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FINAL REPORT DARPA SPECIAL STUDIES

E. Kazakh-AEDS t*
General Linear Model Magnitude Studies
Dynamic (Amplitude) Criteria for Automatic Association
Synthetic Data for Evaluation of Automatic Association

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Several short studies were undertaken to investigate questions of interest in magnitude:yield and automatic association. Approximately 150 t* values were computed for AEDS-E. Kazakh paths, and t* corrections for the AEDS stations were obtained. Application of the general linear model to shots in granite and sandstone-shale in the United States showed that a single hard-rock curve was inadequate for these two different media. New methods were developed for making use of amplitude data and synthetic alphanumerical data was generated in order to test

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ABSTRACT

Several short studies were undertaken to investigate questions of interest in magnitude:yield and automatic association. Approximately 150 t^* values were computed for AEDS-E. Kazakh paths, and t^* corrections for the AEDS stations were obtained. Application of the general linear model to shots in granite and sandstone-shale in the United States showed that a single hard-rock curve was inadequate for these two different media. New methods were developed for making use of amplitude data and synthetic alphanumerical data was generated in order to test automatic assocation routines. Experimental later-phase distance amplitude relations were determined for this last project by analysis of data from Network Event Processor (NEP) bulletins.

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INTRODUCTION

Several topics of importance for timely research were undertaken in this project this year. In the first instance it was found that insufficient funds were available in the Seismic Research Center Research contract (F08606-79-C-0007), Task 4.6) to completely analyze t* for all of the epicenter-station combinations desired. Thus funds from the present contract were used to analyze the E. Kazakh-AEDS paths. This work was accomplished as discussed in the following section and in Appendix A.

Another topic of importance was the extension of the data base to which the Generalized Linear Model yield estimation work of Shumway and Blandford (1982) had been applied. Results from this work are also discussed in the following section and in Appendix B.

There has been considerable interest on the part of workers in Sweden on the possible uses of "dynamic" criteria for improvement of the automatic association program. For example, how is one to make use of the information that an apparently large magnitude event is observed at only a few stations and is not observed at some stations nearby the hypothesized epicenter? Some work along these lines is discussed briefly in the following sections; and memos outlining the detailed research are given in Appendix C.

Other related work performed under this contract was the generation of synthetic data for testing of automatic association programs. The techniques of generating this data and the uses to which it was put are discussed in an unsigned report written by North and Olsen (1983): Report No. 3, Group of Scientific Experts, Special Study Groups 3 and 5, for the Conference of the Committee (CCD) on Disarmament. This work is also discussed in the following section, and excerpts from the CCD report are included in Appendix D.

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

Kazakh-AEDS t*

With respect to determination of the E. Kazakh to AEDS t* values Appendix A gives the Abstract, Table of Contents, Summary and Conclusions, and Recommendations for Future Research from report SDAC-TR-82-3 in which approximately 150 AEDS-E. Kazakh t* values were determined and reported. In general terms the additional analysis did not change the qualitative conclusions of the report; the chief benefit of the analysis, of exclusive relevance to the AEDS network, was the determination of the actual station t* values themselves which can be of use in determining station corrections for magnitude-yield and for spectral discrimination. The actual t* values themselves are classified and may be determined by reference to the cited report.

General Linear Model Magnitude Studies

In Appendix B we give a full general linear model analysis of WWSSN SP data for the events Shoal, Piledriver, Faultless, Gasbuggy, Rulison, and Rio Blanco. The analysis leads to the conclusion that a single hard-rock curve cannot encompass shots in granite, tuff, and sandstone-shale. We find that Gasbuggy lies 0.3 m_b below the Shoal-Piledriver prediction for granite; and that Rulison and Rio Blanco lies 0.6 m_b below. It is also of interest that the Faultless explosion which has been reported to have a large magnitude for its yield appears to have a large positive effect due to pP. When this effect is removed the shot lies near the theoretical curve passing through Shoal and Piledriver. This is of importance because Der et al. (1982) found attenuation under Faultless to be comparable to that under NTS, and the previously reported anomalously high magnitude of Faultless has been in conflict with this observation.

Dynamic (Amplitude) Criteria for Automatic Association

In Appendix C is a copy of a memorandum outlining the work performed to develop a dynamic method of checking automatic association results. At the time this memo was written it seemed to us that the algorithm was ready to be implemented. However, since that time further thought has suggested two different possible modifications to the procedure.

For the first possibility, referring to Appendix C, in Figure 1 we now suggest that, in the uppermost "box" that the test at a station be whether what happened at that station has a small or large probability. That is: (1) If the signal is not detected, what is the probability that it would be below the noise? (2) If the signal is detected but an amplitude is not reported, what is the probability that the signal is above the noise? (3) If the signal is detected and an amplitude is measured what is the minimum of the two probabilities (I) That it has a difference from the predicted amplitude greater than or equal to that observed? (II) That it would be detected, given its observed amplitude?

The probability threshold would be set low enough that there would be a small chance of a station or amplitude being thrown out in a good event.

To make these functional changes in the subroutines of Appendix C would require substantial coding changes in subroutine detz, and relatively minor changes in subroutine dynkin.

The advantages of these changes are (1) The probability threshold is more intuitively appealing than a scaled magnitude threshold. (2) The program will run much more rapidly because subroutine amp need only be called once in subroutine detz instead of ns (the number of stations) times. The routine should run about ns times more rapidly.

The second new overall approach would simply be to modify the existing "screen" routine in AA as discussed by Blandford et al. (1983). Points would be taken away from the event score if detections, non-detections, or observed amplitudes were out of line with the calculated maximum likelihood magnitude. See Appendix C for a second memorandum discussing this approach. At present it seems to us that this approach is simpler, faster, more well-integrated into normal AA practice; and probably gives better results than even the revised approach of the first memo.

Further research along these lines should be to make the above programming modifications and to apply and test the techniques in an operating AA program, perhaps using as data the synthetic data discussed below.

Synthetic Data for Evaluation of Automatic Association

In order to provide a data base for experiments in international seismic communication using the World Meterological Network (WMO) by participants in the Conference of the Committee on Disarmament (CCD); and to serve as a test data base for exercising the Swedish and Center for Seismic Studies (CSS) automatic association programs, it was desired to generate synthetic arrival data. Appendix D is an extract from North and Olson (1983) which describes fairly completely the technique of generating the data. Here we shall make a few additional comments.

The program used to generate the data was an almost complete rewrite of a program originally written by M. Chinnery and described in Chinnery (1980). The seismicity distribution was retained unchanged. Major changes were made by allowing detection of all phases to be controlled by the same detection criteria as the P phase themselves. This required obtaining distance-amplitude curves for several phases for which such curves were not available in the literature. The curves were ob' ined by the use of the results in Sweetser and Blandford (1973) for PP and all PKP branches; and analysis of phases measured by the NEP analyst for the time period 26 August 1978, through 1 May 1979. The phases analyzed were those with 20 or more reported arrivals in this time period, and as seen in Appendix D included PcP, PKKPab, PKKPbc, PKKPdf, PKPPKP, SKPdf, SKPab, ScP, pP and sP. Scattergrams were also made of the periods for all phases as a function of distance. The phases SKPab, PP, and PKPPKP has periods of 1.3 +/- 0.5 seconds, PcP has 0.9 +/- 0.5. All other phases seemed to have periods of 1.0 +/- 0.5. In the synthetic data these periods were used, assuming a uniform distribution within the indicated limits.

Point 10 in Appendix D is incorrect; the standard deviation of the Gaussian error for each slowness component is 2.0 seconds/degree for small arrays, and 1.0 for LASA and NORSAR. These are values which we have found to be a proper tolerance in practice for "making" small events. As such they probably represent the errors to be expected for small S/N events; and are much larger errors than are found for a calibrated array for large events. Examples of such excellent location capability may be found in Dahlman and Israelson (1977). Typical errors of 200 km would correspond to a slowness error on the order of 0.1 sec/km, one tenth the error listed above for LASA and NORSAR. In future generation of synthetic data it would be best to make the slowness error a function of S/N, perhaps varying from 1.0 to 0.1 as the S/N varys from 1.5 to 10.

As discussed in Appendix D there were complicated rules governing the naming and masking of detected phases. In retrospect some of the conventions were not as well thought through as they should have been. For example, explosions were allowed to generate pP and sP phases because insufficient consideration was given o the interference effects of phases arriving close in time to each other. A rule for the synthetic data generation which should have been implemented would lump detected arrivals within 3-5 seconds of each other into a single arrival with the name and arrival time of the first phase and the amplitude of the maximum amplitude.

Also, the rule that phases were named first and then phases were thrown away if masked by preceding phases occasionally led to anomalous results, related to the fact that pP was not named if P was not detected. Thus, if P was detected and pP named, and if then that P was masked by a preceding phase then the pP was left in the SAQ without a P to go with, an unlikely analyst decision. On the other hand, perhaps this outcome could be allowed to stand as an analyst error in which the analyst associated this phase as pP to the masking phase. But further, it is possible that the masking phase itself was a pP. These problems should be worked out.

Finally, we have the suspicion that the later phase amplitudes are too large in many cases. In real life phases are not detected if they are below the coda, and this may badly bias the amplitude distribution as observed in the NEP and other bulletins. A study should be carried out with the general "Ringdal" approach to better estimate later phase amplitudes; always including a coda measure for the noise when a phase is not detected. In addition, those phases PP, SKPab, and PKPPKP with average periods of 1.3 seconds may be harder to detect than their amplitudes (which are corrected for period) would suggest. Uncorrected for period, considering the typical response of short-period instruments, their amplitude on the film would be about 0.5 times the amplitude of a corresponding 1,0 Hz signal. Furthermore, the noise at that period would be higher than at 1 Hz. These problems should also be investigated; and as a quick fix we would recommend that the amplitudes of these later phases be reduced by 1/2 in any generation of new synthetic data.

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APPENDIX A

Excerpts from SDAC-TR-82-3

Global t* Measurements for the Magnitude Yield Experiment (U)

ABSTRACT (U)

(U) The values of the apparent t* were estimated for a large number of paths from nuclear explosions at various test sites to SRO, AEDS and a small set of LRSM, SDCS and array sites. Multiple regression analyses of the data showed that NTS explosions have, at teleseismic stations a t* .2-.3 sec higher than similar explosions at the Kazakh test sites. The slightly higher (.1 sec) t* estimates for Yucca Flats explosions relative to Pahute Mesa shots must be due to differences in RDP possibly due to the lower rigidity and residual gas-filled porosity of the tuffs at Yucca Flats, since P wave spectra at near regional distances also show the same difference. The estimates of t* for Soviet PNE explosions in the shield areas of the USSR are similar to those derived for the Kazakh test sites. The French nuclear explosions in the Sahara show a depletion in the high frequency content in the P wave spectra relative to Kazakh nuclear explosions recorded at the same sites. The contributions of the upper mantle structures under the recording stations vary within a few tenths of a second in t*, WHYK and ZOBO appear to be the stations with the low Q in the underlying mantle.

