


```

-----
fpfit.f          FORTRAN source, Version 1.4
fpplot.f        FORTRAN source, Version 1.4
fppage.f        FORTRAN source, Version 1.4
ptplot.f        FORTRAN source - plots P- and T-axes on stereonet with mean axes
                  and 90% confidence region of distribution.
mktable.f       FORTRAN source - converts .fps output into readable table
example_hinv.*  example input/output files for HYPOINVERSE format
example_h71.*   example input/output files for HYPO71 format
example_ell.*   example input/output files for HYPOELLIPSE format

```

COMPILING THE CODE

```
tar -xvf fpfit_source.tar
```

edit the Makefile to use either Solaris or GNU compilers

```

make plotkit
make fpfit
make fpplot
make fppage
make ptplot
make mktable

```

This code will produce graphics files that will run ONLY on an X11 windowing system (eg., SUN Openlook).

TESTING THE CODE

1. FPFIT: The first thing that will happen is that a prompt will be given. Type "hel" or "mor" for a list of commands. Type, for example, "@example_hinv.inp" to read control file, and then type "fps" to compute three sample fault-plane solutions. When prompt returns, type "sto" to stop the program

```

example.out      summary of the run parameters and a compilation of
                  statistics resulting from it.

example.fps      extended hypocenter summary cards showing solution
                  parameters for all fault plane solutions determined.

example.pol      intermediate file for use as input to programs
                  FPLOT and FPPAGE.

```

These three files should be identical to the like-named "example_hinv" files provided.

3. Test the interactive program FPLOT and answer the prompt for filename with the response: "example.pol". Answer the other prompts as you please.

4. Test the interactive program FPPAGE and answer the prompt for filename with the response: "example.pol". Answer the other prompts as you please.

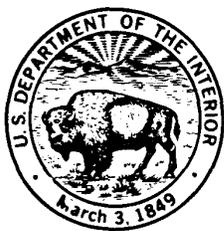
5. Test PTLOT the same way. This program is not described in the Open-File Report. It reads the ".fps" files and generates scatter plots of

the P & T axes with the distribution mean and 95% confidence limits calculated through the use of Bingham statistics [see Bingham, C., An antipodally symmetric distribution on the sphere, *Ann. Statist.*, 6, 1201-1225, 1974].

6. Test MKTABLE by running interactively. It will produce a readable table corresponding to the .fps file

7. If you have trouble making fpfit compute a solution, set the "dbg" option to "T".

Good luck.



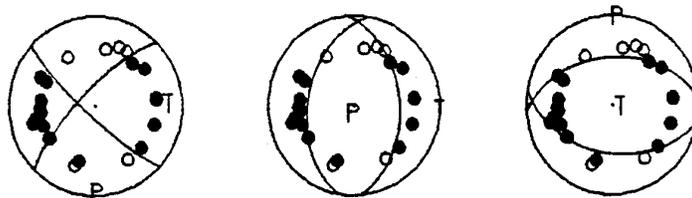
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

OFFICE OF EARTHQUAKES,
VOLCANOES AND ENGINEERING



FPFIT, FPPLLOT AND FPPAGE:

FORTRAN COMPUTER PROGRAMS FOR CALCULATING AND
DISPLAYING EARTHQUAKE FAULT-PLANE SOLUTIONS



OPEN-FILE REPORT 85-739

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

Menlo Park, California

1985

I. FPFIT Overview

Program FPFIT finds the double-couple fault-plane solution (source model) that best fits a given set of observed first motion polarities for an earthquake. The inversion is accomplished through a two-stage grid-search procedure that finds the source model minimizing a normalized, weighted sum of first-motion polarity discrepancies. Two weighting factors are incorporated in the minimization: one reflecting the estimated variance of the data, and one based on the absolute value of the theoretical P wave radiation amplitude (Aki and Richards, 1980). The latter weighting gives greater (lesser) weight to observations near radiation lobes (nodal planes). In addition to finding the minimum-misfit solution, FPFIT finds alternative solutions corresponding to significant relative minima in misfit. Such solutions, when they exist, generally correspond to faulting mechanisms distinctly different from the minimum-misfit solution, and may be deemed the preferred solution after consideration of possible data errors, unmodeled refractions and a priori knowledge of the tectonic environment. For each double-couple source model obtained, FPFIT formally estimates the uncertainty in the model parameters (strike, dip, rake). Finally, FPFIT calculates a uniformly distributed set of solutions within the range of estimated uncertainty. This set is used in the display program FPLOT to graphically define the range of P-axis and T-axis orientation consistent with the data.

