# USE OF DEPTH PHASES IN EVENT SCREENING

David Jepsen and Spiro Spiliopoulos
Australian Geological Survey Organisation

## ABSTRACT

Accurate identification of depth phases is essential in improving the performance of the event screening process. In the first Release of event screening software, the rules for depth phases were insufficient, in that events that had inappropriate depth phase picks could satisfy the depth phase criteria. To strengthen the depth phase criteria so there is more confidence in the results, a new set of constraints were examined. The uncertainty in pP and sP onset times and the variability in the earth's velocity structure were the main factors that had to be accounted for. As a result, the existing criteria of a minimum moveout of 1.5 seconds and at least 3 associated depth phases, had to be extended to include minimum allowable pP-P and sP-P times and a SNR threshold of 2. The application of these new criteria is quite severe, resulting in no events less than 50km and only 20% of all depth phase solutions being screened out. On the otherhand one can be quite confident that no shallow events are screened out.

Much depth phase information is being discarded using these stringent criteria. Research into an independent technique to determine whether the depth-phase solutions are reliable is being investigated. The relative amplitude method (Pearce algorithm), is being employed to search for double couple focal mechanism solutions that are consistent with the amplitudes of P, pP and sP phases associated with the event. The existence or non-existence of these solutions is an indicator of the validity of the depth phase picks.

## 1. Introduction

If an event is confidently deeper than a depth threshold for which it is feasible with existing technology to test an underground nuclear explosion, then it is very likely to be of natural seismic origin. Thus, focal depth is one of the key characteristics used to distinguish earthquakes from underground nuclear explosions. Currently, at the PIDC about 11% of the REB events above mb3.5 have depths determined by depth phases. Compared to the ISC and other bulletins, this percentage is low. Development of improved techniques and procedures at the PIDC to identify and verify more depth phases, will assist in screening out more natural seismic events based on event depth.

There are currently no methods at the PIDC to actually validate the depth phase picks. In the first Release of depth screening criteria, there were simply criteria in terms of the number of depth phases and the amount of moveout of pP-P travel times with distance. These intended to eliminate cases for which the depth phases were too few in number or without expected moveout behaviour to be considered reliable. Based on a study by Jepsen and Fisk (1999), these criteria appear to function as intended for most cases. However there are known REB events with erroneous depth phase picks that satisfy the criteria. In this paper, research on more robust depth phase criteria is described. Although the new criteria is not foolproof, they are set conservatively such that one can be quite confident that no shallow events are screened out.

Much depth phase information is being discarded using these stringent criteria. Research into an independent technique to determine whether the depth-phase solutions are reliable is being investigated and is described in this paper. The relative amplitude method (Pearce algorithm), is being employed to search for double couple focal mechanism solutions that are consistent with the amplitudes of P, pP and sP phases associated with the event. The existence or non-existence of these solutions is an indicator of the validity of the depth phase picks.

## 2. Current depth event screening criteria

The depth screening criterion recommended by the IDC Technical Experts Group on Event Screening, May 1999, and which is in the Release 3 IDC software, is as follows (see CTBT/WGB/TL-2/31). An event will be screened out if:

$$\hat{D} - 2\sigma_D > 10km$$

where

$$2\sigma_D = 2\sqrt{s_{zz}} + k,$$

The value of k depends on whether depth phase criteria are met:
**k = 0km**      for depth-phase solutions
**k = 20km**    otherwise

Comparisons of REB depth estimates with those of the PDE and local bulletins has shown that REB depth estimates exhibit significant regional biases and that the depth uncertainties do not adequately reflect all of the model and random errors. As an interim approach, a constant term k has been introduced to account for errors not adequately represented by $s_{zz}$. It has been shown by Jepsen and Fisk (1999) that the value of k=40km in Release 2 could be reduced to 20km and still provide the appropriate coverage at the specified level of confidence.

It was recommended that the depth screening criteria be applied to all events in the REB with mb >= 3.5, and for which depth estimates were not constrained by an analyst. This criterion, including the two-sigma term, is equivalent to requiring that the 97.5% one-sided confidence interval is entirely deeper than 10km.