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SUMMARY AND CONCLUSIONS (U)

(U) The main conclusions of this study regarding the variations of attenuation under the source and receiver regions studied are as follows;

a) The most significant differences in apparent t* are between the source region terms of Kazakh and NTS, which are in the range of .2 - .3 sec, with the higher t* associated with NTS.

b) There appears to be a smaller but significant differential of the order of .1 sec in the raw apparent t* between paths involving Yucca Flat and Pahute Mesa explosions at common stations. A possible source function with low overshoot (B = 0) and lower rise time due to the soft sediments at Yucca Flats may be the explanation.

c) The contributions of the upper mantle under the receiving stations show smaller relative variation than the test site (source region) terms. Stations with relatively higher attenuation in the upper mantle are WHYK and ZOBO. The relative variations of the station terms remain similar after the source spectra are factored out.

d) The available data from the French nuclear explosions in the Sahara indicate a significant loss of high frequency content in the P waves relative to those originating at Kazakh. This is indicative of high attenuation under the Sahara test sites.

e) The t* estimates from Soviet PNE explosions in shield areas are not significantly different from those obtained from nuclear explosions at the two main Kazakh test sites at common stations.

f) The spectra of the two WUS granite explosions PILEDRIVER and SHOAL, when scaled to a common yield at the common station NPNT, are not significantly different from those of other NTS explosions, but show less high frequency content than the Kazakh explosions.

g) Comparison of spectra for common events recorded at RKON and NORSAR indicate a slightly higher attenuation in the mantle under RKON compared to NORSAR. More data is needed, however, to establish this with certainty.

h) Analysis of short period S waves from shallow earthquakes in plates or at the edges of the Russian shield that, even assuming a delta function source, the waveforms are inconsistent with an apparent t* of 4 sec; the best fit is around 2 sec. The values of the observed S/P ratios may, on the other hand, be reconciled by higher t* (absolute).

Other results of this study are summarised below:

a) Most P waves from the nuclear explosions analysed contained source related secondary arrivals besides the surface reflection pP.

b) Spectral ratios of pairs of events at many sensors of NORSAR become dissimilar beyond 2-3 Hz, indicating that the concept of "relative receiver functions" breaks down at high frequencies.

c) Determination of the times and amplitudes of secondary arrivals is inherently limited in accuracy by the uncertainties of the source time function (self-noise) and useful, coherent signal bandwidth, which is in turn determined by t*, background noise and random fluctuations in the media of propgation. These factors can be evaluated for each event, and the uncertainties in the estimated source depths and yields can be formulated in terms of bandwidth and signal to noise ratio.

RECOMMENDATIONS FOR FUTURE RESEARCH (U)

(U) Although the results presented in this report give a good first look at the variations of Q under some important test sites and recording stations, it is clear that the amount of data used was not sufficient to determine recording station t* terms with the desired accuracy of .05 sec in 95% confidence limits. Moreover, some major data sets, such as the AEDS, SDCS and SRO data, do not have the necessary overlap to determine the relative t* values among stations in the various data sets accurately. The coverage of the various test sites by the SRO stations is also non-overlapping and sparse. There is a need, therefore, to expand the data sets and provide more overlap with common events at common test sites as far as the limitations of geography allow. The AWRE array data can be extremely useful in providing both the overlap and standards of common reference because of the long operational duration of these arrays which overlap in time all of the other data sets. Early in this study, we decided that the hand-digitized WWSSN data is not likely to be reliable for measurement of t*, which critically depends on high frequency information (as we have emphasized repeatedly in this report). We plan to study these stations by using short period S wave data from deep earthquakes which were proven to be sensitive indicators of t* variation in past studies (Der, McElfresh and O'Donnell, 1982; Der, Smart and Chaplin, 1980). In doing this, we plan to make extensive use of the WWSSN chips available at the Center for Seismic Studies.

(U) More work needs to be done to explore the fundamental limitations on the information about the source and path properties contained in band-limited data. In the past, the accuracy of the results obtained was considerably over estimated, or the information available was not optimally utilized. Clearly, it is futile to attempt to derive source information beyond some fundamental limits imposed by the data.

APPENDIX B

Results from Generalized Linear Model Study

APPENDIX B

Blandford and Shumway (1982), hereafter referred to as paper A, developed a Generalized Linear Model (GLM) technique for simultaneously estimating event magnitudes and station corrections while also retaining the advantages of the Ringdal (1976) maximum likelihood magnitude estimation procedure in which bias (due to the fact that small amplitudes are not detected and thus not reported) is minimized.

The major task undertaken in the present study on the subject of magnitude:yield is the analysis, using the GLM, of an additional 4 off-NTS underground explosions in the Southwest United States. These events offer us excellent opportunities for determining true errors in magnitude:yield estimation; and, as we shall see, the application of the GLM is important for 3 out of the 4 events because their true magnitudes are less than 5.0.

In Table Ia we see the 6 events considered in the present study, Rulison, Gasbuggy, Faultless, and Rio Blanco, together with two events previously analysed in A: Piledriver and Shoal.

The events were analyzed in this study using exactly the same procedures as in A. Useful readings were obtained from 95 WWSSN stations, and the number of signal detections, as distinct from noise measurements, ranged from 71 for Faultless to 13 for Gasbuggy.

In Table Ib we see the results of the maximum likelihood calculations. The maximum likelihood magnitudes for the smaller events are 0.34 to 0.60 m_b smaller than the simple average of the detecting stations, and also are smaller than the simple magnitudes calculated by Marshall et al. (1978). This latter comparison suggests that there were signals below the noise in the LRSM network from which detection were selected by Marshall et al.

Note that the Faultless maximum likelihood magnitude is 6.49 as compared to the simple average of 6.40; this reflects the presence of 9 clipped signals out of 80 detections.

TABLE Ia

Event	Date	Time	Location	Depth(m)	Yield (kt)	Medium
Rulison	69/09/10	21:00	39.41N 107.95W	2575	40	Sandstone/ Shale
Gasbuggy	67/12/10	19:30	36.68 107.21	1293	29	Shale
Fault- less	68/01/19	18:15	38.63N 116.21W	975	600 (est.(7))	Tuff
Rio- Blanco	73/05/17	16:00	39.79N 108.37W	2010	90	Sandstone
Pile- Driver	66/06/02	15:30	37.07N 116.07W	462	62	Granite
Shoal	63/10/26	17:00	39.2N 118.3E	367	12	Granite

TABLE Ib

	m_b	$\overline{m}_b$	MSR m_2	Y	τpP	Synthetic			pP Corrected m_b
						NOpP	Preferred pP	ΔpP	
Rulison	4.52	5.13	4.94	40	1.57sec (1)	3.26	3.26	+.00	4.75
Gasbuggy	4.67	5.11	5.07	29	.87sec (4) (.70) (2)	3.14	3.13	-.01	4.88
Faultless	6.49	6.40	-	600 (est(7))	.80 (4) (.90) (5)	4.14	4.52	+.38	6.33
Rio Blanco	4.80	5.17	5.31	90	1.30 (3) (1.15) (6)	3.56	3.56	+.00	5.02
Pile Driver	5.49	5.57	5.71	62	.25, (.17)	3.42	3.64	+.22	5.49
Shoal	4.75	5.09	5.01	12	.21, (.15)	2.77	2.99	+.22	4.75

(1) Marshall (1972)
(2) Cohen (1970)
(3) Marshall et al. (1978)
(4) Springer (1974)
(5) Frazier (1972)
(6) von Seggern (1974)
(7) L_g ratio to Greeley at common good quality stations, See Clark (1968)

m_b - maximum likelihood

$\overline{m}_b$ - simple average of detecting stations

m_2^{MSR} - m_2 from Marshall et al., (1978) Theoretical seismograms, shown in Figure 1, were calculated for each of the events using the yield and pP delay parameters given in Table Ib, a pP reflection coefficient varying according to 0.5(1+exp (-f**2)) and a t* value of 0.4, taken to be typical of the average path to a detecting station. The difference between log(A/GT), where G is the instrument correction at period T, for the waveform without pP and the waveform with pP is defined as the pP "correction" and is subtracted from the observed m_b value for the corresponding event in order to take out the pP effect.

As in A, however, the Piledriver pP correction is added back in for all events. In this way the actual Piledriver m_b calculated is retained as a standard and all other events are adjusted relatively to it. Thus there results an m_b:yield curve where the effects of pP have been removed, but the Pildriver m_b has the same numerical value as before the pP correction.

In calculating the pP corrections the pP times used were the preferred one which are <u>not</u> enclosed in parentheses in Table I.

Figure 2 shows the results of these calculations. For those shots in granite and tuff, the magnitudes corrected for pP are seen to fall close to lines with the predicted average theoretical slopes; 1.0 between Shoal and Piledriver, 0.7 between Piledriver and Faultless.

However, the other shots, in shale and sandstone are seen to fall well below this line, (although the two events within 56 kilometers of each other, Rulison and Rio Blanco fall within 0.05 m_b of a line with slope 1.0) suggesting that a curve which is adequate for granite and tuff might not be adequate for sandstone and shale. This suggests that a single "hard-rock" curve could not be suitable for shots in such different media.

Note, however, that if the maximum likelihood estimates for magnitude has not been made, all the events would have fit fairly well on a single curve of lesser slope.

