

IMPROVED FOCAL DEPTH DETERMINATION FOR USE IN NUCLEAR EXPLOSION MONITORING

John R. Murphy,¹ Brian W. Barker,¹ and William L. Rodi²

Science Applications International Corporation,¹ Massachusetts Institute of Technology²

Air Force Research Laboratory

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ABSTRACT

Seismic event location remains as one of the important discriminants for separating natural tectonic and explosive events. In particular, high-confidence estimation of focal depths remains as an outstanding monitoring problem. Over the past several years, we have been pursuing a research program directed toward the development of improved detection and identification procedures for the depth phases pP and sP and the formulation of a new algorithm for computing more reliable confidence intervals on focal depth estimates. With regard to depth phase identification, we have investigated the utility of an automatic network stacking algorithm that maps post-P detection times at a station into candidate depth phases using the pP - P and sP - P delay times predicted by travel-time tables for that epicentral distance, and then combines the individual station results as a function of candidate source depth. This automatic algorithm has been applied to data from a large number of events in the Hindu Kush and in the Hokkaido and Honshu regions of Japan, as well as the region surrounding the Chinese Lop Nor test site. Prominent candidate pP and sP peaks have been identified in the resulting network detection stacks for many of these events, including some with m_b values as low as 3.7 and depths as shallow as 20 km. This algorithm has now been implemented in a software module that interacts directly with the standard Analyst Review Station (ARS) and is being evaluated and tested. While this algorithm promises to be a powerful tool for identifying candidate depth phases, the presence of a prominent peak on the network detection stack does not, by itself, constitute a positive identification that is confident enough to be used for purposes of event screening. Rather, it identifies possible depth phases that have to be validated by further review and testing. That is, since the positive identification of a depth phase with a time delay of greater than about 3 seconds with respect to P conclusively identifies an event as being too deep to be an explosion, it is important that this identification be made with a very high level of confidence. One tool that can be used to help characterize peaks on the network detection stacks is the F detector. The F detector operates on array station beam data and provides a quantitative measure of the probability that detections at a station have vector slownesses consistent with what would be expected for pP and sP phases arriving from the origin. This could provide a powerful means for eliminating false candidate peaks. We have collected a large amount of array data for events that have previously shown promising results during the depth phase stacking process, and are evaluating this F detector to see whether it provides any additional information to help us confirm depth phase identification. We are also continuing to investigate the applicability of calibrated regional S - P arrival time information to the estimation of independent event origin times for use as constraints in the hypocenter location process. Although the trade-off between focal depth and origin time can be complex in practical applications to small events for which few data of limited azimuthal distribution may be available, an ability to independently constrain origin time can often lead to significantly improved focal depth estimates. In particular, differences between origin times determined from regional S - P times and the corresponding origin times determined from standard hypocenter location codes with focal depths constrained to zero can be used to infer focal depth bounds which are useful for event discrimination purposes. We have collected regional seismic data recorded at selected the International Monitoring System (IMS) stations from samples of earthquakes with well determined focal depths located in the Hindu Kush and in Japan and have developed calibrated S - P travel time relations for use in the determination of independent origin times. The resulting regional S-P based origin times are being used in a preliminary hypothesis test, where they are statistically compared with origin time estimates obtained from constrained ($h = 0$) teleseismic solutions to assess whether the event focal depths are greater than 10 km at high confidence levels. Initial results suggest that this approach can consistently identify subcrustal events as being too deep to be explosions with a high degree of confidence. We are in the process of assessing the depth and distance dependent variations in the calibration constants and are attempting to establish a more statistically rigorous version of this test.

OBJECTIVES

The objectives of this research program are to determine more reliable estimates of the uncertainties associated with the different focal depth estimation procedures and to increase the number of events that can be identified as earthquakes on the basis of focal depth through the implementation of new and improved analysis tools. This is being accomplished through the development of improved procedures for identifying and using the teleseismic depth phases pP and sP, the incorporation of regional S-P based origin time constraints into an improved depth estimation algorithm, and the development of more robust statistical hypothesis tests for use in event discrimination. This effort includes the implementation and large-scale testing of these new algorithms on the Space and Missile Defense Command (SMDC) Research and Development Support System (RDSS).

RESEARCH ACCOMPLISHED

Seismic event location remains as one of the most important discriminants for separating natural tectonic and explosive events. Thus, for example, it has been estimated that approximately 80% of known global earthquakes have focal depths greater than 50 km or are located more than 25 km at sea. Since underwater nuclear explosions can be confidently identified to very low yields using hydroacoustic data, it follows that the vast majority of earthquakes can potentially be identified on the basis of location alone. This is an important observation, since global nuclear monitoring may require the screening of tens of thousands of seismic events per year and, in order to perform this function efficiently, it will be necessary to have simple and robust discriminants available that can be used to eliminate the vast majority of these events. However, in order to be useful for such discrimination purposes, the uncertainties associated with seismic locations must be well-defined and reliable; and this has proven to be difficult to accomplish to the required degree of accuracy. For example, during the GSETT-3 experiment, it was found that only about 50% of the event epicenters which have been well-constrained by local data reported to the National Data Centers (NDCs) fell within the corresponding 90% confidence ellipses published by the Prototype International Data Center (PIDC) in the Reviewed Event Bulletin (REB). This indicates that all of the sources of error have not been properly accounted for in the existing statistical location models.