For events with depth-phase solutions, additional depth-phase validation criteria need to be satisfied before the event can be tested for screening. The Release 3 depth phase screening criteria consists of:

- Number of depth phases (ndp) >= 3
- $\Delta T(pP-P)$ >=1.5 seconds for stations between 25 & 100 degrees
- Signal-to-noise = 2.0 for pP and sP, based on peak-to-trough amplitude measurements;
- t(pP-P) > 12.9 &/or t(sP-P) > 19 seconds at the nearest station beyond 25 degrees;

These criteria are an extension of the Release 2 criteria that only required the event to satisfy the first two criterion.

Significant concern was noted by the Experts regarding potential misidentification of depth phases, particularly by inexperienced analysts. Improvements to analyst procedures and guidelines for depth phase identification has been set up to minimise these problems.

## 3. Evaluation and implications of depth-phase validation criteria

Fisk et al. (1999) found several events for which the pIDC analysts mis-identified depth phases, leading to over-estimated depths in the REB. For some cases, the depth-phase criteria were not satisfied, either because there were less than three depth phases or because the moveout of pP-P was less than 1.5 seconds. Thus, these events were not screened out as being deep. However, some cases were found with erroneous depth phases for which the depth-phase validation criteria were satisfied. For example, an event in the Vanuatu Islands region on 97/04/27 has a PDE depth estimate of 42km, while the REB provides a depth estimate of 82km, based on 8 depth phases and pP-P moveout of more than 1.5 seconds. It is clear from the examination of the seismic waveforms in figure 1 that although depth phases are clearly present, the pP arrivals were picked too late in the wavetrain by the analyst. Other similar examples have been described by Jepsen and Fisk (1999), Murphy and Cook (1998), and Bowers (1999). Consequently, new depth phase validation criteria needed to be examined.
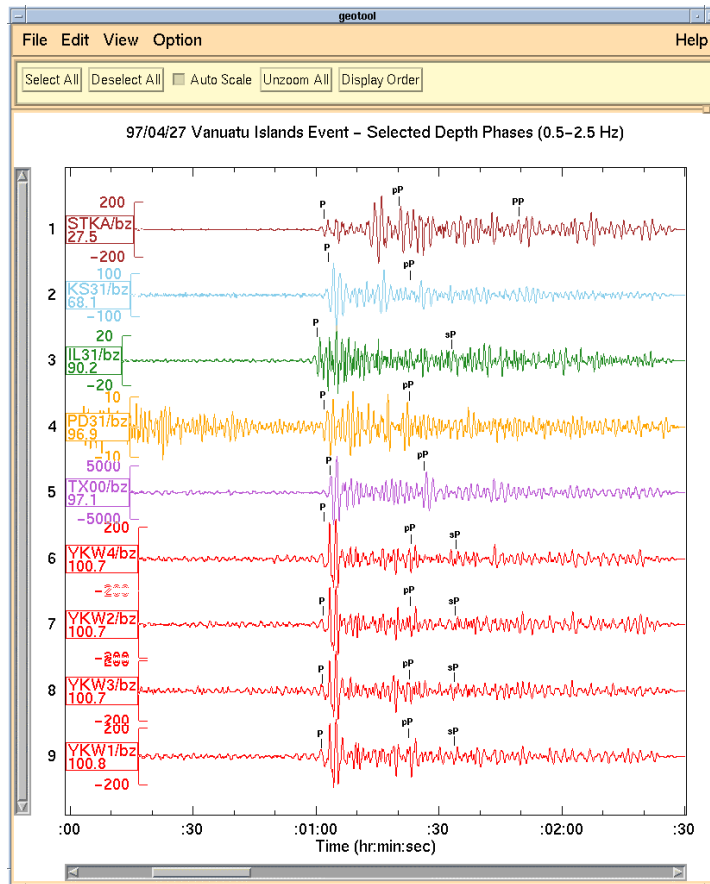
**Figure 1: Bandpassed-filtered waveforms for an event in the Vanuatu Islands region. Analyst picks of depth phases were mis-identified too late in the waveforms, leading to a REB depth estimate that was too deep for this event by about 40km.**

### 3.1 Evaluation results

To evaluate the depth-phase criteria the following questions were addressed:

(i)      Is the existing moveout criterion appropriate?
(ii)     Is a monotonically increasing moveout criteria necessary and/or useful?
(iii)    What is an appropriate signal-to-noise ratio (SNR) that should be required for depth phases?
(iv)    What is an acceptable uncertainty in the timing errors of depth phase picks?