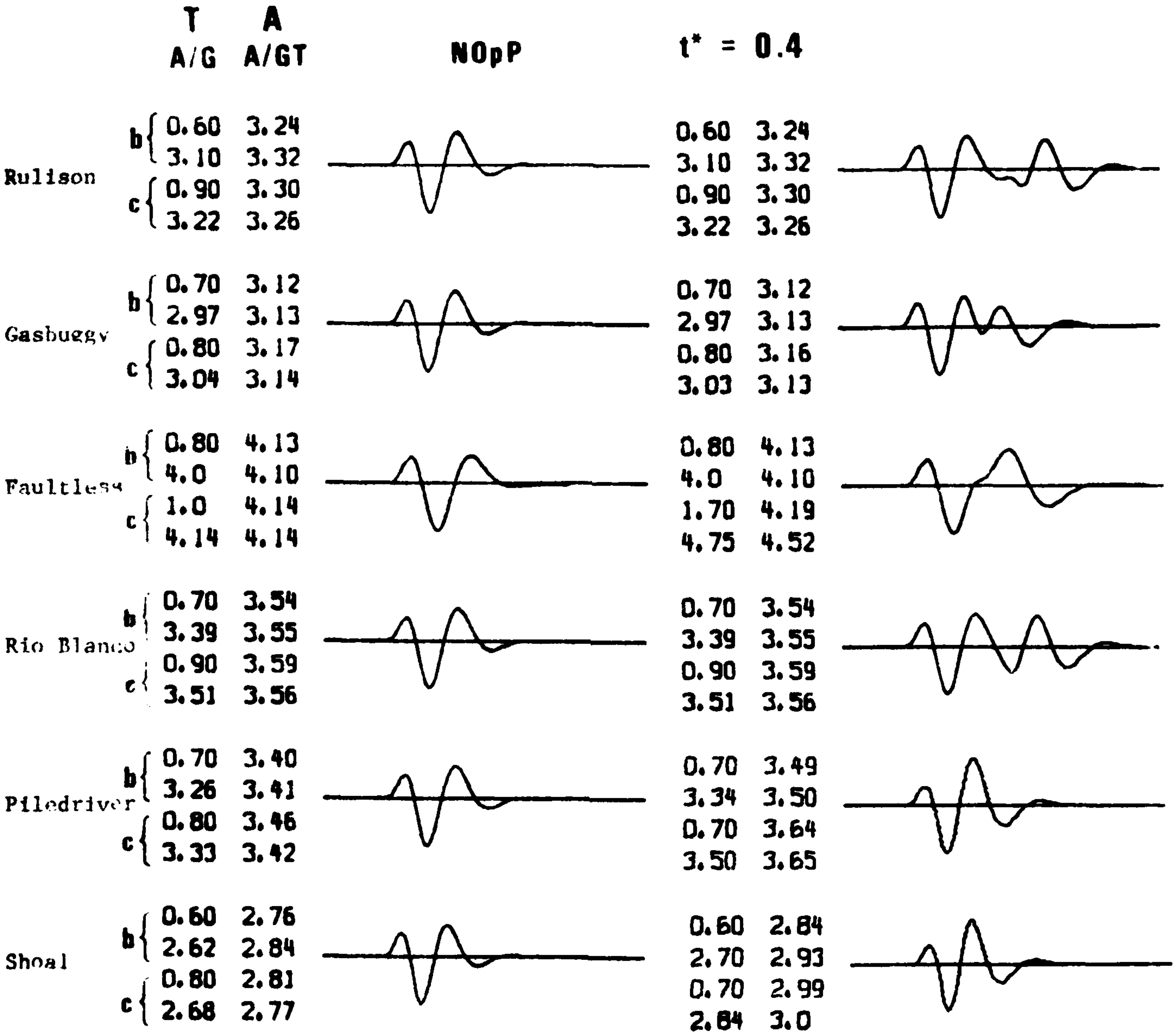
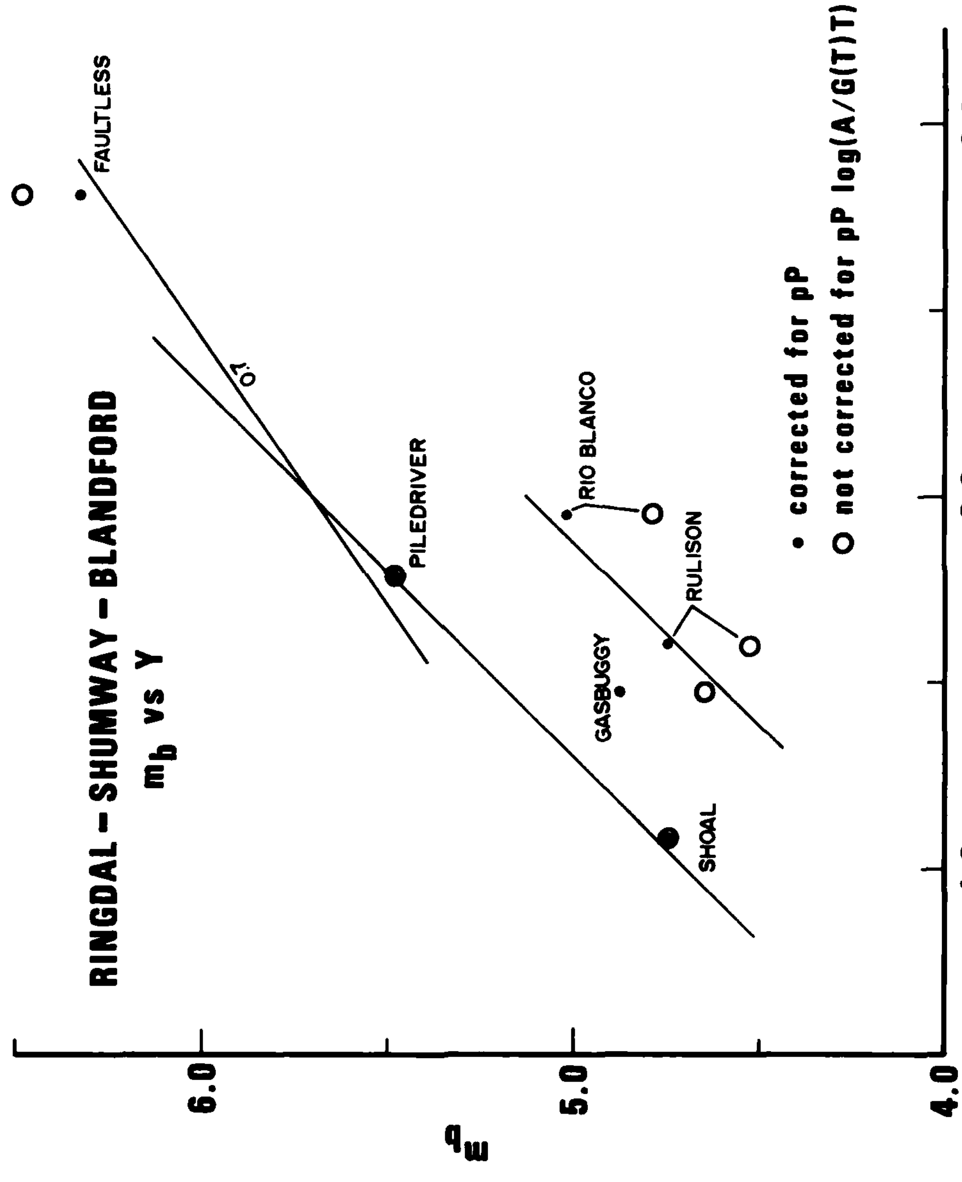

T A
A/G A/GT
NOpP
t* = 0.4
Rulison
b 0.60 3.24
3.10 3.32
c 0.90 3.30
3.22 3.26
0.60 3.24
3.10 3.32
0.90 3.30
3.22 3.26
Gasbuggy
b 0.70 3.12
2.97 3.13
c 0.80 3.17
3.04 3.14
0.70 3.12
2.97 3.13
0.80 3.16
3.03 3.13
Faultless
b 0.80 4.13
4.0 4.10
c 1.0 4.14
4.14 4.14
0.80 4.13
4.0 4.10
1.70 4.19
4.75 4.52
Rio Blanco
b 0.70 3.54
3.39 3.55
c 0.90 3.59
3.51 3.56
0.70 3.54
3.39 3.55
0.90 3.59
3.51 3.56
Piledriver
b 0.70 3.40
3.26 3.41
c 0.80 3.46
3.33 3.42
0.70 3.49
3.34 3.50
0.70 3.64
3.50 3.65
Shoal
b 0.60 2.76
2.62 2.84
c 0.80 2.81
2.68 2.77
0.60 2.84
2.70 2.93
0.70 2.99
2.84 3.0

Figure 1.


RINGDAL - SHUMWAY - BLANDFORD
mb vs Y
FAULTLESS
PILEDRIVER
RIO BLANCO
RULISON
GASBUGGY
SHOAL
1.0
• corrected for pP
O not corrected for pP log(A/G(T)T)
mb
6.0
5.0
4.0
1.0
2.0
3.0
log Y

The observed discrepancy between the Piledriver and Gasbuggy m_b values is consistent with observed reduced displacement potentials (RDPs) for this event. Examination of Figure 3a, b; from Murphy (1978) and Murphy and Bennett (1980) suggests that the Gasbuggy RDP would be between 6000 and 8000 m^3, while the Piledriver RDP would be between 20000 and 80000. Thus we might expect an m_b difference around 60000/6000 or 1.0 m_b units, with a range from 20000/6000 to 80000/6000 or 0.52 to 1.13 m_b. The observed difference is 0.61 m_b; consistent with the RDP differences and much greater than the 0.3 m_b expected from the Shoal-Piledriver curve.

Consistency with the observed RDP values suggests that the even lower scaled m_b values for Rulison and Rio Blanco are not a mistake but reflect true differences. Note that even these 0.6 m_b low values are within the range allowable by the Piledriver/Gasbuggy RDP's.

In this respect it is puzzling that Nuttli (personal communication, 1983) found excellent agreement between L_g magnitudes and yields for these events. In Figure 4 we see that there is very small scatter in the magnitude yield relationship. This is consistent with earlier work by Blandford and Klouda (1980) and others showing very weak dependence of magnitude on medium; but seems to be inconsistent with the large RDP differences. Perhaps the RDP's are not reliable; we now know that they are measured in the non-linear regime, and are thus not truly representative of the far-field. Thus perhaps here again we see the impressive capability of m_b from L_g to give a magnitude independent of medium while m_b from P waves shows a large effect.

We see in Figure 2 that after correction for pP Faultless is close to the theoretical curve. The pP correction for Faultless is very large, 0.38 m_b units as compared to 0.22 for Piledriver. Most of this correction can be traced to the unusually long period of the synthetic Faultless seismogram, 1.7 seconds, which can itself be traced to the fortuitous timing of the pP signal. This can be seen by comparison of Piledriver and Faultless in Figure 1. That this effect is operative in the actual observations was checked by comparing periods at common stations for these two events. The values for Piledriver and Faultless

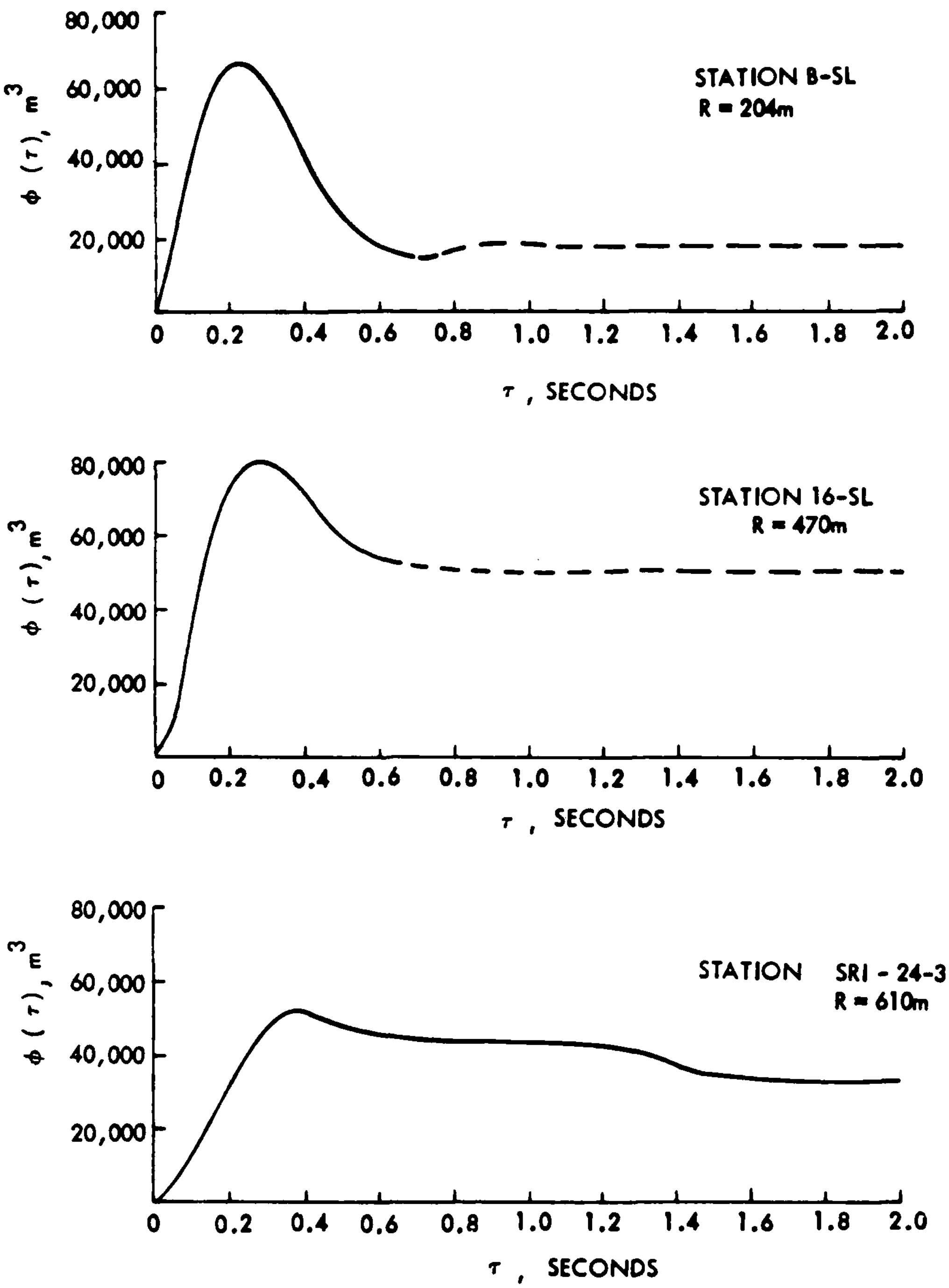


Figure 3 a. Observed Pile Driver Reduced Displacement Potentials, Stations B-SL, 16-SL and SRI-24-3

