IMPROVED FOCAL DEPTH DETERMINATION FOR USE IN CTBT MONITORING

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ABSTRACT

Seismic event location remains as one of the most important discriminants for separating natural tectonic and explosive events. However, in order to be useful for 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. In particular, high-confidence estimation of focal depths remains as an outstanding monitoring problem. During the past year, we have continued to pursue a research program which is directed toward the development of improved detection and identification procedures for the depth phases pP and sP, as well as with the formulation of a new algorithm for computing more reliable confidence intervals on focal depth estimates determined from P-wave first arrival times. With regard to depth phase identification, we have been investigating the potential utility of a fully automated network stacking procedure based on an algorithm originally proposed by Israelsson (1994). In this approach, post-P detection times in the prototype International Data Centre (pIDC) automatic detection file for each station for a given event are mapped into functions of depth using the pP-P and sP-P delay times predicted by the IASPEI travel-time tables for the various station distances. These functions of depth for the selected event are then added together for all the stations in the detecting network to identify arrivals consistent with the predicted depth phase move-outs over the entire range of potential source depths. The results of preliminary tests of this algorithm on a sample of about 30 Hindu Kush earthquakes with m_b > 4.0, and depths in the 200- to 250-km range have been encouraging, in that most of the network detection stacks show candidate depth phase peaks near the corresponding published Reviewed Event Bulletin depth values for these events. In addition, a new algorithm for computing formal confidence intervals associated with seismic focal depth estimates has been formulated and implemented. This new algorithm is general in that it does not require the conventional linearity assumptions and allows for both random and systematic errors in the arrival time data that may be characterized by different distribution functions. In such cases, there is no simple analytic solution for the confidence regions, and it is necessary to define them numerically. In the present case, Monte Carlo simulations are being used to map out the values of an appropriate likelihood ratio on a grid surrounding the maximum likelihood hypocenter solution, and these likelihood ratio values are then used to define precise confidence regions corresponding to the generalized model assumptions. This model is also being evaluated using data from Hindu Kush earthquakes for which the focal depths are well constrained by verified depth phase observations.

Key Words: seismic, focal depth, discrimination, prototype International Data Centre, Hindu Kush

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 which 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 screening.

RESEARCH ACCOMPLISHMENTS

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 10km, the event screening problem would be much easier. However, despite intensive efforts by relatively well-trained and experienced analysts, more than two-thirds of the PIDC Reviewed Event Bulletin (REB) events are currently being assigned artificially constrained depths of zero. Moreover, the cited accuracies of even the few freely determined focal depths are questionable, particularly in the light of the ground truth evidence which indicates that the corresponding epicentral uncertainties are generally underestimated by the hypocentral location algorithm employed at the PIDC. These results indicate that all of the sources of error have not been properly accounted for in the existing statistical location models and, consequently, the prototype PIDC focal depth event screening criterion currently incorporates a crude, empirically derived correction to the formal focal depth uncertainty estimates which significantly limits its applicability.

During the past year, work on this project has focused on the development of improved tools for detection and identification of the depth phases pP and sP and on the continuation of the evaluation of a new algorithm for computing more reliable confidence intervals on focal depth estimates determined from P wave first arrival times alone. With regard to depth phase identification, we have been analyzing IMS data recorded from a sample of Hindu Kush events with REB focal depths in the 200 to 250 km range. The map locations of these REB events are shown in Figure 1 where it can be seen that they occur in a very compact band, which is controlled by the regional tectonic forces acting at this continental collision zone. Surprisingly, depth phase observations from these events are relatively rare, even for the larger, well-recorded events. Thus, for example, depth phase observations are reported in the REB for only about 35% of the subset of these events for which arrival time data are reported from 12 or more IMS stations. One of the principal reasons for this failure to more consistently identify depth phases from such events is illustrated in Figure 2, which shows the vertical component recordings at station MBC ($\Delta \approx 70°$) from a series of these events covering an REB depth range extending from 207 to 248 km. Note that even for these closely-spaced events in a narrow depth range, the variation of the observed pP/P and sP/P amplitude ratios is very large. This kind of variation can presumably be explained by differences in focal mechanisms between these events, but such effects make it much more difficult for the analyst to consistently identify depth phases, even for such closely-spaced events.

In an attempt to overcome such difficulties in single station depth phase identification, we have been investigating the potential utility of a fully automated network stacking algorithm which employs signal analysis procedures similar to those originally proposed by Israelsson (1994) and more recently applied to a sample of Canadian data by Woodgold (1999). In this approach post-P arrivals observed at each station for a given event are mapped from functions of delay time to functions of source depth using the pP-P or sP-P delay times predicted by the IASPEI 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 moveouts over the entire range of potential source depths. This transformation is illustrated in Figure 3, which shows the predicted pP moveout with respect to P as a function of source depth for two different epicentral distances. Using such predicted moveout curves, the observed delay times of all post-P arrivals with respect to P can be translated into equivalent focal depths under the hypotheses that they are either pP or sP arrivals. Those arrivals which are consistent with such hypotheses should then show up as peaks on the stacked network depth function.