In order to perform this study, pIDC and IRIS waveform data from 10 medium-sized earthquakes (mb 5.5-5.9), with depths ranging from 40 to 600km were used. For each event, onset times and amplitudes of P, pP and sP were picked. In most cases the raw waveform had to be deconvolved to broadband displacement before a clear depth phase was observable. A measure of the pre-signal amplitude for depth phases (in the 5 seconds preceding the signal) was also measured for determining SNR.

In general it was found that it was difficult to pick precise arrival onsets. Emergent onsets and precursory effects of filtering were the main factors. The raw (upper) and deconvolved waveforms (lower) from several IMS stations of the deep Fijian event on the 29th March 1998, shown in figure 2, clearly show these problems. On the raw waveforms the pP phases are both barely visible and emergent, but when the traces are deconvolved the pPs are more striking but precursory effects are introduced. As a consequence, many events displayed a large scatter in the pP-P and sP-P times. For example, the sP picks of the 4 January 1998 REB event shown in figure 3 span the distance range 40 - 140 degrees, with a maximum scatter of 3 seconds in the distance range 50-90 degrees. The dashed line on the figure represents the theoretical moveout (based on Iaspei91 travel times) expected for an event at

45km depth, and the lines either side represent 1 second deviations to the theoretical. Although there is a large scatter in the sP-P times, the depth phases fit very well with the assigned depth. Two hundred depth phases were picked for the 10 events, and on average the average residual of the moveout to the Iaspei91 travel time model was 0.7 seconds. It was suggested by Bowers (1999) that more accurate pP-P and sP-P times could be obtained by picking the times of the maximum peaks of the P, pP and sP. Certainly this was the case for the deep Hindu Kush event he showed, but this was not case for the majority of events.
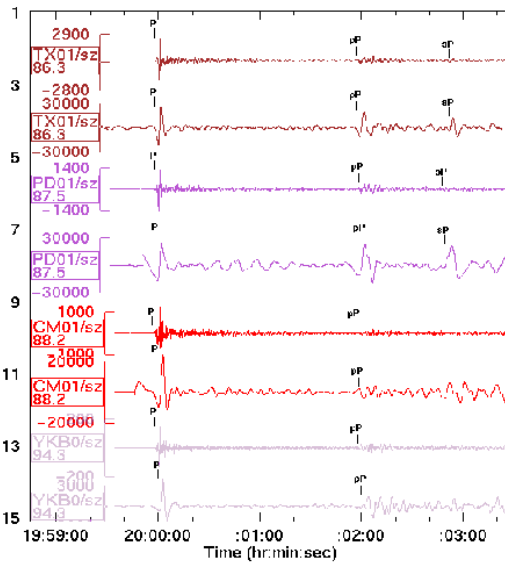


**Figure 2: Raw (upper) and deconvolved waveforms (lower) at IMS stations: TXAR, PDAR, CMAR, YKA of the deep Fijian event on 29/03/1998.**
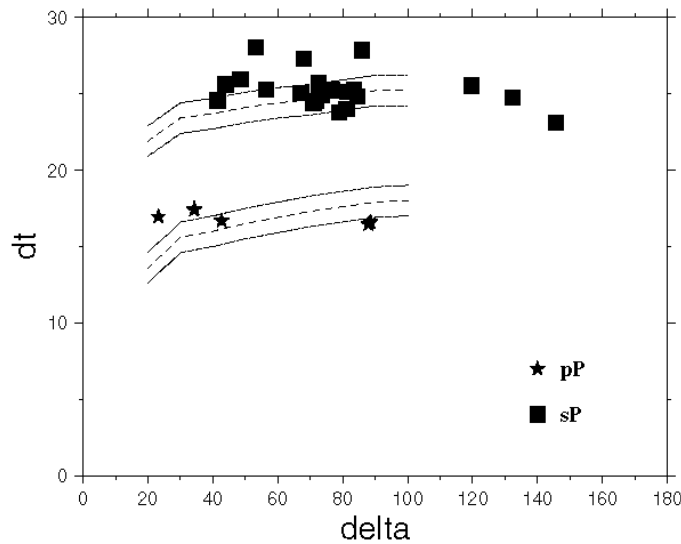


**Figure 3: Travel time differences of pP-P (stars) and sP-P (squares) versus distance for a 04/01/98 REB event. The dashed lines represent the expected moveout, while the solid lines represent one-second deviations.**