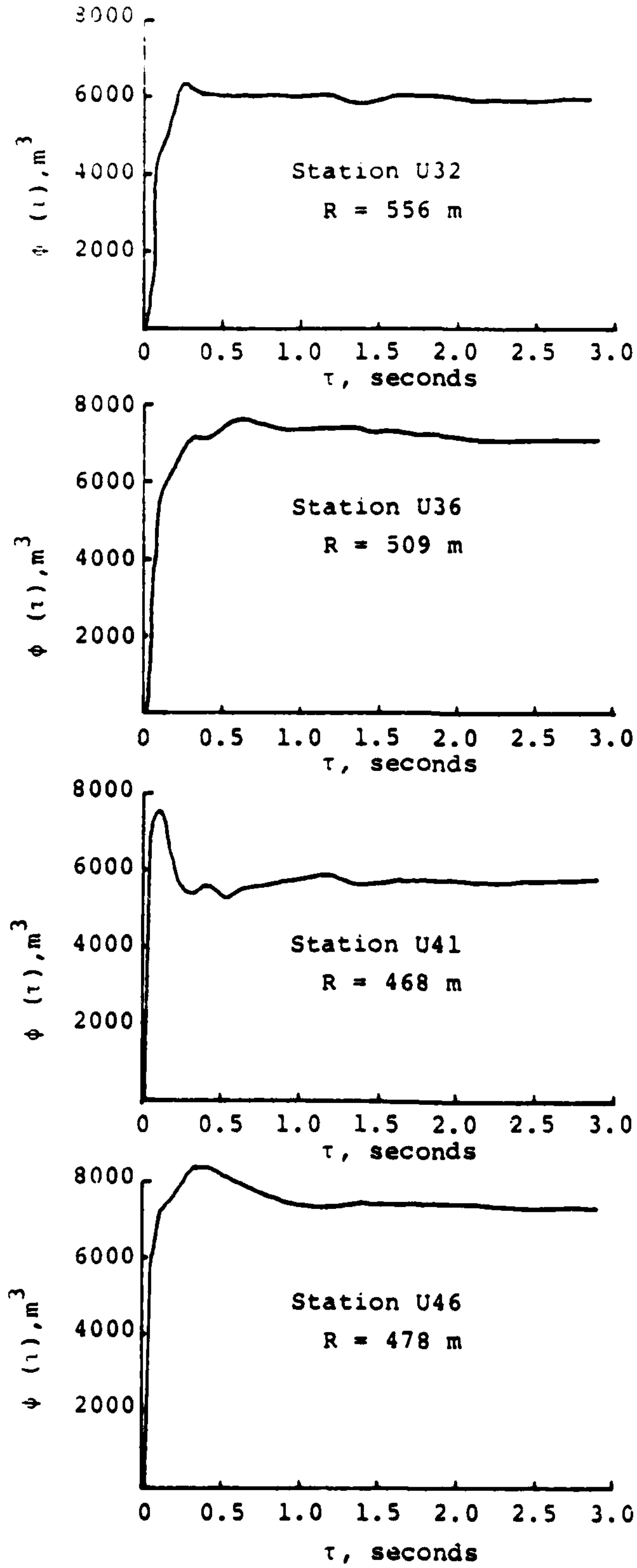
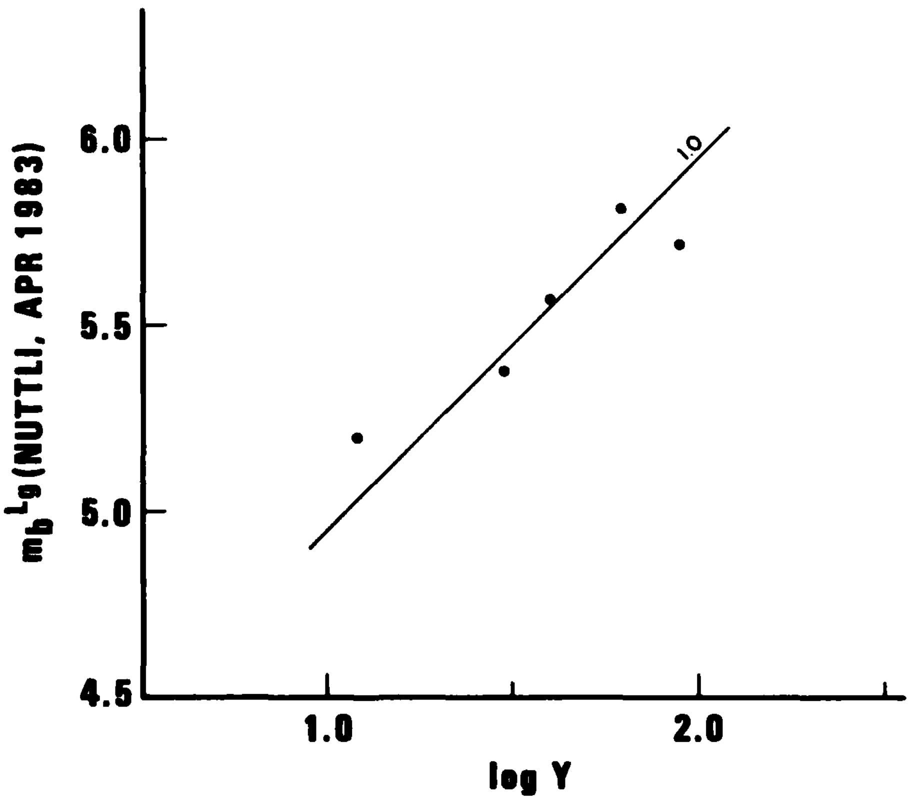


Figure 3b. Observed Gasbuggy Reduced Displacement Potentials Stations U32, U36, U41 and U46.


6.0
5.5
5.0
4.5
1.0
2.0
log Y
m_b^{Lg} (NUTTLI, APR 1983)
1.0

were 0.9 and 1.4 respectively as compared to the theoretical values of 0.7 and 1.7 as seen in Figure 1. (Note that the theoretical difference without pP is only 0.8 and 1.0). The fact that the difference is in the proper direction and general magnitude is encouraging. The discrepancy in precise periods could easily be due to analyst bias toward periods of 1.0 and should be further investigated by careful analysis at stations which possess excellent signal definition and at digital stations.

The fact that after correction for pP Faultless falls close to a theoretical curve suggests that signals emerging from the Faultless test sites are not anomalous as compared to those emerging from NTS. Thus the fact that Der et al., (1982) found t* at the Faultless site to be close to that at NTS does not seem to be anomalous. On the other hand, it seems that the fact that amplitudes of received signals at the Faultless site average 0.3 m_b low (Der et al., 1982) is still a paradox. Reciprocity would suggest that the Faultless m_b should fall below the curve in Figure 2a; not right on or slightly above as it does.

As a secondary topic in this study we mention that in paper A a literature survey was made to determine the geological layer parameters of the WWSSN stations used in the analysis; and Haskell-type calculations were made to determine the resulting elastic station corrections.

As one task in the present work we have tested whether application of these station corrections appears to offer any benefit; and the conclusion is that apparently it does not. (The conclusion is not too surprising the rms station correction is 0.05 m_b units; while the rms residual is approximately 0.3 m_b units). In particular the maximum change in an m_b estimate is 0.01, and the rms residual changes from, 0.312 to 0.314; actually an increase!

APPENDIX C

Dynamic (Amplitude) Criteria for Automatic Association

M E M O R A N D U M

TO: A. Kerr, W. Dean, J. Goncz, R. North, R. Slunga, R. Shumway

FROM: R. Blandford

SUBJECT: Dynamic-Kinematic Criteria for Event Reality

DATE: 7 October 1982

We now have a complete "system" for dynamic-kinematic amplitude checking; attached to this memo. I think this system could be checked out fairly well with the artificial data John Goncz and I are generating. The subroutine amp may diverge if very large or small ID = 1 type values are in the data. Bob Shumway and I will soon distribute an improved version of amp. I think this code is in a "final" state suitable for use in existing AA programs. Only the I/O needs to be modified, and this is fairly well isolated in the event.f and mkpkin.f files.

As long as we are talking about AA, I propose a measure of AA quality, "Association Percentage" defined as follows. Define events which are to be detected; e.g. events with 5 non-array stations; plus events with two arrays and one confirming station, plus events with 2 P waves and one S, etc. All arrivals in this set of events when perfectly analyzed constitute the "base set of arrivals". Now we go down the perfect bulletin and pick out the first event. Is there an event in the AA with (75%) of the arrivals. (Obviously 75% is a variable; probably anywhere between 60% and 90% is alright.) If so, then all correct arrivals in that AA event may be added to the total correct arrivals count; and all incorrectly associated arrivals should be subtracted. I propose that a correctly associated arrival should count even if the phase name is incorrect. (Or perhaps it should get 1/2 or 0 weight if incorrectly identified.) In this way all "perfect bulletin" events are considered. Any remaining arrivals which have been associated into events (which are, presumably "false" or "bad" events and which will give an analyst severe trouble to clean up) will be subtracted from the total correct arrivals count. The Association Percentage is calculated as (total correct arrivals count)/(base set of arrivals).

This measure:

Doubly penalizes the creation of false events and incorrect association to good events.
Rewards correct identification of later phases.
Does not depend on location error which is highly variable depending on event size and travel-time residuals.
Can be easily calculated automatically.
Perhaps too severely penalizes splitting large events, especially an equal split.

INTRODUCTION

The problem of verifying that magnitude estimators for events which have been created by an automatic association (AA) routine are based on a reasonable subset of detecting and non-detecting stations has been considered by Elvers (1980). She developed a "plausibility function" for the amplitude distributions which is essentially proportional to the likelihood of observing a particular configuration of amplitudes when the event is assumed to have occurred.

In this discussion, we attempt to improve several aspects of this procedure. As a computational improvement we also have developed a Newton-Raphson procedure for computing the maximum likelihood magnitude, assuming the signal and noise variances are known. This procedure runs much faster than the search techniques used by previous authors.

We also give a method for discarding single stations with outlying amplitudes (I, see Figure 1) based on the "influence" they exert on the magnitude estimator. This replaces the Elvers procedure of comparing the separate components of the likelihood for the purpose of determining the influential stations. Our procedure for discarding stations is also apparently not so likely to "destroy" the event in the case that a large number of stations are "down" and fail to report, but do not inform the bulletin analysis center of this fact.

Slunga (personal communication, 1982) has pointed out that the "dynamic" amplitude criteria of Elvers seem to erroneously discard arrivals from an event on the basis of amplitude anomalies. On occasion, although the amplitudes are indeed anomalous, the probability that the arrival time could agree by accident seems even smaller, so that it seems unreasonable to totally discard the arrival from the event.

To help remedy this paradox we propose to measure the overall event plausibility with a "kinematic" likelihood ratio (II) in parallel with the dynamic one. If the dynamic criteria suggest that an observed amplitude is unreliable but the kinematic criteria are favorable, then we suggest that the appropriate procedure in most cases is to assume that there is some error in the amplitude measurement and to recalculate the magnitude, after making an appropriate change in the amplitude data, but to continue to use the reported arrival time for estimation of location.

Finally, we have developed a procedure for tying these new computational techniques together. In general terms this procedure is not derived from theoretical considerations but embodies common sense ideas about the causes of erroneous amplitude measurements.

It is important to emphasize that these techniques cannot simply be inserted into an automatic association program as mathematical routines like, for example, the cosine function. Instead the routines contain parameters which are specific to the network, detectors, and methods of analysis. These parameters must be determined by careful statistical analysis of network bulletins which are relatively error-free, and by analysis of false events produced by the automatic association program in which they are to be used.