More specifically, high confidence estimation of focal depths remains as an outstanding seismic monitoring problem. If accurate focal depths could be determined for the majority of earthquakes deeper than 5, or even 10 km, the event discrimination problem would be much easier. However, despite intensive efforts by well-trained and experienced analysts, more than two-thirds of the GSETT-3 REB events were assigned artificially constrained depths. Moreover, the cited accuracies of even those relatively few focal depth estimates is open to serious question, particularly in light of the evidence that the corresponding epicentral uncertainties appear to be significantly underestimated by the current hypocentral location algorithm. Thus, for example, Fisk et al (2000) found a number of cases in the GSETT-3 database where the cited uncertainties in the focal depths of earthquakes in particular areas had been consistently underestimated by the PIDC location program. Such discrepancies are frequently compensated for in a crude fashion by artificially inflating the input variance values until the associated confidence bounds encompass the required percentage of verified values. This was the interim approach taken by Fisk et al (2000) in their formulation of the focal depth discriminant for the experimental event screening system at the IDC. However, this is an ad hoc procedure that does not address the underlying deficiencies in the standard error model and can potentially lead to serious focal depth estimation errors under previously untested conditions. Clearly, improved focal depth estimation procedures are needed that can more fully utilize depth phase information and explicitly account for all sources of error in seismic arrival time data.

Reliable identification of the depth phases pP and sP provides one of the strongest pieces of evidence that a seismic event is a naturally occurring earthquake when the time delay between pP and direct P exceeds about three seconds, implying a focal depth of greater than 10 km. However, confident identification of such phases on actual recordings is not always a simple matter. That is, it is first necessary to unambiguously identify a phase onset in the P coda background; and it is then required to confirm that this phase is actually a depth phase and not some other P phase, such as PcP, which might have an expected arrival time within the time window being analyzed. Thus, with regard to identification of a detected secondary phase as a depth phase, it is generally further required that the subject arrival be detected at several stations at different epicentral distances and that the time interval between its onset time and the associated P onset time be an increasing function of epicentral distance. This distance dependence is commonly referred to as "step-out," and the IASPEI 91 travel time tables used at the IDC predict step-outs between 30 and 90 degrees of approximately 0.4 seconds for a focal depth of 15 km, 4.4 seconds for a focal depth of 100 km

and 13.7 seconds for a focal depth of 300 km. Thus, even with high quality data for which it is possible to determine pP-P time of arrival differences with an accuracy of about 1 second, it is generally not possible to apply the step-out identification criterion to pP for events with focal depth less than about 50 km.

We have continued to focus on the development of improved tools for the detection and identification of the depth phases pP and sP and on the evaluation of the use of calibrated regional S-P time intervals to constrain event origin times for use in focal depth determination. With regard to depth phase identification, we have been attempting to improve the frequency and reliability of the identification of the depth phases, pP and sP, through the use of network beam-forming (Murphy *et al*, 2000). In our approach, post-P arrivals observed at each station for a given event are mapped from functions of delay times with respect to P to functions of source depth using the pP-P and sP-P delay times predicted by the IASPEI-91 travel-time tables for the various station distances. These functions of depth for all the stations in the detecting network are then added together to identify arrivals consistent with the predicted depth phase move-outs over the entire range of potential source depths. That is, the observed delay times of all post-P arrivals with respect to P are translated into equivalent focal depths under the hypothesis that they are either pP or sP arrivals. Those arrivals that are consistent with such hypotheses should then show up as peaks on a stacked network depth function. In the present application, difficulties associated with the variability of observed short-period signals between widely separated stations are avoided by stacking unit amplitude boxcar functions centered on the post-P detection times, which are automatically determined at each station by front end signal processing procedures. One advantage of this approach is that not only is it fully automatic, but it includes only signals that have triggered a detection, which should help to minimize the inclusion of questionable arrivals in the analysis. Figure 1 shows an example of the application of this algorithm to the automatic post-P detection times for three Central Honshu earthquakes. It can be seen that the network detection stacks in these cases show pronounced peaks at depths corresponding to the published REB depths for these events, indicating the presence of good candidate pP phases that should be further reviewed by the analyst. This automatic algorithm has now been applied to data from over 200 REB events located in the Hindu Kush, Lop Nor, Hokkaido and central Honshu regions. Prominent candidate pP and sP peaks have been identified in the resulting network detection stacks for a majority of these events, including some with mb values as low as 3.7 and depths as shallow as 20 km, indicating that this algorithm can provide the analyst with information useful for the confident identification of additional pP and sP phases. In order to make this depth phase stacking procedure available for large-scale testing and further evaluation,