Another clear result was that the moveout typically increased monotonically with distance. However due to the scatter in pP-P and sP-P times this was not often seen for shallow events where the slope in the moveout is of the same order as the possible scatter (eg. an event at depth 50km, the expected moveout is 1.8 and 2.9 seconds for pP-P and sP-P respectively over the distance 30 to 90 degrees). In the case of the deep Fijian event, shown in figure 4 a large number of pP and sP's were observed and both clearly show the monotonically increasing moveout trend.
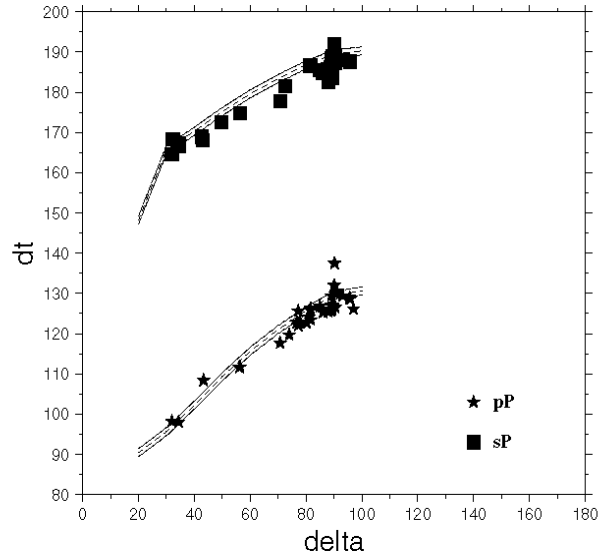
**Figure 4: Travel time differences of pP-P (stars) and sP-P (squares) versus distance for the deep Fijian REB event on 29/03/98.**

The intended use of the existing moveout criteria is to ensure that double explosions will not be screened out. Also it will assist in eliminating screening of events where an analyst may have overzealously picked any signal as a depth phase as long it satisfied a constant pP-P or sP-P time difference for all distances (some cases are known to exist). This criteria is equivalent to not screening out depth-phase events shallower than 50km. However with the large scatter of pP-P and sP-P times, it is possible that shallow events can be screened if they satisfy the 1.5 second moveout criteria. The histogram in figure 5 shows those REB events during 1998 that would be screened out by this criterion. In fact, 138 shallow depth-phase solutions (10km < depths < 50km) in this period were screened out. Since none of these events were shallower than 10km, serious screening errors were not made in these cases. However, this illustrates that there is certainly cause for concern and suggests that additional improvements in the depth-phase validation criteria are needed.
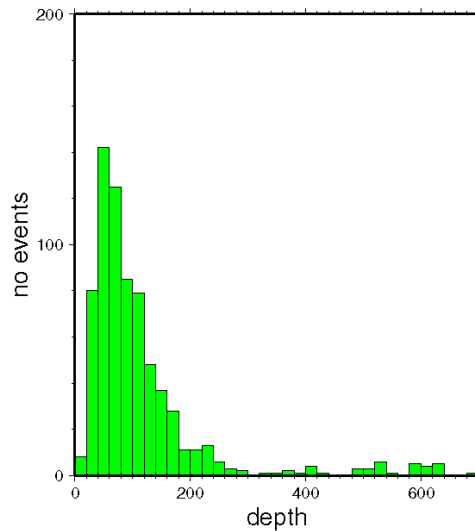


**Figure 5: Histogram of depth-phase solutions in the REB during 1998 that were screened out with the existing (Release 2) criteria.**

A potential improvement investigated is the criteria that pP-P > 12.9s or sP-P > 19.0s at the nearest station beyond 25 degrees. These criteria are equivalent to requiring focal depths deeper than 50km (as is the pP-P moveout criterion of 1.5s). The advantage of including these criteria is that the absolute times (12.9s for pP-P and 19.0s for sP-P) are considerably larger than the average timing errors of 0.7s, hence would provide an additional consistency check that is not as sensitive to timing errors. Results indicate that these criteria do not significantly reduce the number of events (> 50km) to which the depth screening criteria can be applied.

So the Release 2 moveout criteria (moveout >= 1 sec and ndp >=3) can be strengthened by employing two additional criteria: (i) pP-P > 12.9sec & (ii) sP-P > 19.0 sec. As a result no event less than 50km nor any event deeper that does not satisfy the moveout rule will be screened out. This restricts the use of depth phases of shallow events but is necessary to be confident that the screening criteria are working appropriately.