FUNCTIONAL DESCRIPTION

In Figure 1 we see a flow chart of the proposed procedure. The Roman numerals I-II denote the computational techniques referred to in the Introduction.

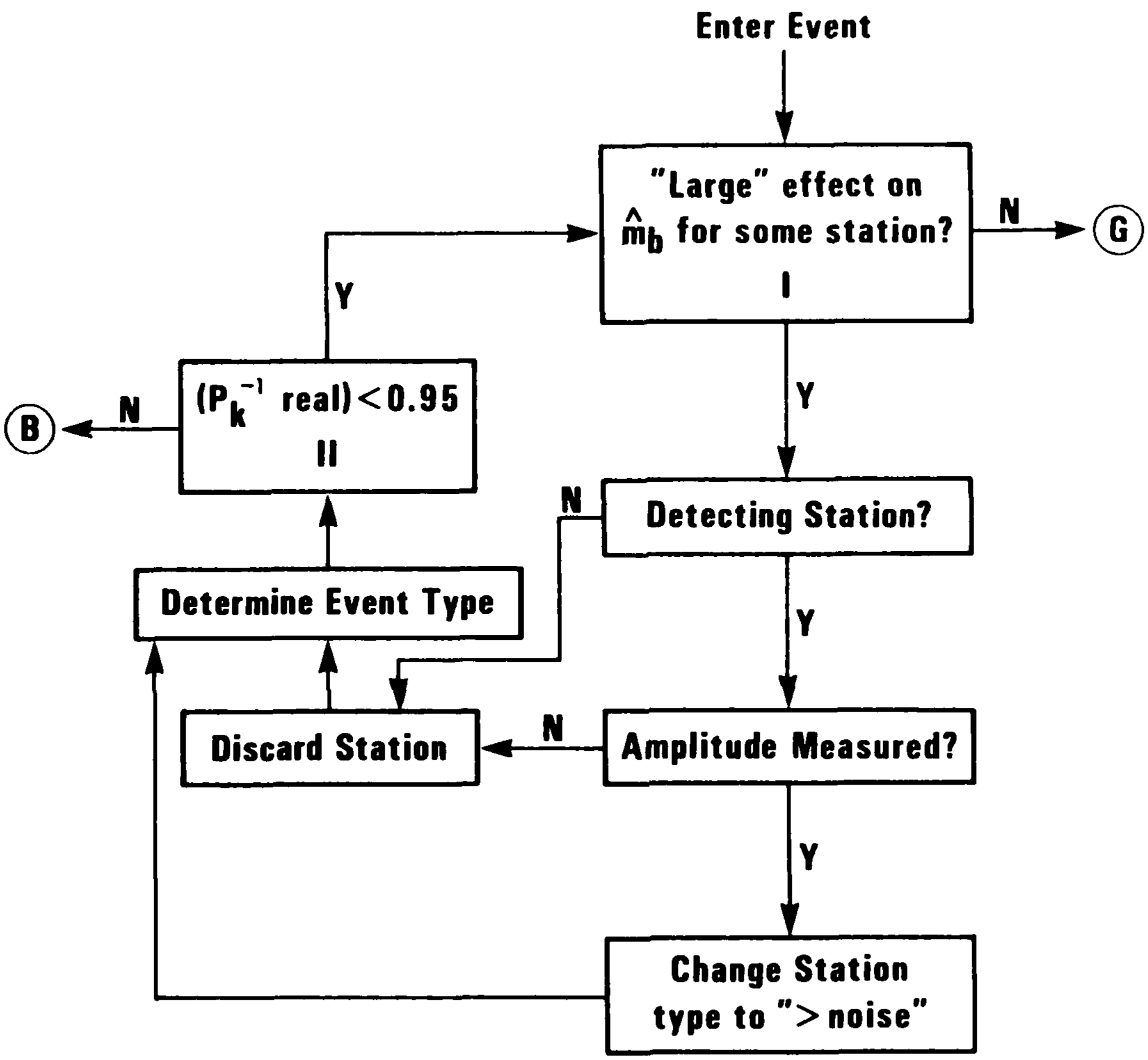
At the top of Figure 1 we see that the event is submitted to the program for analysis. Obviously only those events should be accepted for which the program is prepared. For example we may anticipate that the first version of the program will be prepared to work only on initial P waves. If the event is made up of Pg, S, Lg, etc. then the algorithm has nothing to contribute. On the other hand an event with only one P wave and without an amplitude reading may be submitted. The single detection might be unlikely because many stations with lower thresholds nearby the detecting station did not detect. When this P wave is discarded then the event might be unreliable on kinematic grounds.

The event data is then submitted to a subroutine (I) which computes the Ringdal magnitude and detects outlying magnitudes. In Appendix I is a discussion and listing of a subroutine (amp) which rapidly computes the Ringdal magnitude given station amplitudes and thresholds in terms of magnitudes, and assuming that the signal and noise variances are known. Before this subroutine can be used, of course, distance-amplitude relations must be used to transform amplitudes and thresholds to magnitudes.

The amplitude patterns can be subdivided roughly into n_1 observed amplitudes, n_2 above the noise threshold and with arrival times but not amplitudes reported, and n_3 below the noise threshold and not detected. Of course other subcategories such as clipping might be added. For the general unknown magnitude case the log-likelihood as given by Elvers (1980) would be of the form:

$$\ln L(m) \overset{o}{=} -\frac{n_1}{2} \ln \sigma_s^2 - \frac{1}{2\sigma_s^2} \sum_{j=1}^{n_1} (m_j - m)^2 + \sum_{j=1}^{n_2} \ln \Phi(Z_j) + \sum_{j=1}^{n_3} \ln \Phi(-Z_j) \qquad (1)$$

FLOW CHART FOR DYNAMIC-KINEMATIC ANALYSIS FOR AUTOMATIC ASSOCIATION



Pa – Amplitude probability	(G) – Good event exit
P_k^{-1} – Kinematic probability with one less station if a suspect station has been removed	(B) – Bad event exit

Figure 1.

where m_j are the observed amplitudes, m is the theoretical magnitude and:

$$z_j = \frac{m - \bar{D}_j - C}{\sqrt{\sigma_s^2 + \sigma_j^2}}$$

is a standard value depending on the mean noise level $\bar{D}_j$ with variance σ_j^2, the theoretical magnitude m with observed variance σ_s^2, and a signal-to-noise constant C. Since m is the only unknown, (1) can be maximized using the Newton-Raphson or scoring algorithms, which leads to the maximum likelihood estimator m and its estimated variance $\hat{\sigma}^2_{\hat{m}}$ (see Appendix I). The above approach is essentially that followed by Elvers (1980).

As a modification to the above Elvers (1980) suggests comparing the value of the maximized log likelihood, say $\ln L(\hat{m})$ with some arbitrary threshold, with the first component of (1) modified to behave like an estimated interval probability. If the total plausibility, say $\ln L(\hat{m})$ is too small, then the event can be rejected. The other decision that can be made at this point in the Elvers procedure is to discard a single station value based on a single station component of $\ln L(\hat{m})$. For example the decision to reject a station j which does not observe is based on the value of $\ln(\Phi(-z_j))$, which is the probability of observing a value below the noise threshold at the jth station.

The problem, mentioned by Elvers (1980), with this approach is that the total plausibility depends in part upon point values of the density and in part upon interval probabilities which are integrated densities. Thus it is likely that eliminating an event purely on this criterion will unnecessarily eliminate events. The problem is magnified when one uses the Elvers (1980) procedure to eliminate single stations; purely on the basis of their plausibility values.

As a better method for detecting station outliers, we suggest recalculating the magnitude estimator with each station value missing to obtain, say $m_{(-i)}$ for $i=1,\ldots,n$, where $m_{(-i)}$ denotes the magnitude estimated when station i is left out of the calculation. These can be compared with the original estimator, say m, to determine the "influence of station i. For example, a common measure of influence is "Cook's distance", defined in this case by:

$$z_{(-i)} = \frac{\hat{m} - \hat{m}_{(-i)}}{\hat{\sigma}_{\hat{m}}} \qquad (2)$$

An heuristic procedure suggested by Cook is to reject station i when $z_{(-i)}$ moves further away from zero than $z(\alpha/2)$, where α is some arbitrary probability value.

As an example of how the two procedures for amplitude verification might work in practice, consider the 11 station "event", shown schematically in Table 1. We note first that taking the simple mean of the observed magnitudes yields $\overline{m} = 4.04$, whereas the maximum likelihood estimator is $\hat{m} = 3.78$ with estimated standard deviation $\hat{\sigma}_{\hat{m}} = .12$ so that the censored observations definitely pull the estimator down.

In order to determine whether any of the station values m_i are outliers, we may use the analogue of Cook's distance given in equation (2). The estimated deleted station magnitudes $\hat{m}_{(-i)}$ for i=1,2,...,11 are shown in Table 1 and we note that the greatest change is produced by omitting station 6($\hat{m}_{-6} = 3.89$) which is the value known to be below its noise threshold $\overline{D}_3 = 3$. The elimination of this station then moves the maximum likelihood estimator back towards the mean.

A program, DETZ, which produces the values of $z_{(-i)}$ is given in Appendix I.

TREATMENT OF STATIONS WITH ANOMALOUS AMPLITUDES

Returning to Figure 1 we must ask what course of action to take when an anomalous station amplitude is discovered by procedure I. First we determine if the most anomalous station has reported a detection or if, as in Table 1, it has simply failed to report at all, implying that the signal level is below the noise level. In the latter case we follow the approach suggested by Elvers (1980) and simply discard the station. However, we may look ahead a bit and note that, unlike Elvers we

TABLE 1

MAXIMUM LIKELIHOOD ESTIMATORS FOR MAGNITUDE

Case I	i	Data	$\hat{m}_{-i}$	$\hat{\sigma}_{\hat{m}}$	lnL	$z_{(-i)}$
Station	1	4.0	3.74	.13	1.03	.32
	2	3.6	3.80	.12	.96	-.25
	3	4.4	3.67	.13	2.27	.89
	4	4.0	3.74	.13	1.03	.32
	5	4.2	3.70	.13	1.51	.60
*	6	3.0	3.89	.17	6.14	-1.00
	7	4.0	3.80	.12	3.06	-.23
	8	4.2	3.79	.12	2.87	-.14
	9	3.9	3.81	.12	3.20	-.29
	10	4.5	3.78	.12	2.73	-.05
	11	5.0	3.78	.12	2.68	-.00
	Overall		3.78	.12	2.68	

immediately test for the kinematic probability of this event (II) and if the probability of the event being real is less than say 0.95 then we exit the routine with a bad event flag. That is, non-detection by this station suggests that there is something wrong with the event, and unless the kinematic probability is high the event is discarded. On the other hand, if the kinematic probability of the event is high, then probably there was something wrong at the station, and we return to further analyze the event without considering this station. Since in practice many stations fail to report due to operational consideration we should probably set a less restictive threshold for the non-detecting stations, that is, we should tend to reject them first. For example, if for a non-detecting station $z_{(-i)} \leq -0.7$ reject it (see Table I) but otherwise require $z_{(-i)} \geq 1.0$ for rejection. Probably we should have no anomalous non-detecting station remaining before considering other stations. Further work, perhaps empirical is needed to best determine those thresholds.

If the anomalous station did detect we ask if an amplitude was measured or not. If no amplitude was measured then we must have the situation where this station could not have been expected to detect; typically a station in a shadow zone to a small event. Again we discard the station and check the kinematic probability. Since we have by this time eliminated many of the incorrectly non-reporting stations, the event magnitude should not be biased too low so that stations should not be incorrectly thrown out at this point.

