one event per file. See the discussion above "Interactive Earthquake Processing" and the BAS command below. There are no parameters

Example: PRO

BAS Set parameters needed for building the input and output filenames used in interactive processing by the PRO command. The filenames consist of a base name unique to the event and a suffix for each file type. See the discussion above "Interactive Earthquake Processing".

- Supply the filname listing events to be processed. For each event, the file must contain the base name (text string) used to form the I/O filenames for the event.
- Number of characters in the base name. Base names are fixed in length.
- Format for reading base names from the file named above.

The following four parameters are the file suffixes for the file types read or written by HYPOINVERSE for each event. The archive and summary file types are optional and may be suppressed by using "NONE" as a suffix.
- Input (phase or archive) file extension.
- Archive output file extension.
- Summary output file extension.
- Print output file extension.

```
Example:  BAS 'LISTFIL.' 12 '(A12)' '.PHS' '.ARC' '.SUM' '.PRT'
              (the default) or
          BAS 'LISTFIL.8401' 12 '(A12)' 2*'.ARC' 'NONE' '.PRT'
```

---- PRINTED OUTPUT FORMAT --

LST List stations, crust and test parameters at the beginning of the print output file.
- Set the print code:
  0 Print earthquakes only.
  1 Add the location parameters & filenames to beginning of printout.
  2 Add a station list and all crust models.

  If the print code is 2, add two more parameters:
- Set the station detail code:
  0 List no stations.
  1 List station locations, cal factors, first delay etc (1 line per sta)

2 Also list delays for all crust models (adds 1 or 2 lines per station)

- Set the crust model detail code:
  0 List no crust models.
  1 List the layers, nodes and other data for each model.

Note that LST 1 and LST 2 0 0 produce the same result.

Example: LST 1 (the default) or LST 2 1 0

KPR Control the amount of information in the print file for each event.
- Supply KPRINT, which controls print output. Specifying a value also outputs all data output by lower values:

  0 Print final location only (2 lines).
  1 Add station list for final location.
  2 Add the location & adjustments (one line) for each iteration.
  3 Add the eigenvalues, covariance matrix & error ellipse.
  6 Add the station list at each iteration.

Example: KPR 3 (the default).

TOP Start each earthquake at the top of a page in printout file.
- Set a logical flag (T or F) that controls whether to start each new event with a form-feed.

Example: TOP T (the default).

REP Report each earthquake located with a brief message on the terminal. This is useful for verifying that the correct file is being located, and for monitoring the progress of long runs.

- Set a logical flag (T or F) that controls whether to report each event located.

Example: REP T (the default).

---- TRIAL DEPTH, VELOCITY RATIO & ERRORS -----------------------------

ZTR Set the trial depth for the run, which can be overridden for individual events on their terminator/instruction lines.
- Supply the trial depth ZTR.

Example: ZTR 7 (the default).

POS Set the P to S velocity ratio POS. All S travel times are calculated as POS times the model travel time (P velocities assumed). S station delays are derived from P delays by multiplying by POS.
- Supply the P to S velocity ratio POS.

Example: POS 1.75 (the default).

ERR Set the assumed reading and timing error in seconds. This should be the total error from all sources including the reading error and all unmodeled crust and delay time errors. A good value to use is your typical RMS residual after the crust and station delays have been modeled. See the ERC command.

- Supply the reading and timing error RDERR.

Example: ERR .15 (the default).

ERC Set the coefficient ERCOF of the RMS travel-time residual in the expression for the actual timing error:

ACTUAL TIMING ERROR = /[(RDERR)2 + (ERCOF*RMS)2]

Set ERCOF according to the influence you want the fit of your data (the RMS) to play in location error calculation. ERCOF should usually be in the range 0,1 inclusive. The calculated location errors will be proportional to this "actual timing error".

- Supply ERCOF, the error coefficient of RMS.

Example: ERC 1 (the default).

MIN Used to skip events with too few reporting stations. If fewer than MINSTA stations are present for an event, no location is even attempted. This is useful when small events are to be screened out. See also the JUN command.

- Supply MINSTA, the minimum number of stations required to attempt a location.

Example: MIN 4 (the default).

---- CONVENIENCE AND CONTROL COMMANDS ---------------------------------

HEL Typing HELP, HEL or HELL in HYPOINVERSE gets a brief listing of the most important commands. No detailed information is available through HELP.

HE2 Typing HE2 gets a listing of additional commands which do not fit on the basic HELP screen.

@ Files of commands can be executed as if they were typed at the keyboard by typing @filename. A command file may call another command file (returning where it left off) and be nested up to 4 levels deep.

\# Any VAX DCL system command can be executed from within HYPOINVERSE by typing #command. This has no effect on current parameters, and control returns to HYPOINVERSE when the command finishes. This can be used to edit files, check the directory for files, etc.

STO Stop the program. There are no parameters.

SHO List the current input and output files on your terminal.

MAX List the current array maxima for stations, phases, models etc.

TYP Type a line of text on the terminal. This can announce something when running a HYPOINVERSE command file. No string apostrophes are needed.

Example: TYP Now reading stations...

---- EVENT MAGNITUDES & NAMES --

MAG Select the type of coda magnitude algorithm and weighting to use.
- Set the algorithm number MAGSEL:
1 Traditional duration (F-P) magnitude Md (Lee et al 1972; DUR command)
2 Elapsed Time (tau) magnitude Mt (Michaelson 1987; TAU command)

- Say whether to use the coda weight on the phase card (T), or to ignore any coda weight (F). If T, 0 or blank is full weight, 1-3 are partial weights, and 4-9 is no weight. If F, all codas are given full weight except those with a weight code of "X" or "N".

Example: MAG 1 T (the default)

DUR Set constants used to compute magnitude from coda duration. Two formulae may be used spanning different ranges of coda duration. The formulae have the form:

Md = FMA + FMB*log(DURATION) + FMZ*DEPTH + FMD*DISTANCE
+ FMGN * 0.5 * log(4.19/CAL factor)

- Supply FMA1, FMB1, FMZ1, and FMD1 for durations shorter than FMBRK.
- Supply FMA2, FMB2, FMZ2, and FMD2 for durations longer than FMBRK.
- Supply FMBRK, the duration above which the second set of constants are used. Set FMBRK=9999 to only use the first set of constants.
- Supply FMGN (normally 0 or 1) to regulate the use of gain correction.

Example: DUR -5.2 3.89 .013 .0037, -.9 2.026 .013 .0037, 210. 0
(for Hawaii, the default), or
DUR -.87 2 0 .0035, 4*0, 9999 0 (for California)

TAU Define the parameters for the elapsed time (tau, F minus origin time) magnitude scale Mt. This algorithm assumes that the duration (F-P time) is entered on the phase card and adds the P travel time to it to get tau. The formula is:

Mt = DMA0 + DMA1*log(tau) + DMA2*log2(tau) + DMLIN*tau + DMZ*Z
+ DMGN*G + STACOR

where:
tau is the elapsed time (P travel time + coda duration)
Z is the (positive) depth
STACOR is the "dur" mag correction from the station card
G is the gain correction = 0.025*atten - 0.0375 (atten = 12, 18 etc.)
Also G = -0.5*log(CAL factor) + 0.3

The coefficients starting with DM are set with the TAU command and are DMA0, DMA1, DMA2, DMLIN, DMZ and DMGN.