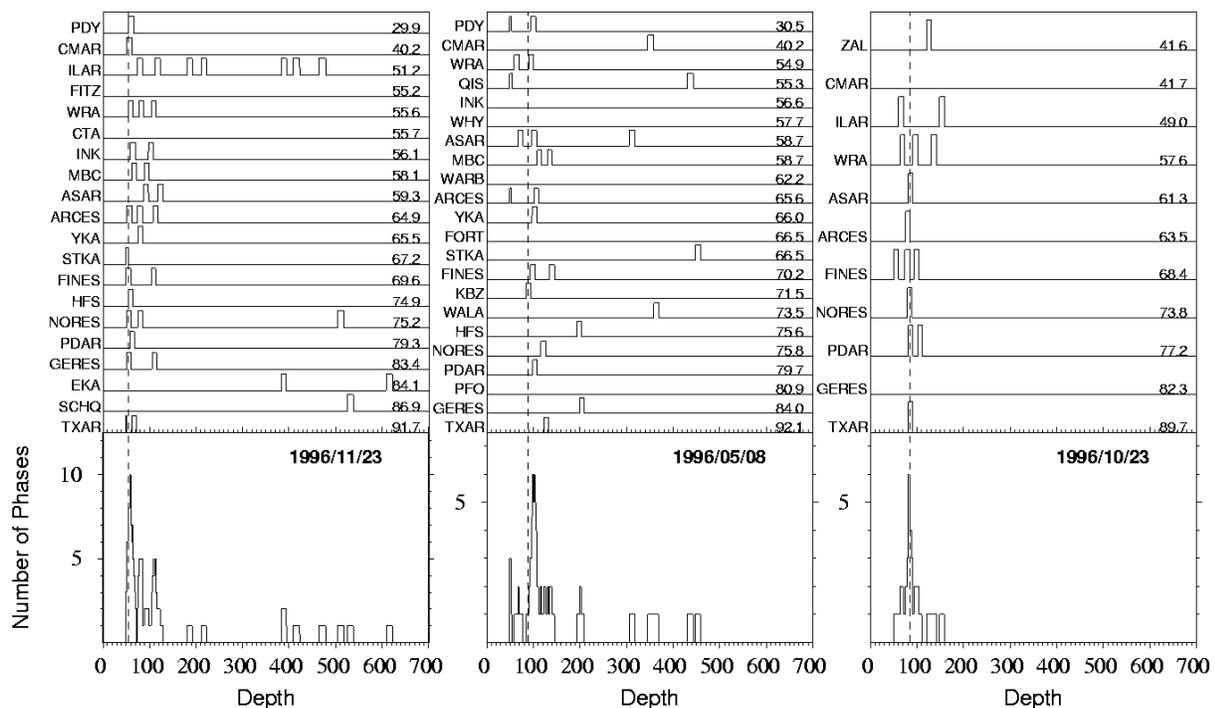


Figure 1. Network detection stacks of pP for the Central Honshu earthquakes of 1996/11/23 ($m_b = 4.32$), 1996/05/08 ($m_b = 3.86$) and 1996/10/23 ($m_b = 3.79$).

the algorithm described in Figure 1 has been integrated into the Analyst Review Station (ARS) software employed at the IDC and the USNDC. In this implementation, the analyst initiates a fully automatic process from the ARS that causes all of the post-P detection times for the current event to be recovered from the automatic detection files and passed to the depth phase stacking module, where they are converted into their corresponding depth traces, stacked, and presented back to the analyst in an X-Window display. Then, by clicking on a candidate peak with the mouse, the analyst initiates a process by which the corresponding waveforms are brought up in the standard ARS display with the data time aligned on the predicted pP times corresponding to the selected trial depth. These data can then be further processed using the bandpass filter routine or any of the other signal processing algorithms available in the ARS. This implementation will allow us to test the procedure at a large scale to determine whether it is powerful enough to be considered for incorporation into routine seismic analysis procedures such as those employed at the USNDC or the IDC.