Finally we have the case where there is an amplitude measurement at the anomalous station: either it is too large or too small. In either case we assume that some blunder has been made and that if a true signal has been detected then the amplitude has been recorded or transmitted incorrectly. Thus we simply change the amplitude measurement (not in the original files of course) to state that the signal was greater than the noise. Again we proceed through the kinematic criterion. Note that if this event comes around again then this detection will not have a measured amplitude so that if it is unlikely that this station could have detected the event at all the arrival will be discarded.

KINEMATIC REJECTION CRITERIA (II)

The kinematic criteria for the event existence [illegible] as follows. First, it is necessary to establish event types which will consist of the number of array stations and the number of non-array stations detecting. These stations may also have to be broken down by the criteria of analyst and automatic detection. For each type of event we may determine the ratio of good events to false events of each type in each day. This ratio then gives directly the probability that an event of each type is real.

PROCESSING AFTER DYNAMIC CHECKING

If any detections have been discarded then the reduced set of arrivals should be used to generate a new trial epicenter. If the same final set of arrivals should result then the iteration should be suspended. Care needs to be taken to avoid an infinite loop.

REFERENCES

Elvers, E. (1980). International Seismological Data Center: Procedures to check events through dynamic information and to estimate magnitudes, FOA Report C 20368-T1. Forsvarets Forskningsanstalt Huvudavdelning 2, Stockholm, Sweden.

Ringdal, F. (1976). Maximum likelihood estimation of seismic magnitude, Bull. Seism. Soc. Am., 66, 789-802.

Slunga, R. (1980). An algorithm for associating reported arrivals to a global seismic network into groups defining seismic events, FOA Report C 20386-T1, Forskningsanstalt Huvudavdelning 2, Stockholm, Sweden.

APPENDIX I

We have developed a Newton-Raphson algorithm for maximizing ln L(m) by noting that:

$$\frac{d \ln L(m)}{dm} = \frac{n_1}{\sigma_s^2} (\bar{m}im) + \sum_{j=1}^{n_2} \frac{R(Z_j)}{w_j} - \sum_{j=1}^{n_3} \frac{R(-Z_j)}{w_j} \quad \text{(A1)}$$

where

$$R(Z_j) = \frac{\alpha(Z_j)}{\Phi(Z_j)} \quad \text{(A2)}$$

and

$$w_j = \sqrt{\sigma_s^2 + \sigma_j^2} \quad \text{(A3)}$$

where z_j given by the equation in the main text with:

$$\Phi(Z) = \int_{-\infty}^{Z} \alpha(x)\, dx \quad \text{(A4)}$$

and

$$\alpha(x) = (2\pi)^{-\frac{1}{2}} \exp\left(- x^2/2\right) \quad \text{(A5)}$$

Also:

$$\frac{\partial^2 \ln L(m)}{dm^2} = -\frac{n_1}{\sigma_s^2} - \sum_{j=1}^{n_2} \frac{(Z_j R(Z_j)+R^2(Z_j))}{w_j^2} - \sum_{j=1}^{n_3} \frac{(Z_j R(Z_j)+R^2(-Z_j))}{w_j^2}$$

Then the Newton-Raphson interations are of the form

$$m_{i+1} = m_i - \frac{\left(\frac{\partial \ln L(m)}{dm}\right)_{mi}}{\left(\frac{\partial^2 \ln L(m)}{dm^2}\right)_{mi}} \qquad (A6)$$

with the final estimator $\hat{m}$ having an estimated standard error given by

$$\hat{\sigma}_{\hat{m}} = \left\{ \frac{\partial^2 \ln L(m)}{dm^2} \right\}^{\frac{1}{2}}_{\hat{m}} \qquad (A7)$$

```
c
c...    Driver program for dynamic-kinematic subroutine
c
        Integer DIMEN,maa,mad,msa,msd
        Parameter (DIMEN=50)
        Parameter (maa=5,mad=0,msa=7,msd=0)
        Real ym(DIMEN),no(DIMEN),sg(DIMEN)
        Real ymc(DIMEN)
        Real fm,se,fl,ss,c,znop,zlrg,zvlrg,pthr,pobs
        Real pkin(0:maa,0:mad,0:msa,0:msd)
        Integer id(DIMEN)
        Integer idc(DIMEN),gb(DIMEN),gbc(DIMEN),ns,i,naa,nad,nsa,nsd
        Integer j,k,l
        Logical ary(DIMEN),anlyst(DIMEN)
        Logical ok
c
c...            See comments in dynkin for the following parameters
c
        ss=.4
        c=1.
        znop=-.7
        zlrg=+1.
        zvlrg=1.5
        pthr=.90
        naa=maa
        nad=mad
        nsa=msa
        nsd=msd
c
c...            Get the kinematic matrix
c
        call mkpkin(pkin,naa,nad,nsa,nsd)
        open (2,status='new',form='formatted',file='event.out')
c       write(2,50)((((pkin(i,j,k,l),i,j,k,l,i=0,naa),j=0,nad),k=0,nsa),
c    &  l=0,nsd)
   50   format(f10.2,4i5)
c
c...            Get event
c
        call event(ym,no,ns,id,sg,ary,anlyst,gb)
c
        write(2,100) (i,ym(i),no(i),sg(i),id(i),ary(i),anlyst(i),
     &  gb(i),i=1,ns)
  100   format (i5,3f8.1,i5,2L5,i5)
c
c...            Main call
c
        call dynkin(ym,no,ns,id,sg,fm,se,fl,ss,c,
     &  znop,zlrg,zvlrg,ary,anlyst,ymc,idc,pthr,pobs,gb,gbc,ok,
     &  pkin,naa,nad,nsa,nsd)
c
        write(2,200) ok
        write(2,250) fm,fl,pobs
  250   format(' fm = ',f10.2,'  fl = ', f10.2,' pobs = ',f10.2)
  200   format (' ok = ',L5)
        write(2,100) (i,ym(i),no(i),sg(i),id(i),ary(i),anlyst(i),
```

```
     &  gb(i),i=1,ns)
        write(2,300) (i,ymc(i),idc(i),gbc(i),i=1,ns)
  300   format(i5,f10.2,10x,2i5)
        stop
        end
```

```
      subroutine  dynkin(ym,no,ns,id,sg,fm,se,fl,ss,c,
     & znop,zlrg,zvlrg,ary,anlyst,ymc,idc,pthr,pobs,gb,gbc,ok,
     & pkin,naa,nad,nsa,nsd)
c
c...  Subroutine to examine amplitudes of an event and determine
c...  if they are anomalous.
c
c...  id(.)=1 if observed and amplitude measured
c...  id(.)=2 if observed but amplitude not measured so signal
c...          greater than noise
c...  id(.)=3 if not observed so signal is less than noise
c
c...  idc(.)  same as id except with changed values as appropriate
c...          on return
c...  gb(.)=1 if station is good and should not be
c...          thrown out
c...  gb(.)=0 if station is bad and should be thrown out
c
c...  gbc(.)  same as gb except with changed values as appropriate
c...          on return
c...  ym      input array of ns magnitudes with distance and station
c...          corrections applied
c...  ymc     returned array of ns magnitudes
c...  no      array of station noise levels with distance and
c...          station corrections applied.
c...  sg      noise standard error (typically 0.2, but smaller
c...          if noise measured especially for this event)
c...  se      standard error of network magnitude estimate
c...  fl      log-likelihood of fm
c...  ss      standard error of signal amplitudes (typically 0.4)
c...          might want to make this an array if signal variance
c...          were known to be small at some station
c...   c      S/N required for detection
c
c...  pthr probability threshold required to pass kinematic
c...          test, typically .95.
c...  pobs    returned kinematic probability of the event
c...  ok      ok=.true. , nothing wrong with event as returned,
c...          if ok = .false. the event as returned fails the
c...          kinematic probability test and should be released
c...  ary     ary = .true. station is an array station
c...  anlyst  anlyst = .true. detection verified by analyst
c...            These two variables are used to define four
c...            "types" of detections, and thus the "type" event
c...  aa,ad   number of sites with array and analyst, array
c...          and automatic detector.
c...  sa,sd   same as for arrays but for single site
c
c...  znop    if a station is inoperative it will incorrectly
c...          be "reported" as not detecting because the signal
c...          is below the noise. If this station is left out
c...          then the event magnitude will increase, i.e.
c...          z will be negative. znop is the threshold to
c...          detect these events; we should set its' threshold
c...          fairly high, say znop = -.7
c
```

```
c...      zlrg      a large amplitude generates a positive z, try
c...                zlrg = 1
c...      zvlrg     z for throwing out wild values, try zvlrg = 1.5
c
          Parameter (DIMEN=50)
          Real ym(ns),ymc(ns),no(ns),sg(ns),fm,se,fl,ss,c,z(DIMEN),ss
          Integer naa,nad,nsa,nsd
          Real pkin(0:naa,0:nad,0:nsa,0:nsd)
          Real zma,zmin,znop,zlrg,zvlrg,pthr,pobs
          Integer id(ns),idc(ns),gb(ns),gbc(ns),ns,i
          Integer izma,izmin,aa,ad,sa,sd,izf
          Logical ok,ary(ns),anlyst(ns)
c
          ok = .false.
          do 10 i = 1,ns
          ymc(i) = ym(i)
          idc(i) = id(i)
          gbc(i) = gb(i)
   10     continue
          call type(ary,anlyst,idc,gbc,ns,aa,ad,sa,sd)
c
   20     call detz(ymc,no,ns,idc,sg,gbc,fm,se,fl,ss,c,z)
          call maxv(z,idc,gbc,ns,zma,izma)
          call minv(z,idc,gbc,ns,zmin,izmin)
c
c...               first throw out wild ones
c
          if(abs(zma).gt.zvlrg.or.abs(zmin).gt.zvlrg) then
                  if(abs(zma).gt.abs(zmin))then
                          izf=izma
                  else
                          izf=izmin
                  endif
          else
c
c...               then check others
c
                  if (zmin.gt.znop.and.zma.lt.zlrg) then
                          ok = .true.
                          return
                  endif
                  if (zmin.le.znop) then
                          izf=izmin
                  else
c
c...                       consider large amps only if no anomalous
c...                       small amplitudes remain
c
                          izf=izma
                  endif
          endif
          if((idc(izf).eq.3).or.(idc(izf).eq.2)) then
                  gbc(izf) = 0
                  idc(izf) = 3
          endif
          if(idc(izf).eq.1) then
```

```
                idc(izf) = 2
                ymc(izf) = 0.0
c
c...            above formula assumes noise levels are in magnitude
c...            units
c
        endif
        call type(ary,anlyst,idc,gb,ns,aa,ad,sa,sd)
        if(aa.le.naa.and.ad.le.nad.and.sa.le.nsa.and.sd.le.nsd)then
                pobs = pkin(aa,ad,sa,sd)
        else
                pobs = .999
        endif
        if(pobs.gt.pthr) then
                go to 20
        else
                return
c
c...                    returns with ok = .false
c
        endif
        end
```

```
      subroutine detz(ym,no,ns,id,sg,gb,fm,se,fl,ss,c,z)
c
c...    Calculate z(.), an array of normal variables showing
c...    influence of ym measurement on fm. After Bob Shumway
c...    June 1982
c
c...    id(.)=1 if observed and amplitude measured
c...    id(.)=2 if observed but amplitude not measured so signal
c...            greater than noise
c...    id(.)=3 if not observed so signal is less than noise
c...    gb(.)=1 if station is good and should not be thrown out
c...    gb(.)=0 if station is bad and should not be thrown out
c
c...    ym      array of ns magnitudes with distance and station
c...            corrections applied
c...    sg      noise standard error (typically 0.2, but smaller
c...            if noise measured especially for this event)
c...   "xxi"    variables internal to amp so that variables don´t
c...            scrambled
c...    se      standard error of network magnitude estimate
c...    fl      log-likelihood of fm
c...    ss      standard error of signal amplitudes (typically 0.4)
c...            might want to make this an array if signal variance
c...            were known to be small at some station
c...     c      S/N required for detection
c
      Parameter (DIMEN = 50)
      Real ym(ns),no(ns),sg(ns),se,fl,ss,fm,z(ns)
      Integer id(ns),gb(ns),ns
      Real ymi(DIMEN),noi(DIMEN),sgi(DIMEN),fmr,ser,flr,c
      Integer idi(DIMEN),ic,i,k,j,L,gbi(DIMEN)
c
      ic = 1
      call amp(ym,no,ns,id,sg,gb,ic,fm,se,fl,ss,c)
      do 20 i = 1,ns
      k = 1
      do 15 j = 1,ns
      if(j.eq.i) go to 15
      ymi(k) = ym(j)
      noi(k) = no(j)
      idi(k) = id(j)
      sgi(k) = sg(j)
      gbi(k) = gb(j)
      k = k + 1
   15 continue
c     write(2,101)(i,L,ymi(L),noi(L),idi(L),L=1,ns-1)
  101 format(2i5,2f10.3,i5)
      call amp(ymi,noi,ns-1,idi,sgi,gbi,ic,fmr,ser,flr,ss,c)
      z(i)=(fm-fmr)/se
   20 continue
      return
      end
```

```
      Subroutine amp(ym,no,ns,id,sg,gb,ic,fm,se,fL,ss,c)
c
c...   Calculate log likelihood of amplitude configuration;
c...   or
c...   Maximum likelihood estimator for magnitude using Newton-
c...   Raphson method
c
c...   by Bob Shumway, June 1982
c
c...   ic   =0 if likelihood only at fm needed
c...   ic   =1 if Newton-Raphson estimator for fm needed
c
c...   id(.)=1 if observed and amplitude measured
c...   id(.)=2 if observed but amplitude not measured so signal
c...           greater than noise
c...   id(.)=3 if not observed so signal is less than noise
c
c...   gb(.)=1 if station is good and should not be thrown out
c...   gb(.)=0 if station is  bad and should not be thrown out
c
c...   ym      array of  magnitudes with distance and station
c...           corrections applied
c...   no      array of noise magnitudes with distance and station
c...           corrections applied; substituted for ym when
c...           id.ne.1
c...   sg      noise standard error (typically 0.2, but smaller
c...           if noise measured especially for this event)
c...   se      standard error of network magnitude estimate
c...   fL      log-likelihood of fm
c...   ss      standard error of signal amplitudes (typically 0.4)
c...           might want to make this an array if signal variance
c...           were known to be small at some station
c...    c      S/N required for detection
c...   toler   magnitude tolerance for terminating iterations
c
      Parameter (toler = .002)
      Integer ns
      Real ym(ns),no(ns),sg(ns),se,fL,ss,fm,c
      Integer id(ns),gb(ns),ic
      Real fmb,d1,d2,z,ph,r,w,sss,lc
      Integer nl,it,j,k,nit
      Real probf,p
c
      nit=20
      sss=ss*ss
      lc = log10(c)
     if(ic.eq.0) go to 15
      fmb=0.
      nl=0
     do 10 j=1,ns
     if((id(j).gt.1).or.(gb(j).eq.0)) go to 10
      nl=nl+1
      fmb=fmb+ym(j)
 10   continue
      fmb=fmb/(Real(nl))
      fm=fmb
```

```
      go to 17
 15    nit=1
 17    continue
c
      do 40 it = 1,nit
       fL=0.
       d1=0.
       d2=0.
      do 35 j=1,ns
       if(gb(j).eq.1) then
               k=id(j)
               go to (20,25,30) ,k
       else
               go to 35
       endif
 20    fL=fL-log(sss)-((ym(j)-fm)**2)/(2.*sss)
       d1=d1+(fmb-fm)/(sss)
       d2=d2-1./(sss)
      go to 35
 25    w=sqrt(sss+sg(j)*sg(j))
       z=(fm-no(j)-lc)/w
       ph=probf(z)
       r=p(z)/ph
       fL=fL+log(ph)
       d1=d1+r/w
       d2=d2-(z*r+r*r)/(w*w)
      go to 35
 30    w=sqrt(sss+sg(j)*sg(j))
       z=(no(j)+lc-fm)/w
       ph=probf(z)
       r=p(z)/ph
       fL=fL+log(ph)
       d1=d1-r/w
       d2=d2+(-z*r-r*r)/(w*w)
 35    continue
c
       se=sqrt(-1./d2)
       if(it.eq.nit.or.abs(d1/d2).lt.toler) go to 40
       fm=fm-d1/d2
c      write(2,100) it,fm
100    format(' it,fm =',i5,f10.3)
 40    continue
       return
       end
```

```
4.0  3.9  0.2     1.true.    .true.      1
3.6  3.9  0.2     1.true.    .true.      1
4.4  3.9  0.2     1.false.   .true.      1
2.9  3.9  0.2     1.false.   .true.      1
0.0  5.2  0.2     2.false.   .true.      1
0.0  2.0  0.2     3.false.   .true.      1
0.0  4.2  0.2     3.false.   .true.      1
0.0  4.2  0.2     3.false.   .true.      1
0.0  3.9  0.2     3.false.   .true.      1
0.0  4.5  0.2     3.false.   .true.      1
0.0  5.0  0.2     3.false.   .true.      1
```