The depth-phase criteria could also be strengthened by: (1) ensuring that mis-timed depth-phase picks (with large timing residuals) are thrown out; (2) requiring that clear depth phases with SNR > 2 are used. Currently a 2 second residual is allowed by the location algorithm at the pIDC for depth phase picks. This ensures that mis-timed depth phase picks are thrown out and it ensures a monotonically increasing moveout with a maximum allowable residual of 2 seconds. However it was found that many depth-phase solutions (~40) were found which had associated depth phases with residuals greater than 2 seconds. This indicates that the pIDC location algorithm or rules employed by the analyst should be reviewed.

As expected, by varying the allowable residuals and the number of depth phases required for all depth phase solutions (> 50km) in the REB during 1998, the number of events screened out increased with residual size and decreased with the required number of depth phases (see table 1). Ensuring only a 2 second residual for each depth phase and that there are at least 3 depth phases associated, results in a few less events being screened out than with the existing criteria (543 to 582). The difference is due to some 39 events exceeding the allowable residual of 2 seconds. Further study is needed to assess appropriate restrictions on the allowable timing residuals. Another result was that depth phases with a SNR >= 2 were quite obvious and amounted to 90% of the depth phases analysed.

| No. depth phases | Residual 1 sec | Residual 2 sec | Residual 3 sec |
|---|---|---|---|
| ndp >= 3 | 487 | **533** | **543** |
| ndp >= 4 | 348 | 417 | 425 |
| ndp >= 5 | 257 | 316 | 327 |

**Table 1. Number of events with depth-phase solutions that could be screened out for various values of allowable residuals and number of depth phases.**

## 3.2 Implications

These criteria are conservative in that no shallow events (< 50km) with depth phases are screened out. Application of these criteria to all REB events in the 2nd half of 1999, it is found that only 128 out of 661 events with depth phases are screened out (see figure 6). Although not foolproof, one can feel quite confident that no shallow events are screened out. It should be noted that the depth-phase criteria described above test for physical consistency of the depth phases, and are primarily intended to prevent the depth screening criteria from being applied to depth-phase solutions with erroneous depth-phase picks. However, they do not actually validate that the phases that were picked are truly depth phases nor do they assist in identifying more valid depth phases.

To utilise much of the depth phase information bring thrown out above, the relative amplitude method is being trialed to investigate an approach to validate the depth phase picks.
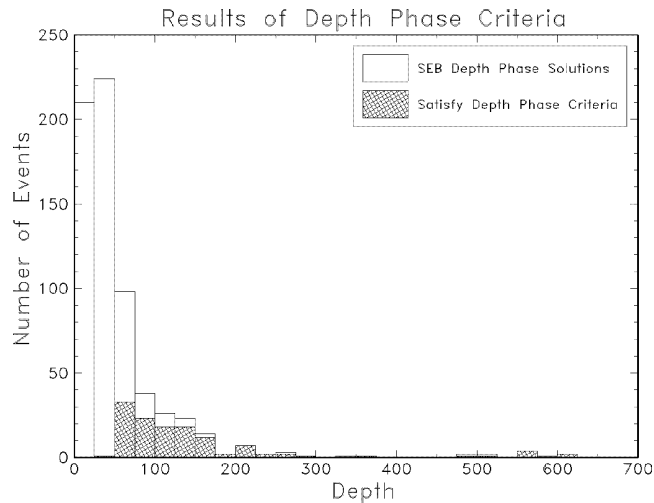
**Figure 6: Histogram of total number of depth phase solutions and those that satisfy the depth phase criteria, in 25km depth bins.**

## 4. Relative Amplitude Technique

The relative amplitude technique (RAMP) developed by Pearce (1977) can be used to calculate and validate source mechanism solutions for seismic events, since the impulse on the recorded seismogram is proportional to the amplitude of the pulse (for simple earthquakes with mb < 5.5 recorded at short period, and for simple deep and larger earthquakes recorded at long period). Pearce (1994) noted that the relative polarities and amplitudes of P and associated depth phases depended on three factors: (i) the direction of emergence from the source; (ii) the relative attenuation (of the short depth-surface two-way path); and (iii) the source type and orientation (i.e. the source radiation pattern). The relative attenuation can be accounted for by including an above source structure in the processing. Hence the presence of a number of stations (at varying emergence angles and azimuths), can then be used to fix on the source radiation pattern of the event. RAMP searches the strike-slip-dip parameter space using the relative amplitudes and polarities of P, pP and sP and/or the 3 components of S, at a number of stations, to determine the range of moment tensor solutions that are consistent with the input data.