FPFIT calculates fault-plane solutions sequentially for a suite of earthquakes and accumulates statistics on the entire suite, such as the cumulative discrepancy rates for each station and for each data class (0-weight, 1-weight, etc..). FPFIT also accumulates statistics on the suite of misfit scores, estimated solution uncertainties, and other calculated quantities that characterize the overall quality of the inversion results. Based on an examination of these statistics, adjustments to the inversion procedure, such as revising the estimated data variance, or removing or reversing one or more individual seismograph stations, may be indicated. Such an iterative use of FPFIT provides an easy and sound way to identify and avoid some common problems in the computation of fault-plane solutions, including the

presence of stations that consistently receive refracted rays that cross a nodal plane, stations with reversed polarity, and noisy data.

Certain caution must be exercised when interpreting fault-plane solutions computed by FPFIT. Non-double-couple solutions are not considered in the program, and hence adoption of a source model obtained by FPFIT implies the assumption that the earthquake is a double-couple source. Furthermore, data errors, unmodeled refractions, and oversimplified layer boundaries in the hypocentral solution should always be critically assessed in the evaluation of fault-plane solutions. Hence, we strongly recommend that all applications of FPFIT include careful consideration of reported multiple solutions, as well as a visual check for unreported alternate solutions, and that the results not be uncritically adopted.

II. Computational Procedures used in FPFIT

For each earthquake, E^j , FPFIT compares the observed polarity at the k th station with that calculated for a suite of source models $[M^i]$. A one-norm misfit function, $F^{i,j}$, is defined as

$$F^{i,j} = \frac{\sum_k \left\{ |p_0^{j,k} - p_t^{i,k}| \cdot w_0^{j,k} \cdot w_t^{i,k} \right\}}{\sum_k \left\{ w_0^{j,k} \cdot w_t^{i,k} \right\}} \quad (1)$$

where $P_0^{j,k}$, $P_t^{i,k}$ are terms representing, respectively, the observed and theoretical first-motion polarity (0.5 for compression, -0.5 for dilatation). The term $w_0^{j,k}$ is the observation weight that must be estimated and assigned to the data. The term

$$w_t^{i,k} = [A(i,k)]^{1/2}$$

is the square root of the normalized theoretical P-wave radiation amplitude, $A(i,k)$, expected at the k th station for source model M^i . This weighting scheme down-weights observations near nodal planes, thereby minimizing the effect of inconsistencies near nodal planes, such as those caused by unmodeled refractions. The misfit function, $F^{i,j}$ is

calculated for each source model in the suite, and the model that minimizes F is adopted as the faultplane solution. An exceptional case occurs when more than one solution have identical values of $F^{i,j}$. This case may occur because, particularly in the case of models perfectly fitting the data, the misfit function may be flat-bottomed. To break the tie in such cases FPFIT applies the additional constraint that the denominator in Equation (1) be maximized. The effect of this constraint is to maximize the distance on the focal sphere between the observations and the nodal planes.

In computation each source model is represented by the strike, dip and rake of one of its nodal planes. Specification of one plane and the associated rake angle is, of course, sufficient to represent both the fault plane and the auxiliary plane. No special importance is attached to the particular plane used to represent each model, and representation of the final solution is consequently in terms of one plane and its rake. In the companion plotting programs FPLOT and FPPAGE, both planes (and "P" and "T" axes) are calculated and displayed for each solution.