sta	mag	noise	noi var	id	ary	anlyst	gb	
1	4.0	3.9	0.2	1	t	t	1	
2	3.6	3.9	0.2	1	t	t	1	
3	4.4	3.9	0.2	1	f	t	1	
4	2.9	3.9	0.2	1	f	t	1	← ①
5	0.	5.2	0.2	2	f	t	1	← ②
6	0.	2.0	0.2	3	f	t	1	← ③
7	0.	4.2	0.2	3	f	t	1	
8	0.	4.2	0.2	3	f	t	1	
9	0.	3.9	0.2	3	f	t	1	
10	0.	4.5	0.2	3	f	t	1	
11	0.	5.0	0.2	3	f	t	1	

ok = t

fm = 3.88 f1 = 2.34 pobs = 0.95

1	4.0	3.9	0.2	1	t	t	1
2	3.6	3.9	0.2	1	t	t	1
3	4.4	3.9	0.2	1	f	t	1
4	2.9	3.9	0.2	1	f	t	1
5	0.	5.2	0.2	2	f	t	1
6	0.	2.0	0.2	3	f	t	1
7	0.	4.2	0.2	3	f	t	1
8	0.	4.2	0.2	3	f	t	1
9	0.	3.9	0.2	3	f	t	1
10	0.	4.5	0.2	3	f	t	1
11	0.	5.0	0.2	3	f	t	1

sta	mag	idc	gb ←
1	4.00	1	1
2	3.60	1	1
3	4.40	1	1
4	0.	2	1
5	0.	3	0
6	0.	3	0
7	0.	3	1
8	0.	3	1
9	0.	3	1
10	0.	3	1
11	0.	3	1

① Detected, noise reasonable for detection but signal measured too low, so retain detection but discard amplitude and say S > N, so idc goes 1 → 2

② Detected, but noise too high, so discard detection - e.g. a shadow zone "detection". So gb goes 1 → 0

③ Not detected, but noise very low - so discard station, it must be down so gb goes 1 → 0

```
      subroutine event(ym,no,ns,id,sg,ary,anlyst,gb)
      Integer DIMEN
      Parameter (DIMEN = 50)
      Integer id(DIMEN),ns,i,gb(DIMEN)
      Real ym(DIMEN),no(DIMEN),sg(DIMEN)
      Logical ary(DIMEN),anlyst(DIMEN)
c
c...          Sample data from 8 September 82 memo by Blandford
c...          and Shumway. Would typically be replaced by access
c...          package to files.
c
      Do 10 i=1,DIMEN
      ym(i)=0.
      sg(i)=0.
      id(i)=0
      ary(i)=.false.
      anlyst(i)=.false.
      gb(i)=0
   10 continue
      ns=11
      open(1,status='old',form='formatted',file='event.in')
      rewind 1
      read (1,1) (ym(i),no(i),sg(i),id(i),ary(i),anlyst(i),gb(i),
     & i=1,ns)
    1 format(3f5.1,i5,2L10,i5)
      return
      end
```

```
      subroutine maxv(z,id,gb,ns,zma,izma)
      Real z(ns),zma
      Integer ns,izma,i,id(ns),gb(ns)
c
c...          Finds max value of z statistics for good stations
c...          Initial value of zma is only -10 because are
c...          working with standard deviation units
c
      zma=-10.
      do 10 i = 1,ns
      if(z(i).gt.zma.and.gb(i).eq.1)then
              zma = z(i)
              izma = i
      endif
   10 continue
      return
      end
```

```
      subroutine minv(z,id,gb,ns,zmin,izmin)
c
c...  gets maximum of z statistics for good stations
c...  zmin initially  so small since working in standard deviations
c
      Real z(ns),zmin
      Integer ns,izmin,i,id(ns),gb(ns)
      zmin = 10.
      do 10 i = 1,ns
      if(z(i).lt.zmin.and.gb(i).eq.1)then
              zmin=z(i)
              izmin = i
      endif
   10 continue
      return
      end
```

```
      subroutine mkpkin(pkin,nnaa,nnad,nnsa,nnsd)
c
c...  Reads in the kinematic probability matrix.
c...  This assumes that Nad and
c...  Nsd are 0. This is an example only; the real matrix should
c...  be derived from analysis of true and false events.
c...
c...                                 nsa
c...  0       1       2       3       4       5       6       7
c naa
c  5  .999    .999    .999   etc.
c  4  .99     .99     .999   etc.
c  3  .97     .97     .97     .99     .999    etc.
c  2  .9      .95     .95     .99     .999    etc
c  1  .0      .5      .8      .95     .97     .99     .99     .999
c  0  .0      .0      .0      .2      .8      .9      .95     .97
c
      Integer naa,nad,nsa,nsd,nnaa,nnad,nnsa,nnsd
      Real pkin(0:nnaa,0:nnad,0:nnsa,0:nnsd)
      open(3,status='old',form='formatted',file='pkin.in')
      rewind 3
      read(3,100)((((pkin(naa,nad,nsa,nsd),naa=0,nnaa),nad=0,nnad),
     & nsa=0,nnsa),nsd=0,nnsd)
  100 format(6f5.3)
      return
      end
```

```
      function p(x)
      Real p,x
      p=exp(-x*x/2.)/2.50662828
      return
      end
```

```
      function probf(x)
      double precision q,t
      Real x,probf
      t=abs(x)
      q=((((t*.00063419-.00010754)*t+.01057706)*t+.04833145)*t+
     & .10882473)*t+1.09050773
      q=1./(q*q)
      q=q*q
      probf=q*q
      if(x.le.0.) go to 2
    1 probf=1.-probf
    2 return
      end
```

```
      subroutine type(ary,anlyst,id,gb,ns,aa,ad,sa,sd)
      Integer ns,id(ns),gb(ns),aa,ad,sa,sd,i
      Logical ary(ns),anlyst(ns)
      aa=0
      ad=0
      sa=0
      sd=0
      do 10 i = 1,ns
      if(gb(i).eq.0.or.id(i).gt.2) go to 10
      if(ary(i).and.anlyst(i))              aa = aa + 1
      if(ary(i).and..not.anlyst(i))         ad = ad + 1
      if(.not.ary(i).and.anlyst(i))         sa = sa + 1
      if(.not.ary(i).and..not.anlyst(i))    sd = sd + 1
 10   continue
      return
      end
```

M E M O R A N D U M

TO: J. Goncz

FROM: R. Blandford

SUBJECT: A Better Approach to Handling Amplitude Data in AA

DATE: 19 April 1983

1. Compute maximum likelihood m_b using the observing stations plus a fixed set of about 20 reliable stations. An m_b is calculated with each station omitted in turn. Assume an <u>a-priori</u> $\sigma = 0.35\ m_b$ throughout.