The network beamforming algorithm described above is proving to be a powerful tool for identifying candidate depth phases. However, the presence of a prominent peak on the network detection stack does not, by itself, constitute a positive identification that is confident enough to be used for purposes of event screening. Rather, it identifies possible depth phases that would have to be validated by further review and testing. As a result, the development, implementation and testing of improved analyst tools and quantitative tests will play a key role in the completion of any new depth phase identification system. One tool that can be used in the characterization of prominent peaks on the network detection stacks is the F detector. The F detector (Blandford, 1974) operates on array station beam data and provides an output trace which is approximately equal to the time averaged power on the beam divided by N times the average variance of the individual channels and the beam, where N is the number of array stations. Its potential value for the present application is that it provides a quantitative, statistical means of assessing the likelihood that an arrival has the same vector slowness as the beam. Therefore, it provides a potential mechanism for evaluating whether particular detections at a station have vector slownesses that are consistent with what would be expected for pP and sP arrivals from the origin. This could provide a powerful means for eliminating false candidate peaks associated with source and receiver complexity or the presence of unidentified phases. We have implemented this algorithm and are evaluating its capabilities as a tool to assist in characterizing our depth phase stack peaks. Figure 2 shows the results of the F detector processing for an earthquake on July 9, 1997 located in the Honshu region of Japan and recorded at the YKA array in Canada. The top of the figure shows the beam trace steered to the location of the event and filtered between 0.5 and 3.0 Hz. The middle trace is the F-Trace, calculated using a 2 second moving window, and the bottom of the figure shows the 'probability' trace, which is derived from the F-Trace and is used to indicate the probability that a phase is arriving at the same vector-slowness that the beam was steered to. Also marked on the traces are the predicted pP and sP arrivals for the estimated REB depth of 71 km for this event. It can be seen from the beam trace that there is energy arriving near the time of the predicted pP phase for this event depth, and this energy also appears on the F-trace. The probability trace on the bottom indicates that there is a high probability that this energy represents a phase arriving with the same azimuth/slowness that the beam was steered to, giving us confidence that it might represent a true depth phase. The sP phase is not apparent on any of the traces, however. It may be that this phase is buried in the coda of another unknown phase arriving a few seconds earlier than the predicted sP time. Figure 3 shows an additional example of the application of the algorithm to the station YKA recordings of a shallow Lop Nor earthquake on 1999/01/27. Marked on this figure are the predicted pP and sP times for the REB assigned depth of 18 km. In this case, the traces show that there is evidence that our candidate depth phases are being generated at the event source and that they appear to correspond to the depth phases, pP and sP. A more specific application of the F detector, as a tool to provide confirmation of depth phase stacking results, is illustrated in Figure 4. In the top of this figure we show the depth phase stack results for an event in the Hindu Kush region. It indicates a pronounced peak at a depth of approximately 226 km that is in agreement with the REB depth shown by the dashed line, but also shows a number of prominent secondary peaks that need to be evaluated. We have calculated the F detector results for six of the array stations that contributed to this stack, and have used these results to weight the detections using the corresponding F probability traces. The weighted detections after this processing were then converted to depth and stacked to produce the new results shown in the bottom of this figure. The peak at 226 km has been retained, while secondary peaks have been greatly suppressed, which supports our initial interpretation of the stacking results. We are continuing with the development of a more general tool that will combine our depth phase stacking results with the F detector results to assist in the detection and validation of depth phases.