The procedure by which the suite of source models $[M_i]$ is tested is a two-stage three-dimensional grid search*. The first (coarse) stage uses 20° increments in each of the three parameters (strike, dip, and rake). All possible gridded values of rake and dip are included in the course search. However, only half the range of possible values of strike (from 0 to 160 degrees) is searched to avoid computing M_i for both the fault plane and its associated auxiliary plane. The course search identifies the solution corresponding to the minimum misfit, F_{min} , and, when they exist, multiple solutions corresponding to significant relative minima in misfit. The relative minima are detected in the course search up to a level of misfit $F \leq F_{min} + DFITC$, where $DFITC$ is an input parameter. Each of these solutions is

* In the following discussion we assume that the default values of the search parameters are used. The default values ensure that all regions in solution space are searched. When a restricted search (that is, one in which only a subset of the possible solutions is considered) is desired, the search parameters may be explicitly set in the input control file.

then taken as the center of a second stage (fine) 3-dimensional grid search. The fine search uses grid point spacing of 5° for strike and dip, and 10° for rake. Parameter ranges in the fine search are, relative to the central value, $\pm 45^\circ$ in strike and dip, $\pm 30^\circ$ in rake. It is in the fine grid search that the final solutions are identified, and estimates of solution parameter uncertainty are calculated. When multiple solutions are identified for an event, the solutions are distinguished by an asterisk in the output files.

III. Estimation of Parameter Uncertainty and Solution Quality

It is possible to determine formal confidence intervals for the parameter of fault-plane solutions obtained with a grid-search procedure. The misfit measure (Equation 1) is a sum of terms that take on discrete values, most of which are zero. Accordingly, the variance in F , and the associated 90-percent one-sided confidence interval for F , are estimated from the data using the method described in Appendix A. Having obtained the confidence interval for F , we determine the range of each solution parameter, relative to the minimum-misfit value, within which the solution misfit is bounded by the confidence interval for F . These ranges are taken as the uncertainties for the solution parameters.

For each fault-plane solution, FPFIT calculates the uncertainties described above and several other quantities designed to characterize the quality of the final solution. These quantities are reported, together with the fault-plane solution, in the program's output. They are:

1. $F_j = \text{minimum } [F_{i,j}] \text{ or a relative minimum of } F_{i,j}$. Note $F_j = 0.0$ represents a perfect fit to the data, while $F_j = 1.0$ represents a perfect misfit.
2. NOBS = number of observations used in the solution.

$$AVWT = \frac{1}{NOBS} \sum_{k=1}^{NOBS} w_o^{j,k} .$$

3. AVWT is the mean data weight used in the solution; it is an overall measure of the quality of the data used in the solution. AVWT ranges from 0.0 to 30.0, with larger values reflecting solutions computed from higher quality data.

$$STDR = \frac{\sum_{k=1}^{NOBS} (w_o^{j,k} \cdot w_t^{i,k})}{\sum_{k=1}^{NOBS} w_o^{j,k}}$$

4. STDR is the station distribution ratio ($0.0 \leq STDR \leq 1.0$). This quantity is sensitive to the distribution of the data on the focal sphere, relative to the radiation pattern. When this ratio has a low value (say, $STDR < 0.5$), then a relatively large number of the data lie near nodal planes in the solution. Such a solution is less robust than one for which $STDR > 0.5$, and, consequently, should be scrutinized closely and possibly rejected.

5. ΔSTR , ΔDIP , ΔRAK . These quantities are ranges (in degrees) of perturbations to the strike, dip and rake, respectively, of the final solution, that result in a misfit score bounded by the 90-percent confidence interval for F. ΔSTR , ΔDIP and ΔRAK are taken as the uncertainties in the solution parameters. When the distribution of the data on the focal sphere do not tightly constrain one or more parameters of the solution, the corresponding uncertainties are large; when the distribution of the data tightly constrain the solution these quantities are small.

FPFIT summarizes the quality of the adopted fault-plane solution with two letter codes, each of which may be "A", "B" or "C". The first letter code, QF, summarizes the value of F i . The second quality code, QP, summarizes the three parameter uncertainties ΔSTR , ΔDIP , and ΔRAK , as follows:

<u>E</u>	<u>QF</u>
F < 0.025	A
0.025 < F < 0.1	B
F > 0.1	C
<u>ΔSTR and ΔDIP and ΔRAK</u>	<u>QP</u>
< 20°	A
20° to 40°	B
> 40°	C

IV. Restricted Search Mode

FPFIT may be run in either of two modes. In the "unrestricted search" mode, all possible gridded solutions are tested. This mode is the usual mode of operation for FPFIT and is the one described in Section II. However, if the user chooses to search only a subset of the possible fault plane solutions, the "restricted search" mode may be used. In this mode the user may limit the ranges of strike, dip and rake from which test solutions are drawn in the search procedure. For example, the user may specify that only thrust solutions (rake = 90 degrees), or only vertical dextral strike-slip solutions (dip = 90 degrees and rake = 180 degrees) be considered. FPFIT will search for solutions only within the specified parameter ranges.