2. Analyze each of the above stations in screen as we do now, get the total number of points, then:

   i. If the station <u>did not</u> detect but

   $$p(det) > .95, \ -1 \text{ point}$$
   $$p(det) > .99, \ -2 \text{ points}$$

   Comments: If p(det) > .95 at many stations most stations will have detected if the event is big and loss of points for the occasional random non-detection will not matter. If the event is weak, only a <u>few</u> close stations will have p(det) > 0.95 so the occasional random non-detection is again unlikely to lose points.

   ii. If the station <u>did</u> detect and if, based on noise and m_b alone

   $$p(det) < .01, -(\text{all points due to station})$$

   Comments: If the event is big there will be so many points that occasionally losing one will not be serious. If it is a small event and just trapped (correctly) the one distant station, then the probability of that happening for any particular one out of the 20 distant stations may be smaller than .05 so for that reason we set this threshold at .01 so that only about 1/5 of these events will be incorrectly rejected. It is important to reject <u>all</u> the points due to the station, i.e. those due to azimuth and slowness and those due to local flags and associated S phases.

   iii. If the station <u>did</u> detect, and reports an amplitude A_o, and if, based on noise and m_b alone,

   $$p(det) > .01 \text{ and}$$
   $$p(amp > A_o) < .01 \text{ or}$$
   $$p(amp < A_o) < .01 \text{ then}$$

discard amplitude, A_o (are left with estimated noise) and return to (1)

Comments: That is, compute all the negative points and m_b values over because the bad amplitude probably distorted all the m_b values. Note that this procedure does not "fiddle" with an event. It either results in complete acceptance or discards the event so that the kinematic processing has a new chance to do better.

RRB/paw

APPENDIX D

Excerpts from

Results of the 1982 WMO/Prototype IDC Experiment
GSE/SG3-SG5/3

by
R. North and H. Olsen

1. Steps Taken in the Generation of Short-Period Arrivals

(1) For each event-station pair, a true event distance was computed.

(2) For each phase valid at this distance, B-factor tables were used to compute a station value for the amplitude/period ratio of the arrival. For P, distance <100 degrees, the B-factors given by Veith and Clawson (1969) were used ; for all other phases, the B-factors given in the tables at the end of this appendix were applied. The mb bias values listed in table 1 of US/GSE/7 were included for P only. Scattering in the earth was modelled by a Gaussian term with standard deviation 0.3 mb units. The period T was then selected randomly in a small interval about 1 second and the amplitude A computed in nanometers.

(3) For events at distances D less than 6 degrees, Pg amplitudes A were computed using

$$\log(A) = mb - 1.6 - 3 \log(D)$$

and S amplitudes were taken to be twice those of P.

(4) The amplitude A of each phase was then compared to the station noise values given in CCD/558. If the signal to noise ratio was less than 1.0, the arrival was not accepted; if between 1 and 2 , it was accepted with a random probability of 50% ; if between 2 and 3, it was accepted with a random probability of 75%; if greater than 3, the arrival was accepted.

It should again be noted here, as in Chapter 2, that the noise levels given in CCD/558 were doubled in order to keep the number of arrivals within reasonable bounds. A Gaussian term with 0.2 mb unit variance was added to the noise before computing the signal to noise ratio.

(5) Station downtime was modelled by allowing the user of the program to specify two down intervals per day for each station.

(6) The phase type of arrivals reported was always given as P or blank (unnamed) according to (13) below, except for depth phases (see (11) below) and Pg and S phases, which were correctly named.

(7) The standard deviation of travel times was set at 1 second for all phases and distances.

(8) Arrival times of the onset were then computed from the true event time

(9) To simulate operator error, in 1% of all arrivals (selected randomly) an error of 1 was included in the minute designator (randomly positive or negative). A 10-second error was randomly introduced in 3% of all cases except for array stations.

(10) For array observations, an error in vector slowness with standard deviation 1.5 seconds/degree was added to each component of the slowness vector calculated from the true azimuth and tabulated slowness for each phase.

(11) Depth phases are named according to the following rules :

a. If P is not detected, pP or sP are not named (blank).

b. If P and sP are detected, but pP is not, and (P-sP)time <1 min , label sP as pP.

c. If P and PcP are detected but pP and sP are not, and (P-PcP)time < 1 min., label PcP as pP.

(12) After all arrivals for a given station and time interval have been generated, the following process is applied to screen out arrivals that probably could not have been determined because of interference from larger earlier arrivals :

a. As a definition, there is a signal S with amplitude As, possibly hidden by a previous signal of amplitude A.

b. If there is not a signal in the 60 seconds before S, let S exist.

c. If there is a signal in the previous 60 seconds, let S exist if As >0.1A, otherwise reject S.

d. If there is a signal in the previous 10 seconds, let S exist if As >0.5A, otherwise reject S.

e. Even if S is rejected, it can still hide arrivals coming after it according to c. and d..

(13) Except for Pg and S (see (6) above) and depth phases (see (11) above), phases are named as follows :

a. If P, named P unless there is another arrival less than 1 minute beforehand, in which case it is unnamed.

b. If anything other than P, named P if there have been arrivals in the preceding 3 minutes ; otherwise unnamed.

B-FACTORS for SECONDARY PHASES

Phase	Dist. (deg.)	B	Phase	Dist. (deg.)	B
P	101	4.590	PKPdf	126	4.280
	102	4.640		127	4.250
	103	4.705		128	4.225
	104	4.780		129	4.215
	105	4.860		130	4.225
	106	4.980		131	4.250
	107	5.125		132	4.290
	108	5.225		133	4.350
	109	5.200		134	4.390
	110	5.025		135	4.410
PKPdf	111	4.820		136	4.410
	112	4.750		137	4.400
	113	4.715		138	4.390
	114	4.675		139	4.375
	115	4.650		140	4.365
	116	4.630		141	4.350
	117	4.600		142	4.100
	118	4.570		143	4.000
	119	4.530		144	4.000
	120	4.490		145	4.000
	121	4.460		146	4.000
	122	4.425		147	4.000
	123	4.385		148	4.000
	124	4.350		149	4.000
	125	4.315		150	4.000
PKPbc	141	4.250		151	4.000
	142	4.250		152	3.980
	143	4.010		153	4.010
	144	3.650		154	4.035
	145	3.510		155	4.060
	146	3.490		156	4.075
	147	3.480		157	4.100
	148	3.480		158	4.140
	149	3.500		159	4.170
	150	3.520		160	4.175
	151	3.550		161	4.185
PKPab	<153	3.580		162	4.185
	154	3.630		163	4.185
	155	3.720		164	4.175
	156	3.800		165	4.175
	157	3.860		166	4.175
	158	3.920		167	4.175
	159	4.000		168	4.170
	160	4.065		169	4.160
	>160	4.150		170	4.160
				171	4.160

B-FACTORS for SECONDARY PHASES

Phase	Dist.	B
PP	10	3.0
	11	3.1
	12	3.2
	13	3.3
	14	3.4
	15	3.5
	20	3.7
	25	3.9
	30	4.0
	35	3.7
	40	3.6
	45	3.6
	50	3.7
	55	3.8
	60	3.9
	65	4.0
	70	4.1
	75	4.1
	80	4.2
	>80	4.2
PcP	0-80	4.00
PKKPab	all	4.60
PKKPbc	all	4.60
PKKPdf	20	5.5
	30	5.4
	40	5.2
	50	5.0
	60	4.7
	130	4.7
	140	4.8
	150	5.0
	160	5.2
	170	5.4
	180	5.5
PKPPKP	30	5.4
	40	5.3
	50	5.0
	55	4.6
	95	4.6
	100	5.0
	110	5.3
	120	5.4
	130	5.4
	140	5.4

Phase	Dist.	B h<70	B h>70
SKPdf	105	5.4	4.6
	110	5.4	4.6
	113	5.2	4.3
	117	5.0	4.1
	120	4.8	3.9
	125	4.7	3.8
	130	4.6	3.7
	140	4.4	3.5
	180	4.4	3.5
SKPab	all	3.9	3.7
ScP	all	4.4	3.9
pP	all	B(P) -0.3	B(P) -0.5
sP	all	B(P) -0.3	B(P) -0.5

APPENDIX V

SYNTHETIC EVENT LIST

This list contains only those events which could have been located on the basis of the event definition criteria given in GSE/SG5/5.

Columns labelled NP, NdP and Nt give, for each event, the number of defining (P/PKPdf), depth (pP,sP) , and total of all, arrivals . An asterisk (*) in the following column indicates that the event appeared (within the margin of error) in the final bulletins given in Appendix IV.

day	time			lat.	long.	dep.	mb	Ms	NP	NdP	Nt		
1	0	33	58.7	63.36	-150.94	88	4.18	3.67	7	2	13	*	CENTRAL ALASKA
1	0	51	16.8	53.49	149.20	10	3.60	3.26	2	0	3		SEA OF OKHOTSK
1	1	36	26.2	-2.53	127.31	30	4.96	4.31	10	7	52	*	CERAM SEA
1	2	5	0.3	31.77	132.95	37	3.81	3.28	3	0	3		SOUTHEAST OF SHIKOKU, JAPAN
1	2	24	8.3	68.00	0.37	32	4.05	3.52	11	8	25	*	NORWEGIAN SEA
1	2	33	22.4	-1.33	105.09	49	4.21	3.96	5	5	12	*	SOUTHERN SUMATRA
1	3	0	16.5	43.69	92.62	18	5.29	4.74	35	23	144	*	NORTHERN SINKIANG PROV., CHINA
1	4	54	49.5	52.80	-177.97	58	4.31	3.60	9	9	23	*	ANDREANOF ISLANDS, ALEUTIAN IS.
1	5	6	4.4	28.59	139.34	286	4.35	3.95	10	3	21	*	BONIN ISLANDS REGION
1	5	25	5.1	51.85	-175.54	7	4.72	4.02	18	13	69	*	ANDREANOF ISLANDS, ALEUTIAN IS.
1	5	49	48.4	48.54	20.74	30	4.47	3.68	10	10	41	*	CZECHOSLOVAKIA
1	5	50	12.2	-44.19	104.65	8	4.72	4.47	7	2	30	*	SOUTHEAST INDIAN RISE
1	7	17	51.0	-2.30	113.91	193	4.46	4.02	8	2	26	*	BORNEO
1	7	22	34.0	38.64	139.89	31	4.14	3.66	4	4	14		NEAR WEST COAST OF HONSHU, JAPAN
1	8	16	12.4	48.50	149.45	78	4.34	4.06	11	6	26	*	NORTHWEST OF KURILE ISLANDS
1	8	57	32.9	21.38	124.63	41	4.29	3.63	9	7	25	*	SOUTHEAST OF TAIWAN
1	10	4	28.6	35.14	143.95	42	3.78	3.42	3	1	4		OFF EAST COAST OF HONSHU, JAPAN
1	12	6	45.1	40.21	34.83	13	3.87	3.33	4	1	7		TURKEY
1	12	13	52.6	49.74	157.09	50	4.11	3.36	4	4	12	*	KURILE ISLANDS REGION
1	13	6	11.4	75.58	0.50	8	3.62	3.27	3	0	4	*	GREENLAND SEA
1	13	22	19.9	37.13	74.14	72	3.86	3.35	3	0	5		TADZHIK-SINKIANG BORDER REGION