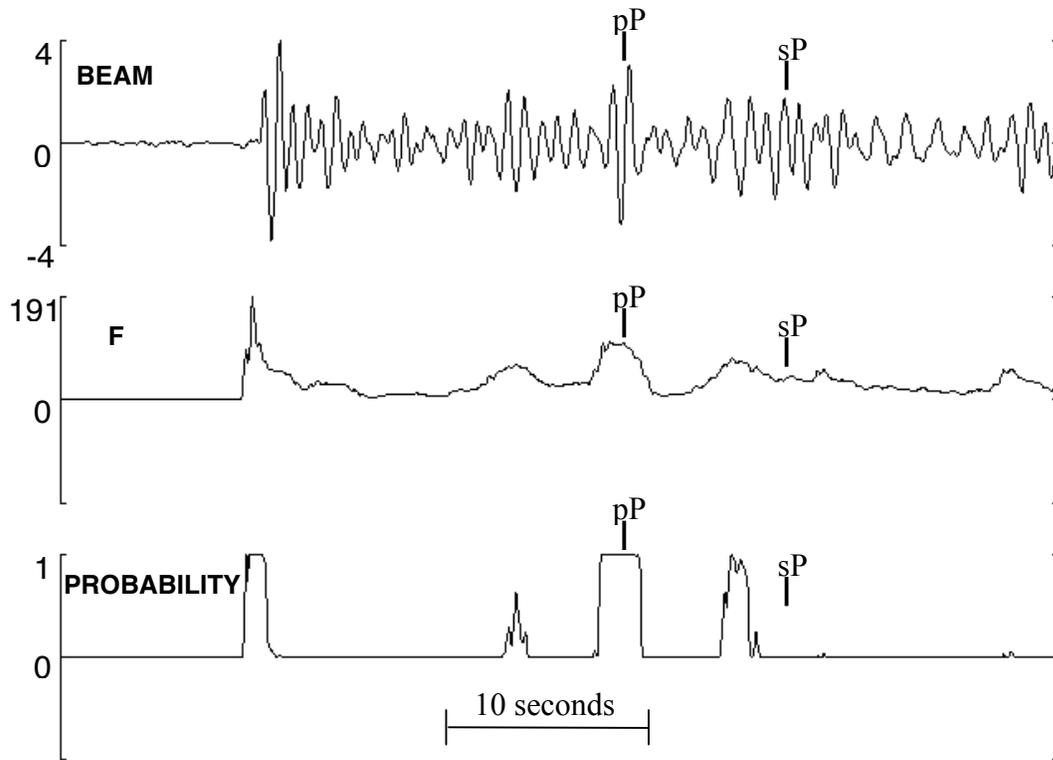


Figure 2. Best beam trace (top), F-trace (middle), and probability trace (bottom) for the Central Honshu earthquake of 1997/07/09, $m_b = 3.94$. The depth phase predictions are based on the REB depth of 71 km.

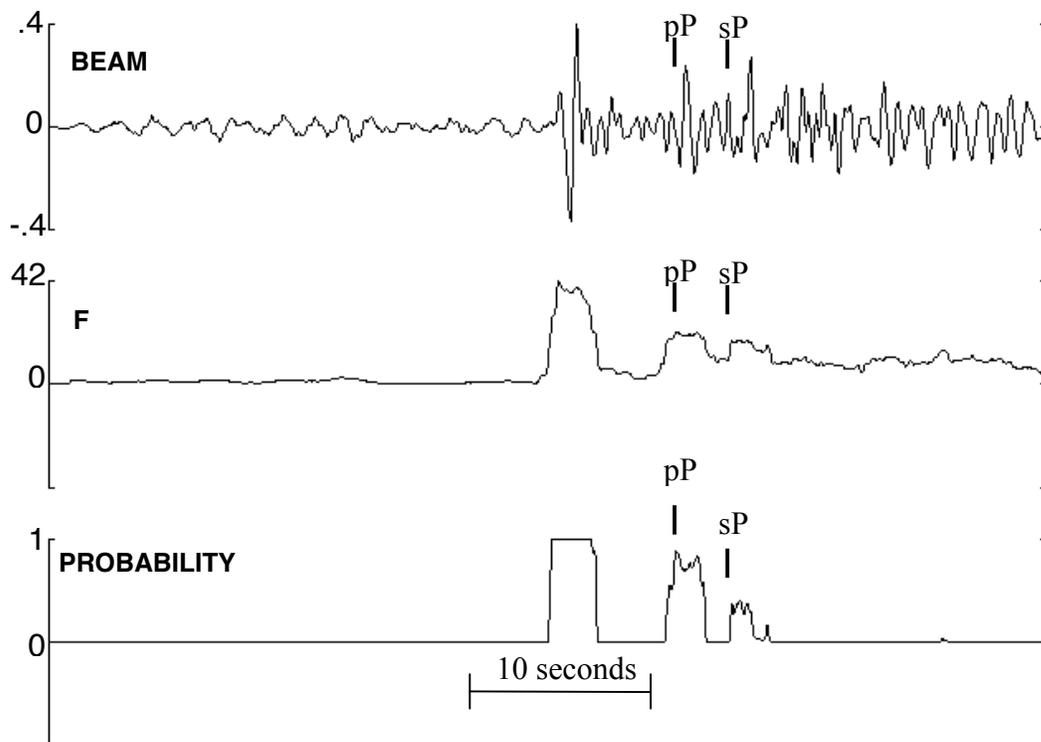


Figure 3. Beam trace (top), F-trace (middle), and probability trace (bottom) for the Lop Nor earthquake of 1999/01/27, $m_b = 3.90$. The depth phase predictions are based on the REB depth of 18 km.