If the restricted search mode is used, two points should be kept in mind. First, the resulting solution may not be a true minimum-misfit (zero-derivative) solution, as the adopted solution may lie at the edge of one of the restricted parameter ranges. Second, the estimates of uncertainty for the solution parameters (Δ STR, Δ DIP, Δ RAK, QF and QP) are invalid, owing to the inability of FPFIT to perform its uncertainty analysis without a full range of solutions neighboring the adopted solution. Hence, the restricted search mode should only be used in special studies in which a "forced" solution is desired and estimates of solution uncertainty are not needed.

The unrestricted search mode is invoked by including in the input control file only lines 1, 2 and 3, and (optionally) station status lines, as in Appendix examples B.1.a and B.1.b (see also Section V.B).

The restricted search mode is invoked by including in the input control file an additional line specifying the ranges of the restricted search, as in Appendix examples B.1.c and B.1.d.

V. Input Files

A. Data File: FPFIT reads the print output file from program HYP071 (Lee and Lahr, 1975). This file contains the hypocenter summary card, followed by (for each P-wave observation) the station-to-epicenter distance and azimuth, P-remark, angle of incidence, and flag denoting phase data discarded due to Jeffrey's weighting.

B. Control File (see appendix B.1): This file sets parameter values to tailor the computation to suit the particular requirements of the data set. At least three lines are required:

Line 1 - DISTMX, FMAGMN, MINOBS, IPRNT, NEFF, NEV, DFITC (free format)

<u>Name</u>	<u>Explanation</u>
DISTMX	Maximum epicentral distance in km. Phase data from stations at epicentral distances greater than DISTMX are ignored.
FMAGMN	Minimum magnitude. Fault-plane solutions are not computed for events with magnitudes smaller than FAGMN.
MINOBS	Minimum number of observations. Fault plane solutions are not computed for events for which NOBS < MINOBS.
IPRNT	Print output control. If IPRNT = 1, FPFIT generates a listing of the misfit function for each test solution in the fine search. Normally, IPRNT = 0.
NEFF	Jeffrey's weighting control. When IJEFF = 1, inversion includes phase data discarded by Jeffrey's weighting in HYP071. When IJEFF = 0, phase data discarded by Jeffrey's-weighting are omitted
NEV	Maximum number of events for which fault plane

solutions will be calculated. Solutions are calculated sequentially from the input file until NEV events have been processed.

DFITC Depth of search for relative minima in misfit. Relative minima with $F \leq F_{\min} + \text{DFITC}$ are considered. We recommend the value DFITC=0.05 be used for most applications.

Line 2 ERATE(1), ERATE(2), ERATE(3), ERATE(4) (free format)

<u>Name</u>	<u>Explanation</u>
ERATE	Estimated weighted error (discrepancy) rates for classes of hand-picked data. ERATE(J+1) corresponds to assigned pick quality J. Set ERATE(J+1) = 1.0 to exclude all data from class J. For $0.0 \leq \text{ERATE}(J) < 0.5$ lower values reflect better-quality data. Use actual weighted error rates reported in a previous run of FPFIT on same data for best estimates of ERATE.

Line 3 - ERATE(5), ERATE(6), ERATE(7), ERATE(8) (free format)

<u>Name</u>	<u>Explanation</u>
ERATE	Same as Line 2, except for classes of machine-picked (e.g., RTP) data, which are denoted by an 'X' in the first position of the P-remark field, as in XPUO. ERATE(J+5) corresponds to assigned pick quality J for machine-picked data.

Line 4, 5, ..., , N - STATUS, STATN (a1, 1x, a4) (Optional)

These lines are included if data from some stations are to be omitted from the inversion, or if first motion directions from some stations are to be reversed.