Example: TAU -1.312 2.329 0 0.00197 0 1

ATN Select whether to assume that station cards have CALibration factors (ATN F) or attenuation settings (ATN T). The attenuations (in db) are entered in place of CAL factors on the station cards and must be a multiple of 6. Conversion to CAL factors is as follows: 6, 11.6; 12, 5.58; 18, 2.8; 24, 1.4; 30, 0.7; 36, 0.352; 42, 0.176; 48, 0.089; 54, 0.044; 60, 0.022. If a value is entered whose nearest integer is not a multiple of 6, or if

conversion is disabled using the ATN command, the CAL factor is left as is.
- Set a flag F for Cal factors or T for attenuations.

Example: ATN F

NET Set the network number for assigning names to earthquakes based on their locations. This option requires that prior definition of earthquake regions be coded into the KLAS subroutine. If you do not have a net with defined names, use a NET of 0. Present nets are 1=Hawaii, 2=Northern California. See the QPLOT documentation for a list of regions. The 3-letter region codes are written to the summary, archive and print files. The full name is written to the print file.

- Supply the net number.

Example: NET 0 (the default).

VER Set an additional amplitude magnitude (XMAG) correction for all vertical stations. This is added to all other corrections, but only for instrument type 1 (USGS standard SP) with a component (5th letter of station code) of V or Z. Empirically, a value of +.25 applies to northern California.

Example: VER 0 (the default)

---- WEIGHTING OF ARRIVAL TIMES --

JUN Specify whether to force a solution of small and poor (junk) events. If the number of stations remaining after distance and residual weighting are applied is less than the minimum number (set with the MIN command), the event will normally abort. Setting the junk flag to TRUE cancels all distance and residual weighting for events which would otherwise abort.

Example: JUN F (the default)

DIS Set the parameters that govern progressive downweighting of more distant stations. DMIN2 is the distance to the second closest seismic station in km. The distance weight is 1.0 for stations closer than DMIN2*DISW1, 0.0 for stations beyond DMIN2*DISW2, and is tapered between those distances. If DMIN2 is smaller (closer) than DISCUT, DISCUT is used in place of DMIN2 in the above distances.
- Supply ITRDIS, the iteration on which distance weighting is to begin. Iteration continues at least until distance weighting begins.
- Supply DISCUT.
- Supply DISW1.
- Supply DISW2.

Example: DIS 0 50 1 3 (the default).

RMS Set the parameters that govern progressive downweighting of stations with larger travel time residuals. RMS is the root-mean-square travel time residual. The residual weight is 1.0 for stations with residuals less than RMS*RMSW1, 0.0 for stations with residuals larger than RMS*RMSW2, and is tapered between these residuals. If the RMS is smaller than RMSCUT, RMSCUT is used in place of the RMS in the above cutoff residuals.
- Supply ITRRES, the iteration on which residual weighting is to begin. Iteration continues at least until residual weighting begins.

- Supply RMSCUT.
- Supply RMSW1.
- Supply RMSW2.

Example: RMS 0 .16 1.5 3 (the default).

SWT Set the S wave weighting factor. Use 1.0 to give all S readings full weight, and 0 to not use any S readings.
- Supply SWT, the factor by which all S weights will be multiplied.

Example: SWT 1.0 (the default).

---- ITERATION AND CONVERGENCE PARAMETERS ----------------------------

CON Set parameters governing tests for convergence of iterations to a final earthquake solution. The solution is considered final as soon as either the hypocentral adjustment or RMS change falls below set limits or the maximum number of iterations is exceeded.

- Supply ITRLIM, the maximum number of iterations allowed (20). Use an IRTLIM of 0 to fix the hypocenter and calculate an origin time and travel time residuals.
- Supply DQUIT. If the hypocentral adjustment falls below DQUIT km, iteration stops (.04).
- Supply DRQT. If the change in RMS residual falls below DRQT seconds, iteration stops (.001).

Example: CON 20 .04 .001 (the default).

DAM Set iteration and damping controls affecting hypocenter adjustments.

- Supply DXFIX. Keep the depth fixed until the epicentral adjustment is less than DXFIX km (7).
- Supply DZMAX, the maximum depth adjustment in km allowed without a forced damping of the adjustment vector (30).
- Supply DZAIR. If the depth adjustment would place the hypocenter in the air, move the depth upward by this fraction (0.5).
- Supply DAMP, the mandatory damping factor for all hypocenter adjustments (0.9).
- Supply EIGTOL, the minimum eigenvalue permitted before no hypocentral adjustment is taken in its direction (0.012).
- Supply RBACK (.02). See BACFAC.
- Supply BACFAC (0.6). If the RMS increases by more than RBACK from one iteration to the next, move the hypocenter by the fraction BACFAC back toward the last location and continue iterating.

Example: DAM 7 30 .5 .9 .012 .02 .6 (the default)

OUTPUT FILE FORMATS AND PARAMETERS

PRINT OUTPUT

The amount of information in the printed output can be varied somewhat. The LST command controls the quantity of station, crust model and parameter data at the beginning of the print output file before any earthquakes are located. The KPR command governs the level of data seen for each earthquake.

Station table

NAME	The 4-letter station code. In USGS practice, the first 3 letters are the site code and the fouth is the network code.
C	The 5th letter of the station code (the component in USGS practice)
R	The 1-letter station remark (region code in USGS practice).
LAT	In degrees and minutes (north).
LON	In degrees and minutes (west).
PDLY1	P delay for the first model. Model code appears above the column.
A	An "A" here designates stations for use with alternate models.
FCOR	Duration magnitude correction.
FWT	Duration magnitude weight factor.
XCOR	Amplitude magnitude correction.
XWT	Amplitude magnitude weight factor.
PSWT	Weight factor for P and S phase times.
CAL	Calibration factor (gain).
CAL.EXPIR	Expiration date (Y,M,D,H) of CAL factor. 0 means no expiration date
TYP	Station instrument or response type code.
PDLY2	P delay for the 2nd model. Model code appears above the column.

Part two of the station table lists the 4-letter station codes, components, and delays for all of the crustal models. Complete data listed for each crustal model includes the velocity at the top and depth to the top of each layer. If regional crustal models are in use, a listing of all geographic nodes assigned to the model is given. Each node is indicated by its number, center latitude and longitude, and the inner and outer radii of the transition zone surrounding the circle for which the model exclusively applies.

In the earthquake output, one line of information per iteration is printed when the print control set with the KPR command is 2 or larger. The final location data is always written to a print file, and the station list data is written if the print control is 1 or larger.

Earthquake iteration output data

I	Iteration number.
ORIGIN	Seconds part of origin time.
LAT N	Latitude.
LON W	Longitude.
Z	Depth.
NWR	Number of P & S readings with final weights larger than 0.1.
RMS	The root-mean-square travel time residual using weights.
DT	Origin time adjustment to get to the next iteration location.
DLAT	Latitude adjustment in km, positive north.
DLON	Longitude adjustment in km, positive west.

DZ Depth adjustment, positive down.
RR Length of adjustment vector in km.
NF Number of free hypocenter parameters solved for and adjusted. Normally 4, but will be 3 on the first iteration since depth is held fixed. If N is less than 4, it is because the solution is poorly constrained and one or more eigenvalues are less than EIGTOL (see the DAM command).
MOD The primary (largest weight) crustal model code for this epicenter.