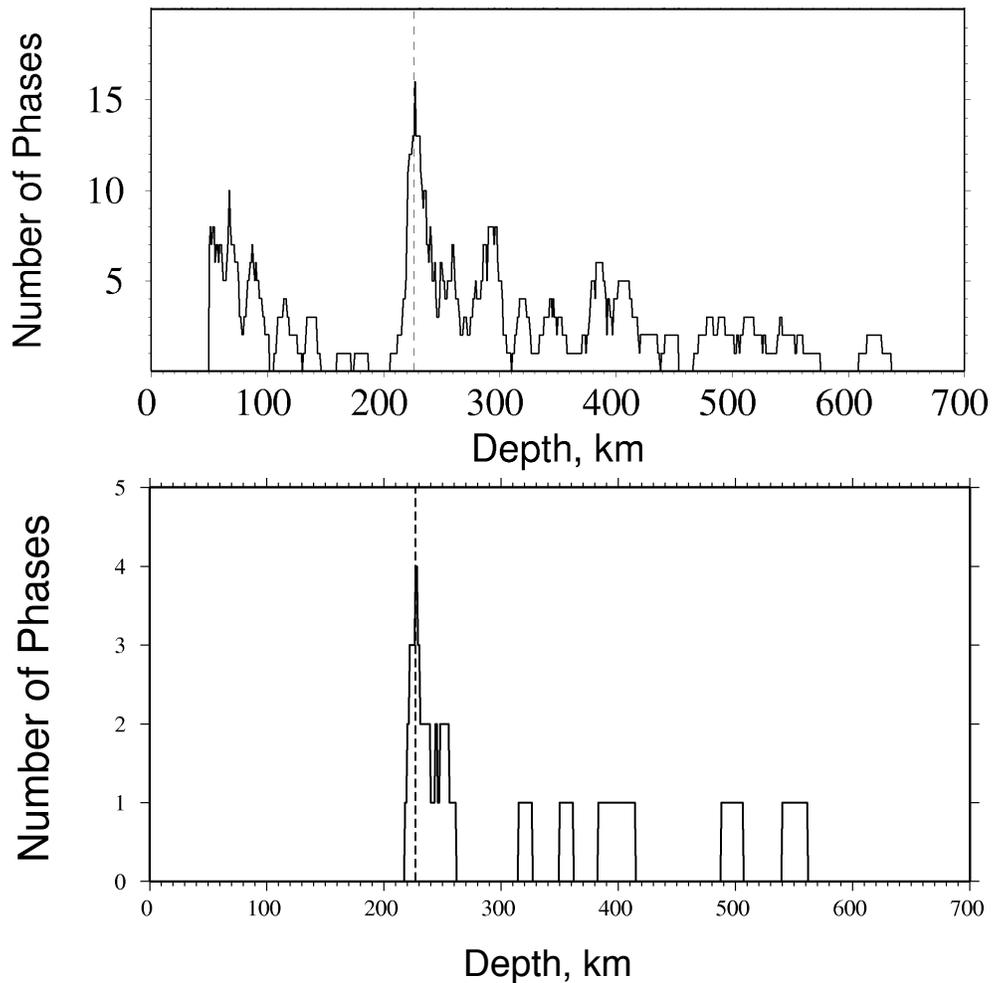


Figure 4. Network detection stack of pP for the Hindu Kush earthquake of 1998/02/14 (top). Array detection stack after confirmation by F detector results (bottom). The dashed vertical lines coincide with the REB depth estimate of 226 km.

It is important to recognize that, even if depth phase identification can be significantly improved by employing new analyses techniques such as those described above, there will still be many earthquakes for which focal depths can only be estimated through analyses of observed P wave first arrival times. Because of the well known tradeoff between event origin time and focal depth in the teleseismic distance range, teleseismic P wave first arrival times alone are not adequate for determining the focal depths of events with depths less than about 100 km with accuracy sufficient for confident event screening. In principal, this limitation can be overcome by incorporating P wave first arrival time observations at near-regional distances into the location procedure. However, as was documented by Murphy et al (2000), systematic biases in regional travel time data that are not well accounted for by the error models used in conventional seismic location algorithms, can lead to serious errors in focal depth determination which are not encompassed by the nominal uncertainty bounds on focal depth. One approach to resolving this ambiguity, which was originally proposed by Wadati some 75 years ago in his studies of deep Japanese earthquakes, is to independently constrain the event origin time using calibrated regional S-P travel time differences. That is, if t_0 is the event origin time and t_s and t_p are the observed arrival times of P and S waves which traveled the same path to a station at distance Δ from the source, it follows that:

$$t_p = t_0 + \frac{h}{v_p} \quad (1)$$

$$t_s = t_0 + \frac{h}{v_s}$$

where v_p and v_s are the average P and S wave velocities along the path. It follows that the P wave travel time can be related to the observed S – P time as

$$t_p - t_0 = \frac{1}{\frac{v_p}{v_s} - 1} (t_s - t_p) \quad (2)$$

Thus, if the ratio v_p/v_s has been determined for a particular path the event origin time can be estimated from observed P and S arrival times through the simple relation