Although there may be some evidence for earthquakes with components of non-double couple mechanisms (Frohlich, 1994), many studies have convincingly shown that seismic source mechanisms, apart from shallow volcanic events, can be described by double couple mechanisms. RAMP can then be used in a restricted way, by only allowing double couple mechanisms to be formed, to determine the focal mechanism of the event. Pearce & Rogers (1989) showed that the use of P and depth phase picks at three strategically positioned stations, could form a well constrained source mechanism. In this study, RAMP is used to test whether each event forms a well constrained double couple solution, and so validate whether the depth phases picked by analysts are correct or not. This will provide a check that is independent of current depth phase screening criteria which is only related to the relative times of the first arrival and associated depth phases.

### 4.1 Data and Processing

A restricted dataset of the 661 REB depth phase events from the 2nd half of 1999 was chosen to evaluate the applicability of RAMP. Only depth phase events with depths between 50 and 100km were used in this study (136 in total), since depth phase picks for shallower events are more likely to be in error and deep events would suffer from the need to make allowances for anelastic attenuation along the whole propagation path.

Full application of RAMP requires both the relative amplitudes and polarities of P and its associated depth phases. It was difficult to measure the relative polarity for most of these events, so in the processing this was left undetermined. As a result this allowed many more combinations of solutions to form, of which a number were redundant. As noted above, the amplitudes of observed phases can be affected by attenuation along the short depth-

surface two-way path, but also by seismic noise, complex pulse shape, interfering arrivals and the instrument response. A 33% uncertainty has been imposed on the amplitudes to encompass these variations. If very strict (i.e. small) uncertainties are imposed, RAMP will quite often fail to form events. On the otherhand if the uncertainty is too large the events may not form well-constrained solutions.

A 5*5*5 degree strike-dip-slip parameter space has been chosen for this study. This grid size allows RAMP to process quickly while being dense enough so solutions can be formed. There are 93312 possible solutions.

Two different approaches of applying RAMP to the dataset were tested. The first method solely involved the amplitude information contained in the REB and was trialed to see whether RAMP could be used as an effective tool. Since most of the events had only a small number of depth phases and the amplitudes were not calculated in the same or equivalent short-period filter band, these events were not expected to form many well constrained events. Secondly a more comprehensive application of RAMP was tested. This involved measuring amplitudes (in 0.8-4.0Hz filter band) of observed depth phases and calculating maximum amplitudes of the waveform data in time windows where the depth phases were expected based on the REB depth of the event. In this process the complete waveforms are being utilised. In both processes, the relative amplitudes at one station were allowed to be incompatible in the forming of solutions.
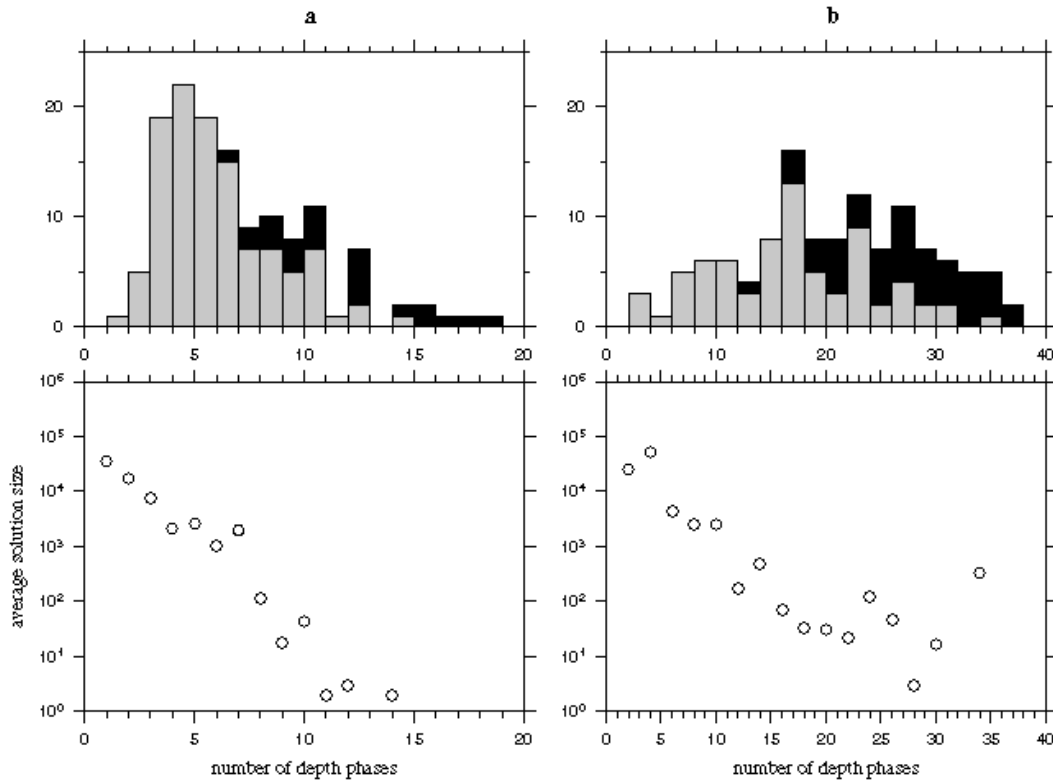