Next you will see the error ellipse data. For each of the three principal errors, SERR is the one-standard-deviation error in km, AZ is its azimuth in degrees east of north and DIP is its dip in degrees.

Final location data

The final hypocenter data is below a printed row of dashes.

YR MO DA Date.
ORIGIN Hour, minute, second.
LAT Degrees and minutes.
LON Degrees and minutes.
DEPTH In km.

RMS The root-mean-square travel time residual using all weights.
ERH The horizontal location error, defined as the length of the largest projection of the three principal errors on a horizontal plane. The principal errors are the major axes of the error ellipsoid, and are mutually perpendicular. ERH thus approximates the major axis of the epicenter's error ellipse.
ERZ The depth error, defined as the largest projection of the three principal errors on a vertical line.
XMAG Weighted median amplitude magnitude.
FMAG Weighted median coda duration or tau magnitude.

NSTA The number of stations (phase cards) read for this event.
NPHS The number of phases (P and S) read for this event.
DMIN Distance to the nearest station.
MODEL The dominant crustal model code for the event. If an alternate model is designated for some stations, a * follows the code.
GAP The largest azimuthal gap between azimuthally adjacent stations.
ITR Number of iterations required to find the solution.
NFM Number of P first motions reported for this event.
NWR Number of P & S readings with weights larger than 0.1.
NWS Number of S readings with weights larger than 0.1.
NVR Number of valid P & S readings (assigned weights larger than 0).

REMARKS The first remark is the 3-letter region code based on location and depth. Two auxiliary 1-letter remarks (F for felt, etc.) may be derived from an optional remark field in the phase data (see phase data input format above). An asterisk (*) indicates convergence problems with the final solution such as running out of iterations, depth held fixed, or failure of the hypocenter to reach a minimum in RMS.

N.XMAG Number of amplitude magnitudes used in the median given as the total of their weights.
XMMAD Weighted median-absolute-difference of the amplitude magnitudes

(the error in the median magnitude).

N.FMAG Number of duration magnitudes used in the median given as the total of their weights.
FMMAD Weighted median-absolute-difference of the duration magnitudes (the error in the median magnitude).

SOURCE The code for the most commonly used data source:
L Location (P & S times).
F Duration magnitude.
X Amplitude magnitude.

REGION The full name of the geographic region.
MODELS USED If you are using multiple crustal models, the codes and weights of the 1, 2 or 3 models actually used are listed.

<u>Station list data</u>

STA Station name. An asterisk after the station indicates that it uses the alternate crust model (see the ALT command and column 34 of the station format).

CR 5th letter of station name (component) and station remark (region).
DIST Epicentral distance.
AZM Azimuth to station in degrees east of north.
AN Angle if emergence at the hypocenter, in degrees up from nadir.
P/S P or S remark code and P first motion.
WT Assigned weight code and weight-out symbol (if any).

SEC Observed arrival time.
TOBS Observed travel time.
TCAL Calculated travel time.
DLY Station delay.
RES Travel time residual. The residual may be flagged (in the following column) by an "X" if that station was given a time but no weight, or an "*" if the residual is larger than 0.50.

WT Actual normalized weight used for this arrival, including assigned weight, weight-out code, distance weight, residual weight, station weight and global S weight. S waves are flagged with an "S" following the weight.
SR The 1-letter data source followed by the 1-letter remark carried from the phase data.
INFO The information or importance contribution of this arrival to the solution. The total importance of all stations equals the number of unknowns (usually 4).

CAL The calibration factor used for magnitude calculation.
DUR Coda duration in seconds.
W Duration magnitude weight code (0-4).
FMAG Duration magnitude for this station.

AMP Peak-to-peak amplitude in mm.
PER Period (in sec) where amplitude was measured.
W Amplitude magnitude weight code (0-4).
XMAG Amplitude magnitude for this station.
RMK The original 3-letter remark from the phase card.

MAGNITUDE DATA OUTPUT

The magnitude data file contains some of the data in the archive file and more detailed data relevant to the magnitude calculations. Magnitudes are written to two decimal places. Enough information is written, for example, to recalculate magnitudes or determine magnitude residuals as a function of time and station. Like the archive format, the data for an event begins with a summary line and ends with a terminator line. Manipulation programs such as EXTRACT may thus be used with either file type. There is one line per station but only for stations reporting a non-zero duration or amplitude. The essential event data like date and event magnitude is written on every station line. The file may thus be sorted by station and each line has enough information to calculate a magnitude residual, for example.

MAGNITUDE OUTPUT FORMAT

Cols.	Format	Data
1-5	A5	5-letter station code (including component).
6-15	5I2	Origin time year, month, day, hour and minute.
16-19	F4.2	Origin time seconds.
20-23	F4.1	Epicentral distance in km.
24-25	A2	P remark from phase card.
26	I1	P weight code.
27-30	F4.2	Calculated P travel time for this station.
31-34	F4.2	P residual (observed TT = calculated TT + residual)
35-37	A3	3-letter event remark (epicentral location code).
38	A1	Data source code for this station.
39	A1	1-letter station remark.
40	I1	Station type (0=Wood-Anderson, 1= 1-second velocity seismometer) from station file.
41-45	F5.3,3X	Calibration factor from station or attenuation file.
49-52	I4	Coda duration (F-P time).
53	I1	Assigned duration magnitude weight code (0-4).
		Duration magnitude data for the event:
54-56	F3.2	Median event duration magnitude.
57	A1	Most common FMAG data source code.
58-60	F3.2	Median-absolute-difference of duration magnitudes.
61-64	F4.1	Total of duration magnitude weights (i.e. number of readings)
65	A1	Station FMAG weight code from station file (0-9 & blank).
66-68	F3.2	Duration magnitude correction from station file.
69-71	F3.2,3X	Duration magnitude at this station.
75-78	F4.1	Peak-to-peak amplitude in mm on Develocorder viewer or paper Wood-Anderson record.
79-81	F3.2	Period at which amplitude was measured (sec).
82	I1	Assigned amplitude magnitude weight code (0-4).
		Amplitude magnitude data for the event:
83-85	F3.2	Median event amplutude magnitude.
86	A1	Most common XMAG data source code.
87-89	F3.2	Median-absolute-difference of amplitude magnitudes.
90-93	F4.1	Total of amplitude magnitude weights (i.e. number of

		readings)
94	A1	Station XMAG weight code from station file (0-9 & blank).
95-97	F3.2	Amplitude magnitude correction from station file.
98-100	F3.2	Amplitude magnitude at this station.