$$t_0 = t_p - \frac{1}{\frac{v_p}{v_s} - 1} (t_s - t_p) \quad (3)$$

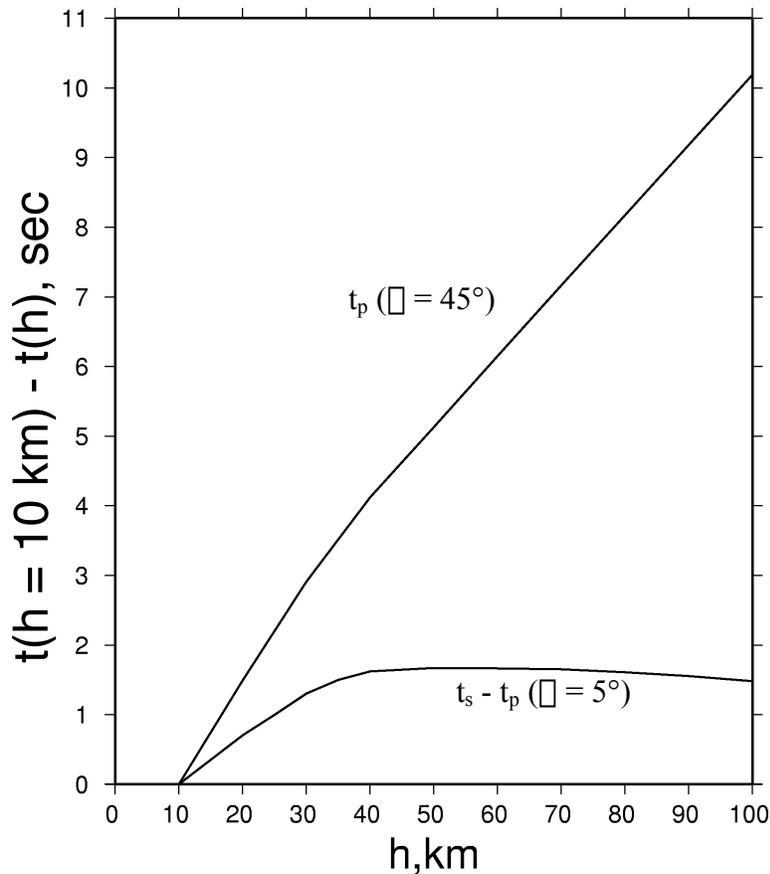


Figure 5. Comparison of $t_s - t_p$ variation as a function of focal depth predicted at a fixed near-regional distance of 5° by the IASPEI91 travel time tables with the corresponding predicted variation in P wave first arrival times at a nominal distance of 45°

The power of this approach is illustrated in Figure 5 which shows a comparison of $t_s - t_p$ variation as a function of focal depth between 10 and 100 km predicted at a fixed near-regional distance of 5° by the IASPEI91 travel time tables with the corresponding predicted variation in P wave first arrival times at a nominal teleseismic distance of 45° . Note that the predicted S-P times are virtually independent of focal depth between 30 and 100 km, while the teleseismic travel time decreases by more than 1 second for every 10 km increase in focal depth over that same range. Consequently, observed S-P times at regional distances can provide very robust constraints on event origin time which are largely independent of focal depth for depths less than about 100 km. This, of course, assumes that the S - P times are calibrated for the propagation paths of interest. As an example, Figure 6 shows such a calibration for a large sample of Honshu earthquakes recorded at the regional IMS station MJAR. This calibration has been used to estimate origin times from observed MJAR S - P times for a sample of 47 Honshu earthquakes that have accurate depth phase constrained focal depths in the range of 50 to 150 km. These origin time estimates were then used as constraints in determining focal depths of these events from P wave first arrival times alone, using a new event location algorithm which combines grid search location and Monte Carlo simulation algorithms to determine focal depths and associated rigorous uncertainty bounds (Rodi and Toksoz, 2000). An important aspect of this new algorithm is that it allows the analyst to specify precise bounds on the uncertainty in the origin time estimate, which is then properly accounted for in the focal depth determination process. The results of applying this new algorithm to the selected sample of 47 Honshu earthquakes are illustrated in Figure 7 where differences in estimated depths with respect to the “true”, depth phase constrained values are compared for the solutions obtained with and without origin time constraints. It can be seen from this figure that the unconstrained depth differences show a significant average bias of 11.7 km and an associated standard deviation of over 32 km, while the corresponding S - P origin time constrained depth differences show a much reduced average bias of 3.7 km and a significantly smaller standard deviation of 8.0 km. These results indicate that earthquakes with depths greater than about 30 km in this region can be shown to be too deep to be explosions (i.e. $h > 10$ km) at a very high level of confidence if S - P constrained origin times are available. We are currently evaluating several candidate hypothesis tests using our generalized error model in order to determine which provides the most rigorous and powerful event screening procedure.