As was noted by Woodgold (1999), one of the difficulties of applying the above algorithm directly to the recorded short-period seismic data is that the depth phase waveforms and dominant frequency contents for a given event can show substantial variability across the network, and this significantly degrades the effective gain of the network stacking procedure. Consequently, we have adopted a modified method in which only the post-P detection times in the PIDC automatic file for each station are used. That is, the observed post-P arrival times and their associated uncertainties (currently assumed to be ±1 sec for pP and ±2 sec for sP) are used to define boxcar functions of unit amplitude centered on the automatic detection time and these boxcars as functions of time are mapped into equivalent boxcars as functions of source depth using predicted IASPEI movement curves such as those shown in Figure 3. It is these simplified functions of depth which are then stacked over the network to identify candidate depth phase consistent with pP or sP.

The results of applying this processing procedure to the automatic detection files for the Hindu Kush earthquake of 02/14/98 are shown in Figure 4, where the functions of depth derived under the hypothesis of pP arrivals are shown for each of the 31 stations which recorded this relatively large (m_b≈5.0) event, together with the network stacking results for the specified candidate depth range extending from 50 to 700km. The dashed vertical line on this figure denotes the reported REB depth, and it can be seen that there is a strong peak in the network detection stack corresponding to this depth which would be identified as a candidate pP phase by the automatic process. Similar examples for several smaller earthquakes from the selected Hindu Kush data set are shown in Figures 5 and 6. In Figure 5 it can be seen that there is again a strong peak in the network detection stack which is consistent with the REB depth of 204 km for this event, and which would be readily identified as a candidate depth phase. Figure 6 shows the corresponding results for the much smaller (m_b ≈4.0) earthquake of 04/08/96, and it can be seen that in this case there is a pronounced peak in the network detection stack which is close to the REB depth estimate of 248 km, but which does not quite encompass it. It is interesting to note that, in this case, no depth phases were reported in the REB and, consequently, the REB depth estimate is based on P wave first arrival times alone. Therefore, it is not surprising that the two independent depth estimates are not in exact agreement given the uncertainties in both estimates. In any case, the automatic process has identified candidate depth phases which, if validated, could be incorporated into the hypocentral inversion to obtain a more robust estimate of source depth.

Of course, because of focal mechanism variations such as those illustrated in Figure 2, as well as other effects, the interpretation of the network detection stacks is not always as unambiguous as for the examples shown in Figure 4-6. For example, Figure 7 shows the pP detection stack for the Hindu Kush earthquake of 12/11/98. It can be seen from this figure that in this case there are a number of peaks at different depths, which are as large or larger than that coinciding with the reported REB depth of 248 km for this event. However, as is illustrated in Figure 8, a sum of this pP network stack and that for the corresponding sP network stack produces a function of depth which shows a maximal value at the REB depth. Data from a sample of 30 of those Hindu Kush earthquakes with m_b>4.0 and focal depths in the 200-250 km range have now been processed using this algorithm, and the results have been quite encouraging in that more than 80% of the resulting network stacks have been found to show significant peaks corresponding to candidate depth phases which are consistent with the REB depth estimates. The procedure is currently being further tested using samples of Hindu Kush events encompassing a wider range in focal depths.

With regard to focal depth estimates based on P wave first arrival times alone, we are continuing with the development of rigorous methods for computing confidence intervals on focal depth and hypothesis tests that can be used as focal depth discriminants. The following complexities are being addressed in our approach:

- Nonlinearity of the travel time vs. hypocenter forward model, especially nonlinearity with respect to event depth.
- Uncertainty in the variance of arrival time picks.
- Uncertainty in travel time corrections for regional stations. (This is in contrast to the standard practice or treating station-correction uncertainty as an additional random error in the data.)

Our statistical formulation uses likelihood ratio tests to define confidence regions and hypothesis tests – for either the vector hypocenter or event depth. The likelihood function is based on a Gaussian error model.

We maximize likelihoods over "nuisance parameters" which are not the target of a test, including origin time, error variance, unknown station corrections and, when focal depth is the target parameter, event epicenter. Given the generality of our formulation, the test statistic used in a given test is not necessarily chi-squared or F distributed, as is usually assumed. Moreover, its probability distributions (needed to define critical values of the test statistic) depend on the problem parameters themselves. To address these complications, we have developed numerical techniques based on Monte Carlo simulation and grid search to calculate confidence regions on hypocenters, confidence intervals on focal depth, and significance levels for focal depth hypothesis tests. We are currently applying these algorithms to events in the Hindu Kush region in an attempt to derive confidence regions and discriminants that are in better agreement with the results of our observational studies.

CONCLUSIONS AND RECOMMENDATIONS

During the past year, the effort on this project has focused on the development of improved tools for detection and identification of depth phases and on the continuation of the evaluation of a new algorithm for computing more reliable confidence intervals on focal depth estimates based on P wave first arrival times alone. A new, fully automatic process has been implemented for stacking network detection data to identify candidate depth phases for further review by the analyst. This procedure has now been tested on a sample of 30 Hindu Kush earthquakes with REB focal depths in the 200 to 250 km range, and it has been shown to provide useful diagnostic information on depth phases for events with REB m_b values as low as 4.0. More specifically, candidate depth phases were identified for more than 80% of these test events, as opposed to the 35% of those events for which analyst determined depth phase observations were reported in the REB. We conclude that this new automatic processing procedure holds promise for providing a useful tool which could be used by the IDC analysts to make more frequent and more reliable depth phase picks. With regard to the determination of improved confidence intervals on depth, a more rigorous statistical method based on Monte Carlo simulation and grid search has now been implemented as is currently being evaluated using data recorded from Hindu Kush earthquakes with well-constrained focal depths.

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