<u>Name</u>	<u>Explanation</u>
STATUS	If STATUS = 'R', FPFIT reverses first motion direction for all phase data from station 'STATN'. If STATUS = 'K', FPFIT ignores all phase data from station 'STATN'.
STATN	Station name

Line N+1 - Blank (Included only if next line is present)

Line N+2 - PHIOC, PHI1, DELOC, DEL1, XLAMOC, XLAM1, DPHIC, DELC, DLAMC, DPHIF, DDELF, DLAMF (free format) (Optional)

This line is included if a restricted search range or non-default values of the grid spacing are desired; if this line is omitted, the default search range values are used, as described in section IV.

Strike is measured clockwise from north; dip is measured down from horizontal; rake of 0 = left lateral, 90 = reverse, +180 = right lateral, -90 = normal.

<u>Name</u>	<u>Explanation</u>
PHIOC	Minimum value of coarse search strike range, in degrees ($0 \leq \text{PHIOC} \leq 180$)
PHI1	Maximum value of coarse search strike range, in degrees ($0 \leq \text{PHI1} \leq 180$)
DELOC	Minimum value of coarse search dip range, in degrees ($0 \leq \text{DELOC} \leq 90$)
DEL1	Maximum value of coarse search dip range, in degrees ($0 \leq \text{DEL1} \leq 90$)
XLAMOC	Minimum value of coarse search rake range, in degrees ($-180 \leq \text{XLAMOC} \leq 180$)
XLAM1	Maximum value of coarse search rake range, in degrees ($-180 \leq \text{XLAM1} \leq 180$)
DPHIC	Strike increment, in degrees, for coarse search ($0 < \text{DPHIC}$)

DDELC Dip increment, in degrees, for coarse search ($0 < \text{DDELC}$)
 DLAMC Rake increment, in degrees, for coarse search ($0 < \text{DLAMC}$)
 DPHIF Strike increment, in degrees, for fine search ($0 < \text{DPHIF}$)
 DDELF Dip increment, in degrees, for fine search ($0 < \text{DDELF}$)
 DLAMF Rake increment, in degrees, for fine search ($0 < \text{DLAMF}$)

VI. Output Files

A. Extended hypocenter summary card file (see Appendix B.2). For each earthquake satisfying the input criteria FMAGMN and MINOBS, FPFIT calculates a fault-plane solution and writes to this file an 'extended' summary card consisting of the original HYP071 summary card concatenated with the fault-plane solution parameters. The format of the extended summary card is as follows:

Column	Explanation
1-80	HYP071 summary card.
82-84	Dip direction (downdip azimuth in degrees, clockwise from north).
86-87	Dip angle in degrees down from horizontal.
88-91	Rake in degrees: 0=left lateral, 90=reverse, ± 180 =right lateral, -90 =normal.
94-97	F_j
100-101	NOBS
103-107	ANT
109-112	STDR
114-117	Ratio of number of machine-picked phases to total number of phases used in solution.
120-121	ΔSTR
123-124	ΔDIP
126-127	ΔRAK
129	Solution quality code QF
131	Solution quality code QP

132 Flag, normally blank. '*' indicates that solution is one of a set of multiple solutions found for this event.

- B. Ray file (see Appendix B.3): This file is used as input to the plotting programs FPLOT and FPPAGE. The first line in this file is the HYP071 heading card. Following it is, for each solution: 1) the extended hypocenter summary card; 2) the number of additional fault-plane solutions in the suite of solutions corresponding to the 90-percent confidence interval for F_j ; 3) the dip direction, dip angle and rake of each solution in the 90-percent confidence suite (Format 11(14,13,14)); 4) the phase data used in the fault-plane determination and the normalized weights assigned to them.

The format of the phase cards is as follows:

<u>Column</u>	<u>Explanation</u>
2- 5	Station name.
7-11	Epicentral distance, in km.
13-17	Azimuth angle from epicenter to station (from north, in degrees).
19-23	Angle of incidence.
27-30	P-remark (eg., IPU2, XPDO, etc.)
32-35	Normalized observation weight W_0 used in inversion.
38	Discrepancy flag. If this field contains a '*', the observed polarity was discrepant with the adopted fault-plane solution. If the field is blank, observation was concordant.

- C. Statistical summary file (see Appendix B.4): This file lists the options specified in the control file and used in the calculation, followed by an alphabetized summary listing of all stations used in the computation of all focal mechanisms. For each station, the summary reports the number of first motion polarity discrepancies, the number of agreements, the total number of observations, the

weighted discrepancy rate (as in the numerator of Equation 1), and the fractional contribution from that station to the accumulated weighted error (misfit) from all stations for the suite of earthquakes processed. This last statistic is a measure of the effect of a station's discrepancy rate upon the entire inversion.