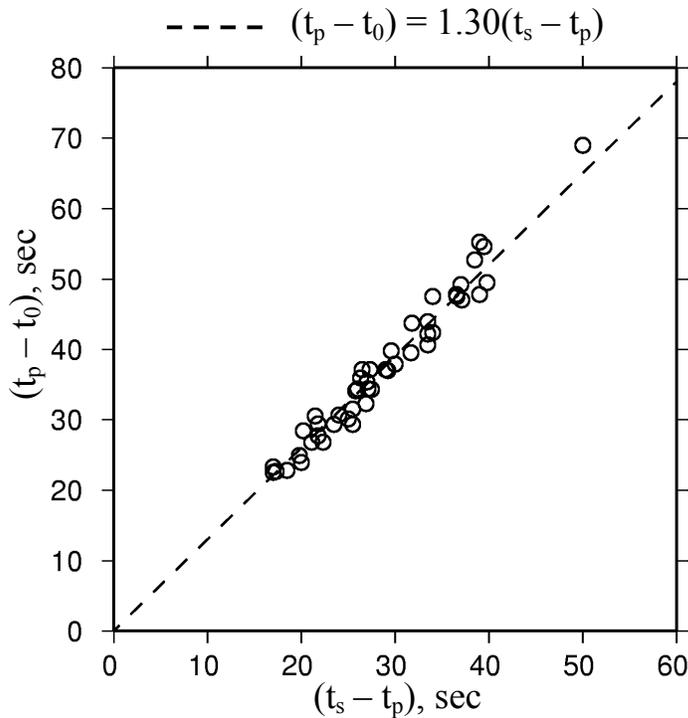


Figure 6. S - P travel time calibration results for a large sample of Honshu earthquakes at the regional station MJAR.

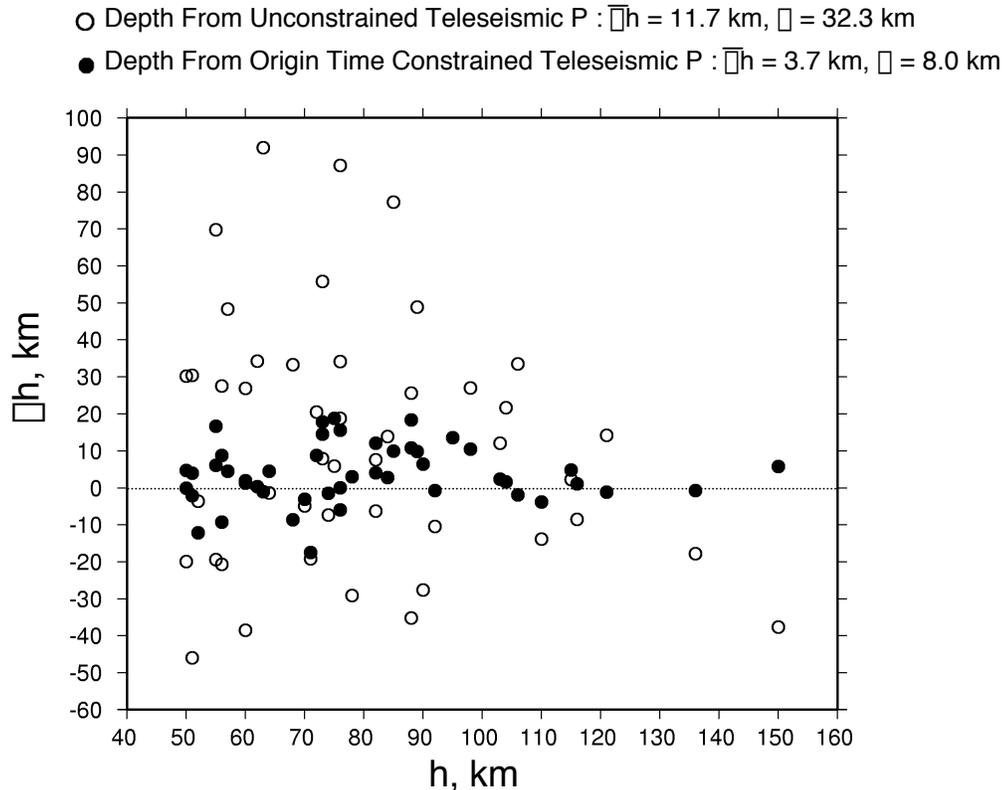


Figure 7. Differences in estimated depths with respect to the “true” depth phase constrained values.

CONCLUSIONS AND RECOMMENDATIONS

The second year of a three-year research investigation directed toward the development of improved focal depth estimates for use in event discrimination has now been completed. One result of this investigation has been the formulation and testing of an automated procedure for stacking raw P wave detection data to identify candidate pP and sP depth phases for further review by an analyst. This algorithm has been integrated into the Analyst Review Station (ARS) software employed at the IDC and U.S. NDC. We have also formulated a procedure that uses F detector output to weight the results of this depth stacking algorithm in order to suppress unwanted secondary peaks that do not originate from the source. This procedure shows promise as a tool that can be used by an analyst to assist in the detection and validation of depth phases. We are also continuing with the formulation of a depth hypothesis test based on the application of calibrated regional S – P travel time intervals to constrain event origin time. Results of application of this procedure to selected well located events in the Honshu region of Japan have indicated that it shows promise for use in event discrimination.

REFERENCES

- Murphy, J. R., R. W. Cook, and W. L. Rodi (2000), Improved Focal Depth Determination for Use in Seismic Monitoring of Underground Nuclear Explosions, *Maxwell Technologies Final Report* MSD-DFR-00-16621.
- Rodi, W., and M.N. Toksöz (2000). Grid-search techniques for seismic event location, *Proceedings, 22nd Annual DoD/DOE Seismic Research Symposium*, New Orleans, Defense Threat Reduction Agency (DTRA).