SUMMARY OUTPUT FORMAT

Cols.	Format	Data
1-10	5I2	Year, month, day, hour and minute.
11-14	F4.2	Origin time seconds.
15-16	F2.0	Latitude (deg).
17	A1	S for south, blank otherwise.
18-21	F4.2	Latitude (min).
22-24	F3.0	Longitude (deg).
25	A1	E for east, blank otherwise.
26-29	F4.2	Longitude (min).
30-34	F5.2	Depth (km).
35-36	F2.1	Amplitude magnitude.
37-39	I3	Number of P & S times with final weights greater than 0.1.
40-42	I3	Maximum azimuthal gap.
43-45	F3.0	Distance to nearest station (km).
46-49	F4.2	RMS travel time residual.
50-52	F3.0	Azimuth of smallest principal error (deg E of N).
53-54	F2.0	Dip of smallest principal error (deg).
55-58	F4.2	Magnitude of smallest principal error (km).
59-61	F3.0	Azimuth of intermediate principal error.
62-63	F2.0	Dip of intermediate principal error.
64-67	F4.2	Magnitude of intermediate principal error (km).
68-69	F2.1	Duration (coda) magnitude.
70-72	A3	Event location remark.
73-76	F4.2	Magnitude of largest principal error (km).
77-78	2A1	Auxiliary remarks (see final hypocenter output above).
79-80	I2	Number of S times with weights greater than 0.1.
81-84	F4.2	Horizontal error (km).
85-88	F4.2	Vertical error (km).
89-90	I2	Number of P first motions.
91-93	F3.1	Total of amplitude magnitude weights.
94-96	F3.1	Total of duration magnitude weights.
97-99	F3.2	Median-absolute-difference of amplitude magnitudes.
100-02	F3.2	Median-absolute-difference of duration magnitudes.
103-05	A3	3-letter code of crust and delay model.
106	A1	Crust model type code (H or T).
107	A1	Most common P & S data source code.
108	A1	Most common FMAG data source code.
109	A1	Most common XMAG data source code.
110	I1	Coda magnitude type code (1=duration 2=tau).
111-13	I3	Number of valid P & S readings (assigned weight > 0).

HYPO71 SUMMARY FORMAT

Cols.	Format	Data
1-6	3I2, 1X	Year, month and day.
8-11	2I2	Hour and minute.
12-17	F6.2	Origin time seconds.
18-20	F3.0	Latitude (deg).

21	A1	S for south, blank otherwise.
22-26	F5.2	Latitude (min).
27-30	F4.0	Longitude (deg).
31	A1	E for east, blank otherwise.
32-36	F5.2	Longitude (min).
37-43	F7.2	Depth (km).
44-50	F7.2	Duration magnitude.
51-53	I3	Number of P & S times with weights greater than 0.1.
54-57	F4.0	Maximum azimuthal gap.
58-62	F5.1	Distance to nearest station (km).
63-67	F5.2	RMS travel time residual.
68-72	F5.1	Horizontal error (km).
73-77	F5.1	Vertical error (km).

STATION ARCHIVE OUTPUT FORMAT

Like phase data, archive data is available in both full and condensed formats. The full-format archive output contains all of the information in the printed station list, but in a compact format suitable for archiving. The archive file may be read by a later program to plot first motions on the focal sphere, compile residual summaries, regenerate a printed output file, extract a subset of events, etc.

Both full and condensed archive files have the same structure. The first line of each event is identical to a HYPOINVERSE summary line (see format above), and acts as a header. Next is one line per station, and a mostly blank line terminates each event. A shadow record follows every header, station and terminator line in full-format archive files.

The condensed archive file format is similar to the condensed phase format, and may be directly re-read as input. Condensed phase files generally use P & S times which are in seconds from the whole minute in the header. The reference second on the header line is thus zero. Condensed archive files, however, use the origin time as the reference second on the header line, and observed travel times as P & S times. Either can be used as phase input, since the rule for reading condensed format is to add the reference second to each P & S time to get the actual arrival time.

Full archive file format

The first (header) line for each event is a HYPOINVERSE summary line with the final location and other data. The terminating line for each event is mostly blank. The format of each station line between is:

Cols.	Format	Data
1-4	A4	4-letter station name code.
5-6	A2	P remark such as "IP".
7	A1	P first motion.
8	I1	Assigned P weight code.
9	A1	Optional 5th letter of station code.
10-19	5I2	Year, month, day, hour and minute.
20-24	F5.2	Second of P arrival.
25-28	F4.2	P travel time residual.
29-31	F3.2	P weight actually used.
32-36	F5.2	Second of S arrival.
37-38	A2, 1X	S remark such as "ES".
40	I1	Assigned S weight code.
41-44	F4.2	S travel time residual.
45-47	F3.0	Peak-to-peak amplitude in Develocorder mm.
48-50	F3.2	S weight actually used.
51-54	F4.2	P delay time.
55-58	F4.2	S delay time.
59-62	F4.1	Epicentral distance (km).
63-65	F3.0	Emergence angle at source (replaces optional remark on some original phase cards).
66	I1	Amplitude magnitude weight code.
67	I1	Duration magnitude weight code.
68-70	F3.2	Period at which the amplitude was measured for this station.
71	A1	1-letter station remark.
72-75	F4.0	Coda duration in seconds.
76-78	F3.0	Azimuth to station in degrees E of N.
79-80	F2.1	Duration magnitude for this station.
81-82	F2.1	Amplitude magnitude for this station.
83-86	F4.3	Importance of P arrival.
87-90	F4.3	Importance of S arrival.
91	A1	Weight-out code for P&S times (from phase column 25).
92	A1	Data source code (from phase column 41).

APPENDIX - RULES FOR FREE-FORMAT INPUT OF PARAMETERS

-Supply the parameters in free-format following the command.

-The type and order of parameters is the same as in the command documentation.

-Free-format values may be separated by either spaces or commas.

-Character strings (for filenames, labels etc.) are delimited by apostrophes like 'MYFILE.DAT' .

-The form n*A stands for n occurrences of the value A.

-A null field will leave the existing value unchanged. A null field is specified by two consecutive commas, by one leading comma or by two trailing commas. Thus , 2 ,, 'MYFILE.' ,, changes only the 2nd and 4th of 5 values.

-A slash (/) at the end of a line means all later fields are null.

-The form n* stands for n occurrences of a null field.

GENERATING TRAVEL TIME TABLES WITH PROGRAM TTGEN

Use of a travel time table

The program reads a travel time table generated independently of the location process, and calculates travel time, travel time derivatives, and emergence angles at the source by interpolation from the table. Three point (parabolic) interpolation is used within the table, and linear extrapolation is used beyond the table. The table itself is a condensed grid of travel times as a function of distance and depth. Two grid point spacings are permitted for each of distance and depth, so that travel times for shallow nearby sources may be accurately modeled without wasting space on deep or distant grid points where the travel time curve changes slowly. The user may generate his own travel time table empirically or with another program (see Appendix 2 for table format) or use the travel time generating program TTGEN to prepare a table from a given velocity-depth function.

Allowable crustal models input to TTGEN

Crustal models consist of from 2 to 15 points at which the user specifies velocity and depth. Linear velocity gradients are assumed to connect the points. The last point fixes the velocity and depth of the homogeneous halfspace underlying the model. The halfspace velocity must be the greatest of any velocities specificed to insure that rays can be refracted along the top of the halfspace.

The use of linear gradients smooths out the discontinuities in travel time derivatives which result from homogeneous layer models, and gives a more realistic spread in emergence angles of downgoing rays than is possible with modeling rays as refracted from discontinunities.

One buried low velocity zone is permitted in the model. This means that velocity may not decrease with depth except for one group of adjacent velocity points. Hypocenters that occur within a low velocity zone may produce a shadow zone at the surface, and rays in this distance range are calculated as if refracted along the layer above the low velocity zone.

TTGEN can handle models with homogeneous layers, (zero gradients), but velocity discontinuities (infinite gradients) are not allowed. Velocity gradients should assume reasoable values such as 0.0 or between 0.02 and 8.0 km/sec/km in the interest of numerical stability.