Following the station list are similar reports of the discrepancy rates for the hand-picked and machine-picked data, calculated separately for each data quality class (0, 1, 2, 3). The reported weighted error rate for each data class should be used as the input value for ERATE in a subsequent run of FPFIT with the same data. A double asterisk ('**') next to a reported weighted error rate indicates that this value differs from the corresponding (estimated) input value by more than 20 percent.

Next is a report of the distribution of the calculated fault-plane solution parameters F_j , ΔDIP , ΔSTR , and ΔRAK . These distributions provide a measure of the variance in the fault-plane set, and highlight the presence of solutions with unusually large uncertainties.

- D. Fit file (see Appendix B.5): This file is optionally generated (when IPRNT = 1). For each solution the extended summary card is followed by a listing of the 3-dimensional fit parameter matrix. This matrix contains the misfit scores F_{ij} (multiplied by 1000) for the source models calculated in the fine grid search, and is organized according to strike, dip and rake. The misfit score for the adopted solution is annotated with an "All; the "additional solutions", corresponding to the 90-percent confidence interval for F , are annotated by an "**".

Examination of this matrix shows the behavior of $F_{i,j}$ for solutions near the adopted solution and provides some insight as to whether the adopted solution is well-constrained. This listing file consists of 3 printer pages per fault-plane solution for the default grid search range.

VII. FPFIT Installation Considerations

- A. The dimension of all arrays are variable, and are set through assignments in the PARAMETER statement at the beginning of the main program. Thus, the array dimensions can be easily modified by changing the variable assignments in the PARAMETER statement and recompiling.
- B. All I/O statements refer to variable names for logical unit numbers. These variables are also set through assignment in the PARAMETER statement. In this way, the program can be tailored to use any convenient logical unit numbers by changing the assignments in the PARAMETER statement and recompiling.
- C. This program was developed on a DEC VAX 11/780 computer with a VMS operating system. The FORTRAN compiler has an extension to the FORTRAN 77 standard which permits character strings following an exclamation point (!) anywhere on a line to be interpreted as a comment. FPFIT takes advantage of this extension to describe the function of each variable in the code on the same line as the variable declaration. These embedded comments may need to be removed for other compilers.
- D. The OPEN statement for logical unit SUNIT in the main program contains the non-standard argument 'CARRIAGECONTROL=LIST'. Under VMS this changes the attributes of the file such that the printer does not interpret the first column of each line as a print control character. Similarly, all WRITE statements to logical unit SUNIT do not have carriage control characters in the first column. The OPEN statement for logical units IUNIT and CUNIT contain the non-standard argument "READONLY". Under VMS this permits the program to open files for which the user does not have "Write Status". This argument may have to be removed for use with other operating systems.

VIII. FPLOT Overview

FPLOT is an interactive plotting program for displaying fault plane solutions calculated by FPFIT. FPLOT produces one frame of graphic output for each solution found by FPFIT. The input file for

FP PLOT is the "RAY" output file produced by FPFIT (see section VI.B). What follows is a brief description of the graphic output from FP PLOT. Refer to any of the examples in Appendix B.6, all of which were produced with FP PLOT.

The top line is an image of the "Heading Card" optionally included in the HYP071 input file used to locate the earthquake. It is reproduced here to provide a convenient label that associates the fault-plane solution with the hypocenter location model.

Below the heading card is the extended summary card, on two lines, as described in Section VI.A.

The 5.75-inch-diameter circle below the extended summary card is a lower-hemisphere equal-area projection of the adopted fault-plane solution and first-motion data. Compressional rays are represented by circle symbols, dilational rays by triangle symbols. Upgoing (direct) rays are indicated by bold-face symbols, downgoing (refracted) rays by light-lined symbols. The size of the symbol is proportional to the observational weight W_0 associated with the ray. The ray symbols are centered on the points of the projection to which they correspond. The bold-face symbols "P" and "T" are centered on the points corresponding to the "pressure-axis" and "tension-axis", respectively, for the adopted solution.