**Figures 7a&b: Average solution size, histogram of events with solutions (grey) and without solutions (black) versus number of depth phases, for a) trial run; b) comprehensive run.**

### 4.2 Results

For the trial run, double couple solutions were formed for 111 out of the 136 events. The solution size varied from 1 to 35874. Whereas in the more comprehensive run, 73 out of 123 events processed formed double couple solutions, with solution size varying from 1 to 53146. Figures 7a&b show the average solution size, and a histogram of the number of events with or without solutions, both versus the number of depth phases (ndp). In both cases, the average solution size decreases with npd phases used. The drop off rate is much faster in fig. 7a

than fig. 7b due to the fact that the extra depth phase information used in fig. 7b (maximum amplitudes in the expected depth phase time intervals) are less constrained than amplitudes of the observed depth-phases, and in the trial run more stations are contributing depth phase information at a given ndp than in the comprehensive run. However the average solution size is offset by the shift in the number of depth phases available for processing.

There are more failures in the second run, as shown in the histogram of figure 7b, but there appears to be an equal or greater number of events that have a solution size less than 500, which is the level chosen in this study at which an event is termed well constrained. This limit was determined through careful examination of the distribution of solutions calculated for the 136 events. Figures 8 a & b show the solutions determined for a poorly constrained event in Southern Greece and a well constrained Fijian event. The poorly constrained event in fig. 8a has 10064 solutions and no clear mechanism at all. The well-constrained event, fig. 8b has 402 possible solutions divided into two mirrored regions. The symmetry of solutions is a feature of not constraining the polarities of the phases. Where available, the solutions have been compared with CMT solutions. Only one event, the 26 August 1999 Philippines event had an available CMT solution, and the solutions determined by RAMP were in agreement.



a                        b
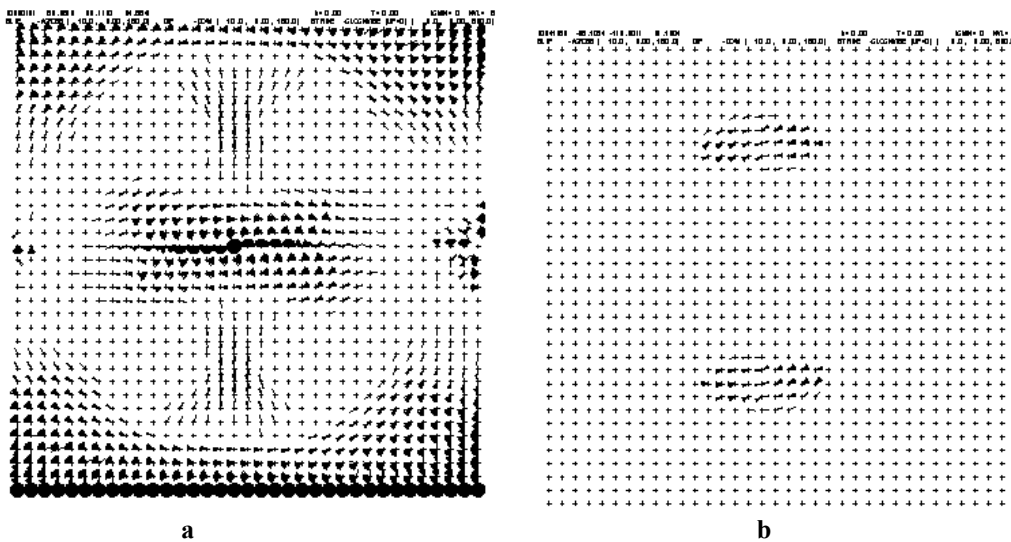
**Figures 8 a & b: Double couple solutions consistent with the input data for the a) poorly constrained southern Greek event and the b) well-constrained Fijian event. The dip, slip are on the vertical and horizontal axes respectively, and the azimuth of the strike for consistent solutions is shown as a vector plotted at each dip-slip position.**