TTGEN operates by shooting rays out from the source and calculating time, distance, and other parameters where (and if) they emerge at the surface. Layers with steep gradients (such as might be used to model a Moho transition) can produce reverse branches in the travel time curve, and such layers should be at least 0.3 km thick to insure that enough rays will bottom in the layer to define the travel time curve properly. Errors can be introduced in the final travel time table by undersampling a too complicated or irrigular velocity model with too few rays.

Using the program TTGEN

At depth intervals specified by the user, the program shoots rays with increasing ray parameter starting with vertically emergent rays, and calculates distance, travel time, and other parameters for each ray (see outputs of TTGEN section). At each depth, a printed listing of these results is produced, noting any reverse branches or rays lost to a low velocity waveguide. The program then produces the final travel time table by interpolating travel times at distance intervals specified by the user. Interpolation is done in the first arrival from among the various branches including refractions from the halfspace and top of a low velocity zone.

Input to TTGEN on the file TTMOD

All model parameters including depth, distance, and ray intervals at which computations are to be performed are input on the file TTMOD. The program uses reduced travel times for the table to save space. One specifies the inverse of the reducing velocity REDV (in sec/km) to use in calculation. The reduced travel time is the absolute time minus distance times REDV. The values of reduced travel time passed to the location program with the table are limited to the range Ø to 32 seconds, and the user is responsible for choosing a suitable reducing velocity to stay within these limits. Using a reducing velocity equal to the halfspace velocity is a good choice.

The user specifies the amount by which the independent parameter Q is incremented to calculate distance and time for rays of various ray parameter and emergence angle. Ray parameter P and emergence angle PHI are functions of Q as follows:

$$\mathrm{PHI} = 2 \cdot \mathrm{TAN}^{-1}\left(\frac{Q}{\mathrm{ZH} + 1/2}\right)$$

$$\mathrm{P} = \frac{\mathrm{SIN\ (PHI)}}{\mathrm{VH}}$$

where ZH and VH are depth and velocity at the hypocenter, respecively. Q is a better independent parameter than either P or PHI since it gives a greater density of rays for deeper penetrations. This also gives the distant travel time points a distance spacing comparable to nearby points.

The parameter Q is incrimented as follows. It takes on the value 0.0 and NQ1 values at increments of DQ1, then NQ2 values at increments of DQ2. The largest value of Q is thus NQ1 • DQ1 + NQ2 • DQ2, and the greatest number of rays (maximum value of NQ1 + NQ2) is 200. Ray calculation stops when downgoing rays begin to penetrate the halfspace, and travel times approriate to a refracted ray are used beyond this point. Values of DQ1 = .08, NQ1 = 100, DQ2 = 0.4, and NQ2 = 100 are a good first try, and generally insure that the entire travel time curve can be adequately defined by less than 200 rays.

The grid points in distance and depth at which travel times are calculated for output to the final table are determined by eight parameters similar in concept to the Q parameters described above. Travel times are calculated at depths of 0.0 and NZ1 values at increments of DZ1, then NZ2 values at increments of DZ2. This permits a fine grid spacing for shallow depths and a coarse spacing at greater depths where the travel time curve will be smoother. Similarly, travel times are calculated at distances of 0.0, DD1, 2DD1, up to ND1 • DD1, and then at ND2 values in increments of DD2. Presently the maximum value of NZ1 + NZ2 is 27, and ND1 + ND2 may be as large as 41.

Velocity model input format (File TTMOD)

Line	Columns	Format	Explanation
1	1-8	4A2	Printed output filename.
1	9-16	4A2	Travel time table output filename.
1	17-22	F6.1	REDV, one over the reducing velocity used to condense the travel time plots and tables.
2	1-5	F5.2	DQ1 Parameters for incrementing the
2	6-10	I5	NQ1 independent parameter Q governing ray
2	11-15	F5.2	DQ2 spacing (see Text).
2	16-20	I5	NQ2
3	1-5	F5.2	DZ1 Parameters for incrementing the grid
3	6-10	I5	NZ1 spacing in depth (see text).
3	11-15	F5.2	DZ2
3	16-20	I5	NZ2
4	1-5	F5.2	DD1 Parameters for incremenating the grid
4	6-10	I5	ND1 spacing in distance (see text).
4	11-15	F5.2	DD2
4	16-20	I5	ND2
5	1-20	10A2	Title to appear on TTGEN output, and earthquake location output.
6	1-5	F5.2	Velocity of first point (km/sec).
6	6-10	F5.2	Depth of first point (km). This format is repeated for each velocity-depth point of the model, one line per point, up to a total of 15 points. The last point given sets the velocity and depth of the halfspace.

Outputs of TTGEN

The condensed travel time table contains all the information necessary to identify itself and be used by of HYPOINVERSE. The format of the table is transparent to the user, but is given in Appendix for completeness.

The printed output of TTGEN contains one tabulation for each depth grid point. One line is printed for each ray calculation until the deepening rays reach the halfspace. The tabulated data is as follows:

J	The ray index used to reference rays defining the endpoints of a shadow zone or reversed branches.
Q	The user-defined parameterizing variable Equal increments of Q are designed to give a greater density of deeper rays where they are needed to define the travel time curve.
EM.ANG	Emergence angle of ray at the source, measured in degrees from zenith.
P	Ray parameter in sec/km.
DIST	Distance in km at which ray reaches the surface. If DIST = -1, then the ray is trapped in a waveguide and does not reach the surface.
TIME	Travel time in seconds.
REDUCED	Reduced travel time in seconds, given by TTIME - DIST • REDV, where REDV is one over the reducing velocity.
L.BOT	The layer in which downgoing rays bottom.
Z.BOT	The depth at which downgoing rays bottom.
V.BOT	The velocity at which downgoing rays bottom.
DDIF	Distance difference between this and the preceding ray. DDIF is negative on reverse branches.
BR	Branch number. It is incrimented by 1 each time a new forward branch is encountered.
AMP	Relative amplitude of the ray at the surface assuming an isotropic source and geometrical spreading. It is just the ratio of the area of a ring on a unit sphere surrounding the source to the corresponding area at which rays emerge at the earth's surface.
AMP*R**2	Amplitude times distance squared. Used to estimate the differences between actual and ideal inverse-square spreading.
REMK	Remark such as RB (reversed branch) or WG (ray in wave guide).

ARRIVAL TIME WEIGHTING

Weighting

The actual weight given an arrival is the product of several factors:

1) Station weight. Will zero-weight a given station for entire run. (Set on station card).
2) S weight (S arrivals only). Will weight all S arrivals for entire run. Any value between 0.0 and 1.0.
3) Assigned weight. Designed to reflect individual arrival quality. May be 0.0, .25, .5, .75 or 1.0 (set on phase card).
4) Distance weight. Can be used to specify a decreasing weight with increasing distance. Will be between 0.0 and 1.0 (see below).
5) Residual weight. Can be used to specify a decreasing weight with increasing travel time residual. Will be between 0.0 and 1.0 (see below).