To the right of the 5.75-inch-diameter circle is a table listing the observations that are discrepant with the adopted fault-plane solution. The table includes, from left to right for each discrepant observation, the station name, epicentral distance, azimuth in degrees from north, angle of incidence in degrees, and the P-remark. If no observations are discrepant, this table is omitted.

The 2.5-inch-diameter circle in the lower right corner of the page is a lower-hemisphere equal-area projection showing the position of the P-axis and T-axis corresponding to the adopted fault-plane solution (bold-face "P" and "IT" symbols, respectively). A set of additional pairs of P- and T-axes are plotted (light lines), corresponding to a set of solutions with misfit scores within the 90-percent confidence interval for F. The resulting distribution of P- and T-axes represents

the range of orientations of P and T consistent with the data, allowing for uncertainty.

IX. FPPLOT and FPPAGE Installation Considerations

In addition to the installation considerations for FPFIT (see section VI), the following apply:

- A. VMS requires that character variables be passed to plot calls by "reference". Therefore, character variables in subroutine argument lists are themselves arguments of the VMS system function %REF. This function may be omitted for use with other operating systems.
- B. The subroutine DELAY calls VMS system routines to achieve a half second delay following the clearing of the plot screen for Tektronix plotting terminals. Installation of PLOTFM on other operating systems will require the corresponding system calls.
- C. All calls to graphics routines conform to standard Versatec or Calcomp software.

X. FPPAGE Overview

FPPAGE is an interactive plotting program for displaying on a single page up to 42 fault plane solutions calculated by FPFIT. The input file for FPPAGE is the "RAY" output file produced by FPFIT (see section VI.B). Refer to the example in Appendix B.7.

Each fault plane solution is represented by a lower-hemisphere equalarea projection. Above each projection is plotted a header consisting, according to the user request, of either the sequential number of the earthquake in the "RAY" file, or the origin time of the earthquake. The header is annotated with an asterisk (*) to indicate multiple solutions. Compressional rays are depicted as solid circles; dilational rays as open circles. Plotting of the first motion symbols may be suppressed by the user. Finally the P- and T-axes of the solution -are plotted. If first-motion plotting is suppressed, only the T-axis is plotted.

XI. References

- Aki, K., and P. G. Richards, 1980, *Quantitative Seismology, Theory and Methods*, Vol. 1, W. H. Freeman and Co., San Francisco, California.
- Lee, W. H. K., and J. C. Lahr, 1975, HYP071 (Revised): A computer program for determining hypocenter, magnitude, and first motion pattern of local earthquakes, U.S. Geol. Surv. Open File Rep., 75-311, 114 pp.

ACKNOWLEDGEMENTS

Some of the computer routines used in FPFIT, FPPAGE and FPLOT were written by our colleagues at the U.S.G.S. in Menlo Park. John Lahr and Fred Klein kindly provided some of the graphics routines; Bruce Julian provided the moment tensor computation routines and showed us how to increase the computational speed of FPFIT with their use. Mark Mathews, at Stanford University, assisted us with the error analysis used in determining the uncertainties in the solution parameters. Donna Eberhart-Phillips assisted in the development of an early unpublished version of FPFIT.

We have had encouraging and stimulating discussions with many colleagues that were helpful in shaping these programs. We especially appreciate the comments of Jerry Eaton, Bruce Julian, John Lahr, Al Lindh, and Chris Stephens. We thank Bruce Julian and John Lahr for their reviews of the manuscript.

APPENDIX A

We wish to know the variance of F in Equation (1) solely from a priori knowledge of the variance of the data. To do this we take advantage of the fact that the data are provided with assigned "quality codes" (0, 1, etc.) that we assume correspond to uniform variances for each data class. This allows us to treat F as a sum of binomial processes. For one earthquake, let

n = the number of observations

N = the number of data classes represented by the observations

n_j = the number of observations in data class j .

$$n = \sum_{j=1}^N n_j$$

Now let

P_k = the error (discrepancy) probability for the k 'th observation

r_j = the error (discrepancy) rate for class j .