### 4.3 Screening with RAMP

If the depth phases for an event can be confidently validated by RAMP in that the event has a well-constrained double couple mechanism, then it can be screened out. In table 2 the number of events that formed solutions those with well-constrained mechanisms is given. Fifty-seven out of the 123 events processed would be screened out in the comprehensive run, which is slightly better than results from the trial run. This compares well with the results of the Release 3 depth-phase criteria, where 55 events are screened out. Also it has an added advantage that the depth phases are validated.

| | Number of events | Number of events with a least one solution | Number of events with a well constrained solution (500) |
|---|---|---|---|
| Trial run | 36 | 11 | 2 |
| Comprehensive run | 23 | 3 | 7 |

**Table 2: Results of the number of events processed, with solutions, and well-constrained solutions for the trial and comprehensive runs.**

The trial run was applied to all the depth-phase events less than 50km, and it was found that 186 out of 434 depth-phase events formed well-constrained solutions. The impact of applying RAMP to these events could mean that approximately 50% of the events with depths < 50km, may now be screened out.


## 5. Future Work

To propose RAMP as an event screening tool a number of tasks need to be researched:

- Determine the appropriate screening level for a well-constrained solution. Both theoretical estimates of solution size with various network configurations, and comparisons to GroundTruth data need to be examined.
- Can significant improvements to the solutions be gained by attempting to read or automatically determine the relative polarities. Will this be a burden on the analysts?
- Test RAMP on the full suite of 661 depth phase events.
- Can the mis-labelling of depth phases over many stations (pP as sP or sP as pP) form well-constrained solutions? If so, what is their consequence?


## 6. Conclusions

Confidence in depth-phase solutions can be improved by imposing criteria on the relative timing and relative amplitudes of the P and depth phases. RAMP has shown that it could be an effective tool for event screening. However the definition of a well-constrained event needs to be more rigorously determined. Further improvements can probably be gained by fine tuning the use of RAMP on depth phase solutions. The current depth-phase criteria based on moveout and SNR will need to be reviewed in light of these results.

## 7. References

Bowers, D. (1999). Depth Phase Identification for Event Screening: Future Improvements, *Proceedings of the IDC Technical Experts Meeting on Seismic-Acoustic Event Screening*, 21-25 May 1999, Vienna, Austria.

CTBT/WGB/TL-2/31. Report of the IDC Technical Experts Meeting on Seismic-Acoustic Event Screening, 21-25 May, 1999.

Frohlich, C. (1994). Earthquakes with Non-Double-Couple Mechanisms, *Science*, **264**, 804-809.

Jepsen, D. and M. D. Fisk (1999). Evaluation of PIDC Depth Estimates, *Proceedings of the IDC Technical Experts Meeting on Seismic-Acoustic Event Screening*, 21-25 May 1999, Vienna, Austria.

Murphy, J. R. and R. W. Cook (1998). A Preliminary Analysis of PIDC Focal Depth Determination in the Northern Hindu Kush Region, Maxwell Technologies Technical Note, Reston, VA.

Pearce, R. G. (1977). Fault plane solutions using relative amplitudes of P and pP, *Geophys J. R. astr. Soc.*, **50**, 381-394.

Pearce, R.G. and R. M. Rogers (1989). Determination of Earthquake Moment Tensors From Teleseismic Relative Amplitude Observations, *Journal of Geophys. Res.*, **94**, 775-786.