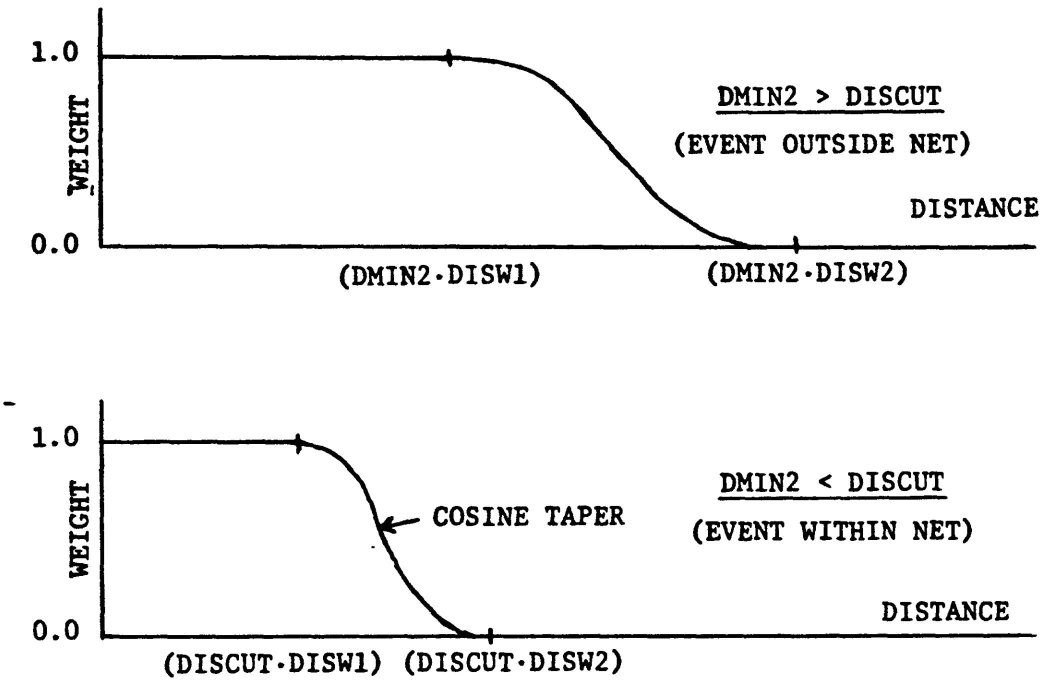

Figure 1 Distance weighting function. DMIN2 is the distance to the second closest station. DISCUT (Km), DISW1, DISW2 are user-defined constants.

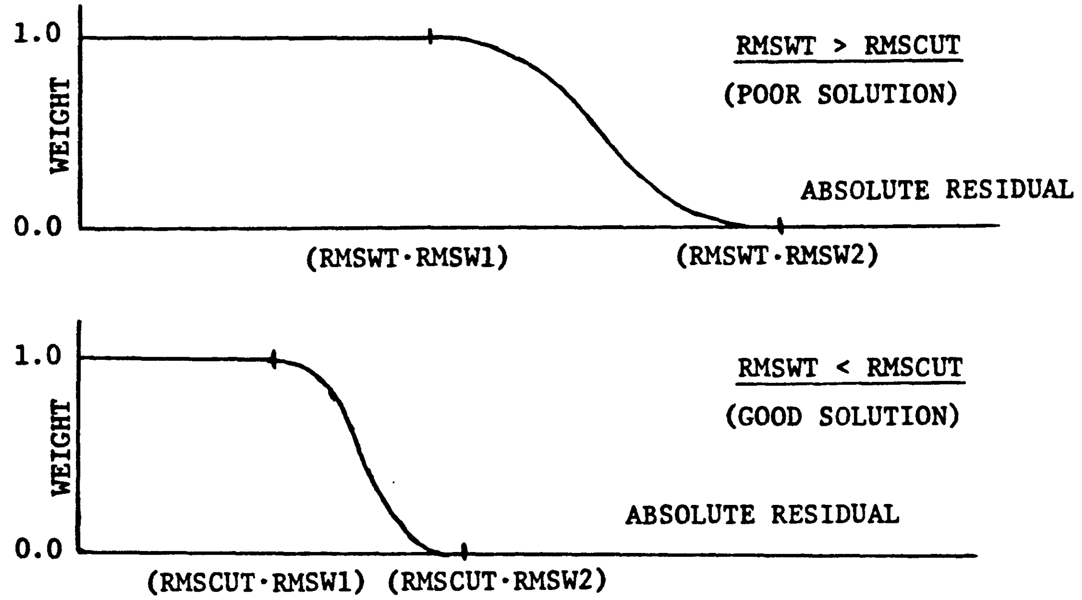

Figure 2. Residual weighting function. RMSWT is the root-mean-square traveltime residual. RMSCUT (sec), RMSW1 and RMSW2 are user-defined constants.

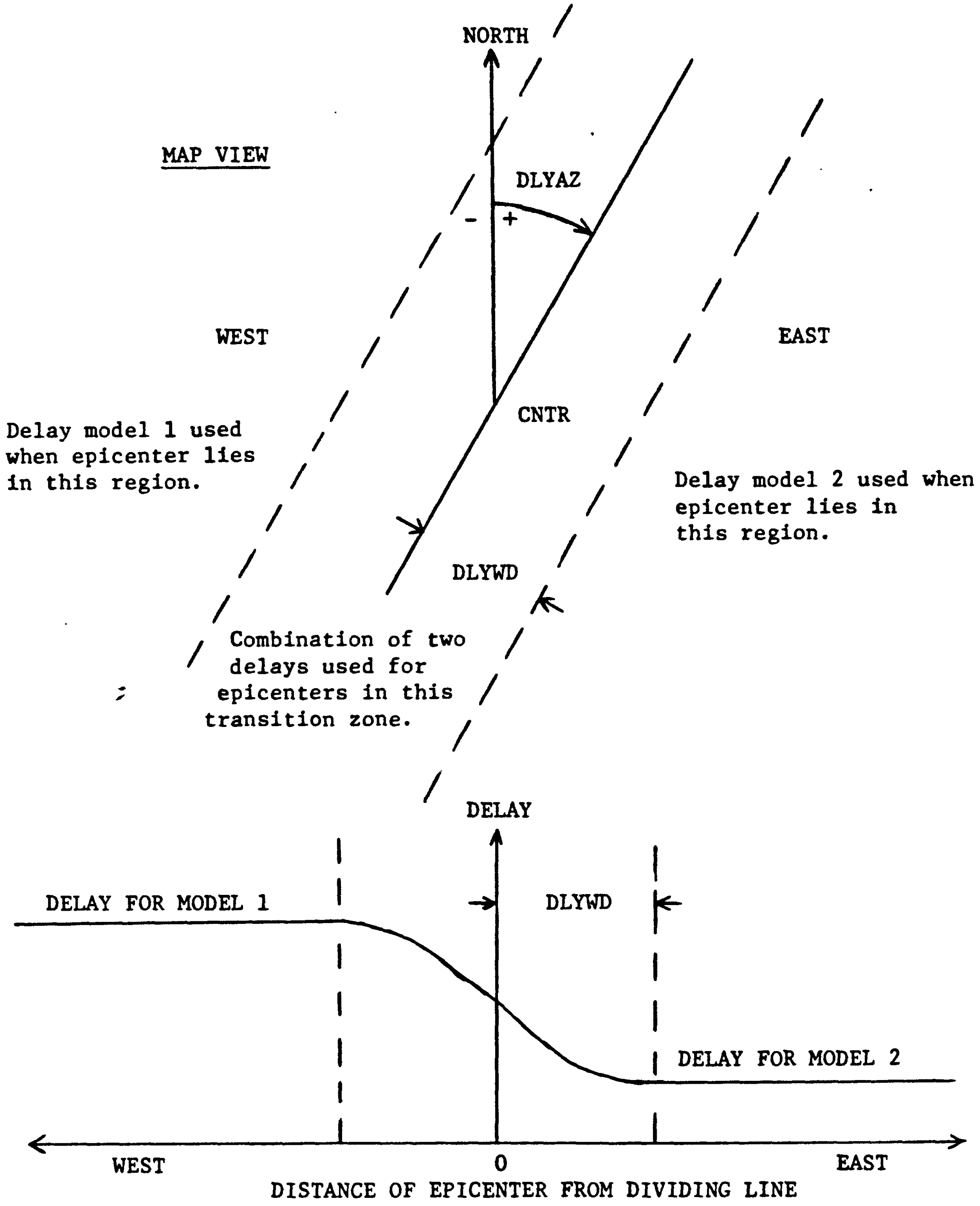

Figure 3. Map view showing delay model geometry. The delay model (or combination of delay models) depends only on the position of the epicenter relative to the dividing line. A cosine taper is used to smooth the transition between delay models.