We may simplify Equation (1) by combining the weighting terms W_0^k and W_t^k into a single term

$$W_k = W_0^k \cdot W_t^k$$

and expressing the misfit term

$$m_k = | P_0^k - P_t^k |$$

where

$$m_k = \begin{cases} 1, & \text{when the } k\text{'th observation is a misfit;} \\ 0, & \text{otherwise.} \end{cases}$$

Then

$$F = \frac{\sum_{k=1}^n (m_k \cdot w_k)}{\sum_{k=1}^n w_k} \quad (\text{A.1})$$

The appropriate weighting terms in (A.1) are

$$w_k = \frac{1}{\sigma_k} = \frac{1}{\sqrt{p_k(1-p_k)}}$$

Equation (A.1) can be rewritten in terms of the observations and weights in each data class as

$$\begin{aligned} F &= \frac{\sum_{j=1}^N \sum_{k=1}^{n_j} (m_{j_k} \cdot w_{j_k})}{\sum_{j=1}^N \sum_{k=1}^{n_j} w_{j_k}} \\ &= \frac{\sum_{j=1}^N \tilde{w}_j \sum_{k=1}^{n_j} m_{j_k}}{\sum_{j=1}^N \sum_{k=1}^{n_j} \tilde{w}_j} \end{aligned}$$

where
$$\tilde{w}_j = \frac{1}{\sigma_j} = \frac{1}{\sqrt{r_j(1-r_j)}}$$

Finally,

$$F = \frac{\sum_{j=1}^N (\tilde{m}_j \cdot \tilde{w}_j)}{\sum_{j=1}^N (n_j \cdot \tilde{w}_j)} \quad (\text{A. 2})$$

where

$$\tilde{m}_j = \sum_{k=1}^{n_j} m_k$$

is the number of discrepancies in data class j . Equation (A.2) is an expression for F in terms of the number of discrepancies in each data class and the (uniform) weights assigned to observations in each data class. The variance of F is easily obtained from (A.2):

$$\text{Var}(F) = \frac{\sum_{j=1}^N (\text{Var}(\tilde{m}_j) \cdot \tilde{w}_j^2)}{\left(\sum_{j=1}^N n_j \cdot \tilde{w}_j\right)^2}$$

$$\text{Var}(\tilde{m}_j) = n_j r_j (1-r_j) = n_j / \tilde{w}_j^2$$

$$\text{Var}(F) = \frac{\sum_{j=1}^N n_j}{\left(\sum_{j=1}^N n_j \cdot \tilde{w}_j\right)^2} = \frac{n}{\left(\sum_{j=1}^N n_j \cdot \tilde{w}_j\right)^2} \quad (\text{A.3})$$

Finally, the standard deviation of F

$$\sigma_F = \sqrt{\text{Var}(F)}$$

is calculated. The 90-percent one-sided confidence interval for F is estimated from σ_F by assuming that F is normally distributed.

To implement this estimation procedure we must start with some estimates of the terms $[r_j]$, recalling that these discrepancy rates include contributions from both data errors and modeling errors. While we may have some idea of the contribution to $[r_j]$ from data (reading) errors, we cannot know the contribution from modeling (refraction) errors until after the inversion is done. Therefore the first run of

FPFIT requires an educated guess for the $[r_j]$. Upon completion of the inversion for a suite of earthquakes, FPFIT reports the actual accumulated dataclass error rates $[r_j]$ for the entire suite. These rates ("WEIGHTED ERROR RATE") should be used as initial estimates in the subsequent run of FPFIT. Such an iterative use of FPFIT provides a "bootstrap" ability to estimate formal error confidence limits from the data.

APPENDIX B

- B.1 Examples of CONTROL FILES for processing a set of fault-plane solutions.
- B.2 Example of EXTENDED SUMMARY CARD FILE.
- B.3 A portion of the RAY FILE corresponding to one selected earthquake.
- B.4 STATISTICAL SUMMARY FILE resulting from a run of FPFIT on a suite of 40 earthquakes.
- B.5 A portion of the FIT FILE corresponding to one selected earthquake.
- B.6 Graphic output from program FPLOT for selected earthquakes.
- B.7 Graphic output from program FPPAGE.

B.1 Examples of CONTROL FILEs for FPFIT.

- a) Control file corresponding to the statistical summary file shown in B.4.
- b) Control file that excludes all machine-picked data.
- c) Control file that allows only vertical right-lateral slip fault planes.
- d) Control file that allows only pure thrust solutions.

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Open-File Report No. 85-739