ITERATION AND CONVERGENCE CRITERIA

Where to begin iterations

In absence of a specificed trial origin time, latitude, longitude, or depth on the terminator card, a standard trial hypocenter is assumed. Any one of the four trial hypocenter parameters may be specified independently, however. The trial origin time is two seconds before the first arrival, and the trial epicenter is near the station with the first arrival. Starting depth is at the trial depth ZTR. During the early iterations (usually just the first), depth is held fixed until the horizontal adjustment is less than DXFIX. If the trial depth ZTR is negative, all events in this run are held fixed at this depth (at the positive value), unless ZTR is temporarily overridden by a trial depth set for a particular event on its terminator card.

How iterative steps may be modified

Various parameters can be defined which damp the epicentral adjustments if the adjustment vector becomes large or unstable. DAMP is the damping factor by which all hypocenter adjustments are always multiplied before an iterative step is taken. Damping is automatically cut in half for the last 1/3 of the allowed number of iterations. Thus, if 15 iterations are allowed and convergence has not been reached after 10 iterations, the remaining 5 iterations will be heavily damped. Empirically this appears to improve convergence. If an iterative step would place the hypocenter in the air, the hypocenter is moved up to the fraction (1.-DZAIR) of its present depth. Thus the depth adjustment is -DZAIR * Z. The depth adjustment may be indepently damped if the adjustment is larger than DZMAX. If it is, the depth variation is damped by the factor DZMAX /(DZ + DZMAX) where DZ is the calculated depth adjustment.

If the value of RMS should increase by more than the amount RBACK from one iteration to the next, the hypocenter is moved back by the fraction BACFAC toward the previous hypocenter. This situation often occurs when a poorly constrained hypocenter iterates across a large velocity discontinuity in the crustal model.

The use of a generalized inverse scheme for finding the hypocenter adjustment for each iteration allows great control over the adjustments actually taken. For example we may choose not to make hypocenter adjustments in directions which are poorly constrained by the arrival time data and which are directions in which location errors are large. The parameter EIGTOL does exactly this, and serves as a cut-off below which eigenvalues of inversion are deemed unstable and are suppressed. A very brief description of the matrix equations of the inversion might aid in using this parameter.

Inversion scheme and use of eigenvalue cutoff.

If the solution to the earthquake location problem were linear and if we had exactly as many independent data (arrivals times) as hypocentral unknowns, the answer would be the solution of

$$\underset{n}{T} = \underset{nxn}{A} \cdot \underset{n}{X} + \underset{n}{G}$$

where T is the n-vector of arrival times, X is the n-vector of hypocenter coordinates and G is constant. A is the n by n partial derivative matrix

$$Aij = \frac{\partial Ti}{\partial Xj}$$

which may be directly calculated from an assumed velocity model. But since the earthquake problem is nonlinear (A is not constant), we must seek successive linearized solutions and iterate toward the true solution until we have converged to the desired accuracy. X and A must also be updated as iteration proceeds. If T_o and X_o are the arrival time and hypocenter vectors calculated at the previous step (or some initial guess on the first iteration) which satisfy

$$T_o = A \,.\, X_o + G$$

then subtracting the equations yields

$$T - T_o = A \cdot (X - X_o) \text{ or } \underset{n}{R} = \underset{nxn}{A} \cdot \underset{n}{DX}$$

where R is the vector of travel time residuals (observed times minus those calculated from the model at the previous step) and DX is the hypocentral adjustment vector, given in this case by $DX = A^{-1} \cdot R$. The number of observations m for the earthquake problem is often in the range 8 to 40, but the number of unknowns is generally only 4. When m exceeds n, however, the true inverse A^{-1} does not exist. We seek the least squares solution which best solves

$$\underset{m}{R} = \underset{mxn}{A} \cdot \underset{n}{DX}$$

in the sense of minimizing

$$(R - A \cdot DX)^2$$

This is done by premultiplying by A^T to get the least-square condition

$$\underset{nxm}{A^T} \cdot \underset{m}{R} = \underset{nxn}{(A^TA)} \cdot \underset{n}{DX}$$

which now only requires inversion of the nxn symmetric matrix A^TA.

The solution can be sought in terms of the generalized inverse of A, and in particular the singular value decomposition (SVD) of A. This not only yields the usual least square solution, but permits manipulation of the eigenvalues of A^TA, calculation of the errors, and evaluation of the information content of the data. This program uses the SVD subroutine and forms the above matrices from elements of the decomposition.

The decomposition of A is given by

$$\underset{m\times n}{A} = \underset{m\times n}{U} \cdot \underset{n\times n}{S} \cdot \underset{n\times n}{V^T}$$

where U and V are eigenvector matrices and S is the diagonal matrix of eigenvalues of A^TA. Also $U^TU = I$, $V^TV = I$, and assuming that the number of linearly independent arrival time data exceeds the number of unknowns, $VV^T = I$. When the resolution matrix VV^T equals the identity matrix, the unknowns are perfectly resolved which is the usual case for the earthquake problem. Then the least-squares solution can be derived by substitution of A into the least-squares condition and is given by

$$\underset{n}{DX} = \underset{n\times n}{V} \cdot \underset{n\times m}{S^{-1}} \cdot \underset{n\times m}{U^T} \cdot \underset{m}{R}$$

The covariance matrix of the solution DX is given by

$$\underset{n\times n}{C} = w^2 \; \underset{n\times n}{V} \cdot \underset{n\times n}{S^{-2}} \cdot \underset{n\times n}{V^T}$$

where w = constant.

We see at once that if one or more eigenvalues in S becomes small, both solution and error become large and unstable. Each eigenvalue corresponds to one of the mutually orthogonal principal directions of the solution, and if one eigenvalue becomes small, both the adjustment and standard error in that principal direction become large in proportion to one over that eigenvalue. The principal direction with the small eigenvalue will in general include components of origin time, latitude, longitude, and depth. Most often, however, the smallest eigenvalue has its largest component in depth. If an eigenvalue should become smaller than the parameter EIGTOL, no adjustment is taken in that principal direction for which the error is also large. The program does not add the term to DX originating from the small eigenvalue. In other words, solutions are prevented from becoming unstable and scattering out in the direction in which their error ellipsoids are very long.

In general, the largest eigenvalue is of order 5 (with its dominant component in origin time) and the spatial eigenvalues are of order 0.3 to 0.7. The difference is size between origin time and spatial enigenvalues arises because a change of several km in hypocenter location is required to produce the same change in an arrival time as a one second change in origin time. Unstable or very poorly constrained situations occur when the smallest eigenvalue becomes less than about .02. Looked at another way, instability occurs when the condition number (ratio of largest to smallest eigenvalue) exceeds about 200. The value of EIGTOL should be chosen after attempting to solve for the most marginal events one wishes to locate with a given network, and studying the eigenvalues and iteration history for these events.

When to stop iterating.

Iteration can stop in any of 3 ways: 1) when the number of iterations reaches the maximum allowed, ITRLIM; 2) When the change in the RMS residual between iterations becomes less than DRQT sec; 3) When the hypocenter adjustment vector is less than DQUIT km. The last two tests are only applied after the depth has been freed from its trial value for at least one iteration.

ERROR CALCULATIONS

The covariance or error matrix

The covariance matrix is calculated from elements of the decomposition of the A matrix (see section on inversion scheme) as

$$\underset{n\times n}{C} = w^2 \underset{n\times n}{V} \cdot \underset{n\times n}{S^{-2}} \cdot \underset{n\times n}{V^T}$$

where S and V are matrices composed of eigenvalues and eigenvectors in the "solution space" of the hypocenter. w^2 is the variance (standard error squared) of the arrival time data. The program calculates w^2 as

$$w^2 = RDERR^2 + ERCOF \cdot RMS^2$$

where RDERR and ERCOF are parameters set in BLOCK DATA and RMS is the root mean square travel time residual. RDERR represents the estimated reading error in seconds of the arrival time data. ERCOF is just a weighting factor for including the effects of a poor solution in the error calculations. If you want the calculated errors in the hypocenter to reflect only errors introduced in reading the data, set ERCOF = Ø. This will give objective errors which include the effects of array geometry. If you want to include effects of poorly modeled travel times such as weaknesses in the crustal or delay models, then set ERCOF = 1. ERCOF can be set to any positive value or Ø.

The covariance matrix is a 4 x 4 symmetric matrix whose diagonal elements are the variances (standard errors squared) of origin time (in sec), and latitude, longitude and depth (all in km). The off-diagonal elements are the covariances between these quantities. This allows, for example, a quantitative estimate of origin time error and the tradeoff between origin time and depth. The error ellipsoid is specified by the 3 x 3 sub-matrix with origin time removed.

Error ellipsoid and vertical and horizontal errors.

The error ellipsoid is specificed by the 3 x 3 sub-matrix derived by removing origin time from the covariance matrix. The 3 x 3 covariance matrix must be rotated into the principal coordinates of the solution, whose axes are the major axes of the error ellipsoid. The three principal standard errors are calculated by taking square roots of the eigenvalues (diagonal elements in diagonal form) of the 3 x 3 covariance matrix. The earthquake then has a statistical probability of 32% of lying inside an ellipsoid of error whose major axes are given by the three principal standard errors. An error ellipsoid whose major axes are 2.4 times the standard errors calculated by this program has a 95% chance of containing the "true" hypocenter. The program also calculates the azimuths and dips of the principal axes of the error ellipsoid.

The vertical error ERZ and horizontal error ERH are simplified errors derived from the lengths and directions of the principal axes of the error ellipsoid. Each of the three principal axes (whose lengths are the standard errors) are projected onto a vertical line through the hypocenter, and the largest value is ERZ. ERH is simply the length of the longest of the principal axes when viewed from above (projected onto a horizontal plane).

EIGENVALUE AND STATION IMPORTANCE OUTPUTS

Eigenvalue and error output

If KPRINT is 3 or larger, the four eigenvalues of the principal directions of the solution are listed in descending order. These are useful in gauging the relative stability and error of the solution in the four principal directions. Under each eigenvalue are the column eigenvectors corresponding to it. The eigenvectors together make up the matrix V. The elements of the column eigenvectors give the components of origin time, latitude, longitude and depth in the principal direction corresponding to that eigenvalue. In other words, the matrix of eigenvectors accomplishes the "rotation" between the principal and geographic coordinates. The last eigenvector gives the mix of latitude, longitude and depth which are most poorly determined and associated with the smallest eigenvalue.

The covariance matrix gives the variances (diagonal elements) and covariances of origin time, latitude, longitude and depth. The errors listed are the standard errors of origin time (in sec), and latitude, longitude and depth (in km) with the other three variables held fixed. They are the square roots of the diagonal elements of the covariance matrix. The error ellipsoid consists of the lengths of the principal axes SERR and their azimuths AZ and dips DIP in degrees. The principal axes are the standard errors in those directions in units of km. The hypocenter statistically has a 32% chance of lying within the error ellipsoid given. To obtain a 95% confidence ellipsoid, multiply the standard errors by 2.4. See the sections on the inversion scheme and error calculations for more information.

The station importance or information density.

This is a new parameter which is a by-product of the generalized inverse approach and which is not computed by other standard location programs. It is a quantitative measure of the contribution a particular arrival makes to the hypocenter solution, and includes the effect of weight on the arrival data. Computation of the importance may be suppressed and program execution made a bit more efficient by setting KINFO = 0 (in BLOCK DATA). To get the importance set KINFO = 1.

A result of the singular value decomposition of the partial derivative matrix A (see section on inversion scheme) is the information density matrix B = UU^T. This is an m x m matrix, where m is the number of arrival times reported. Each diagonal element b_{jj} of B is thus associated with the ith arrival alone, and is the quantity printed and referred to as the importance of the arrival.

A feeling for what importance means quantitatively may come from realizing that the rows of U are linearly related to the rows of the partial derivative matrix A. In other words, when the partial derivatives of travel time to the ith station with respect to the jth hypocentral coordinate dT_i/dX_j are large for the ith station, (the ith row of A) then the ith row of U and hence the station importance b_{ii} will also be large. Thus a large leverage, through the partial derivative matrix A, of a particular station on the solution is equivalent to a large station importance. This can be seen intuitively from the relation:

$$\underset{m\times n}{A} \cdot \underset{n\times n}{V} = \underset{m\times n}{U} \cdot \underset{n\times n}{S}$$

where the matrices are as defined in the inverison section. When the ith row of A is large (corresponding to the ith station), the ith row of this equation and hence of U will be large. The ith diagonal element s_{ii} of UU^T will also be large.

An illustration of the relation between importance and partial derivatives is the fact that an S reading has a greater importance than a P reading from the same station. The partial derivatives d(travel time)/ d(space coordinate), are larger for S arrivals at the same station by the factor Ts/Tp, and this means that rows of the U matrix and consequently the importance will be larger for the S arrivals. This has an important consequence for assigning weights to arrivals. When and S arrival cannot be read to the same precision as a P arrival, it should be given less weight to compensate for its intrinsically larger importance.

The importance is a measure of the redundancy in the data, and for example is small in distances and azimuths where there are many stations. This can be seen from the following argument. The inversion process for the overdetermined earthquake problem extracts n linearly independent combinations of partial derivatives from the m combinations in the matrix A. One "unit" of importance is attributed to each of these n independent combinations. Hence the sum of importances of all stations for a full earthquake solution is 4. If several data are redundant, i. e. linearly dependent or nearly so, then the unit of importance must be distributed among them and the importance of each redundant datum goes down.