Constraining the Depth and Source Mechanism for Smaller Events at Far-regional to Teleseismic Distances

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ABSTRACT

Techniques for source mechanism inversion are well established for using long period recordings for large events. The challenge for extending such methods to smaller events is to ensure that sufficiently accurate synthetic seismograms are available for comparison with observed records which include the interference with surface multiples and appropriate crustal reverberations.

An effective approach for teleseismic synthetics has been developed for both P and S arrivals which can allow for different crustal structures at the source and receiver with a full allowance for shallow multiples and conversions. Core reflections and refractions, which can become important in different distance ranges, can also be included. With the aid of these full synthetics it is possible to test different levels of approximation. For P waves at least we can reproduce much of the behaviour using simplified approximations.

The simplified synthetics are being used to develop a systematic nonlinear inversion scheme linking a travel-time location scheme and waveform inversion (including depth phases) to constrain both depth and source mechanism. Both the location and waveform inversion procedures make use of the Neighbourhood Algorithm developed by Sambridge (1999).

Because location using a sparse network is most effective when arrivals of different character can be employed, an effort has been made to develop systematic means of detecting and identifying seismic phase, particularly in the far-regional to near teleseismic regime. The combination of a range of methods using amplitude, frequency character and correlation properties can indicate the presence of arrivals even in the presence of significant noise. Polarisation measures can then help to assign phase character and thus aid identification. The phase information can then be used in the nonlinear location scheme.

Key words: Event location, source mechanism, waveform inversion, depth phases, phase detection

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OBJECTIVE

The prime objective of this work is to provide procedures which can exploit the character of seismic observations at far-regional to teleseismic distances and so transfer analysis of both source-mechanism and depth based on waveform inversion to smaller events.

Such analysis is regularly applied for large events using long-period seismograms, but for smaller events has to be carried out on shorter period information. In consequence it is necessary to make a careful development of the propagation model, including realistic models of crustal and uppermost mantle at both source and receiver. The work is directed to the far-regional to near-teleseismic interval (12°-50°) for which there is usually moderately good recording of P and on broad-band recordings, often reasonable S. The details of structure in the mantle become less important as the range increases. Waveform inversion will be focussed on simplified propagation models but full calculations of synthetic seismograms will be needed as a check on the results.

The inversion procedure builds on information from location using travel times yielding latitude, longitude and origin time and then employs a range of depths to try to exploit the interference between the direct arrivals and their surface multiples as a depth control. Feedback is required between the depth and source mechanism inversion and the primary location estimates.

The accuracy of event location is enhanced if multiple seismic phases can be employed and so a further objective is to develop techniques which can help seismic analysts to recognise and exploit later seismic phases.

The primary utility of this research in promoting discrimination of seismic events lies in the effort to enhance the quality of location estimates and to provide constraints on the source mechanism. The source depth should be better constrained and therefore more useful as discriminant by isolating events beyond the depth of penetration by man-made activities. The extent to which a source mechanism is compatible with an isotropic (explosive) component will also be significant.

RESEARCH ACCOMPLISHED

The approach which we are pursuing depends on being able to exploit selected segments of observed seismograms using information derived from synthetic seismogram calculations. Detailed matching depends on the availability of a good estimate of the source location and particularly the depth, as well as a fair estimate of the source mechanism.

Synthetic seismogram generation and utilisation

Full response

Our object is to construct synthetic seismograms at teleseismic distances and we do this by an adaptation of the reflectivity method (Kennett 1983, 1988a,b). We build the response of a stratified medium in the frequency-slowness (ω, p) domain in terms of the reflection and transmission properties of different parts of the structure.

We construct the response in a form which allows the introduction of different structures in the vicinity of the source and receiver above z_J and a simple mantle structure below extending down to a level z_L. The surface ground motion for a source at a level z_S is then

$$\begin{aligned} \mathbf{w}_0^{tel} \;=\; & \mathbf{W}_U^f[\mathbf{I} - \mathbf{R}_D^{0J}\mathbf{R}_U^f]^{-1}\,\mathbf{T}_U^{0J}\cdot && (r) \\ & \cdot\mathbf{R}_D^{JL} && (m) \\ & \cdot\mathbf{T}_D^{SJ}[\mathbf{I} - \mathbf{R}_U^{fS}\mathbf{R}_D^{SJ}]^{-1}\,(\boldsymbol{\Sigma}_D^S + \mathbf{R}_U^{fS}\boldsymbol{\Sigma}_U^S), && (s) \end{aligned} \qquad (1)$$

where we have written the expression in a way that emphasises the different parts of the propagation process. The propagation elements (s) represent the radiation from the source and reverberations in the structure near the source, the middle term (m) represents the mantle contribution and the first group of terms (r) correspond to the contribution from structure in the neighbourhood of the receiver.

For receiver ranges between 3500 km and 9500 km it is common to represent the PP, SS or HH elements of the mantle reflection matrix $\mathbf{R}_D^{JL}$ via approximations such as

$$(\mathbf{R}_D^{JL})_{PP} \sim \exp\{i\omega\tau_m(p) - i\tfrac{\pi}{2}\}Q(\omega), \qquad (2)$$

where $\tau_m(p)$ is the phase delay for the mantle below the separation level z_J and we have also included an allowance for attenuation.

The surface ground motion can be recovered from the frequency-slowness response by making use of the vector surface harmonic representation of the seismic wavefield. We can achieve good results by using a discrete representation of the slowness integral using a bundle of slownesses centred on the geometric slowness for the *P* or

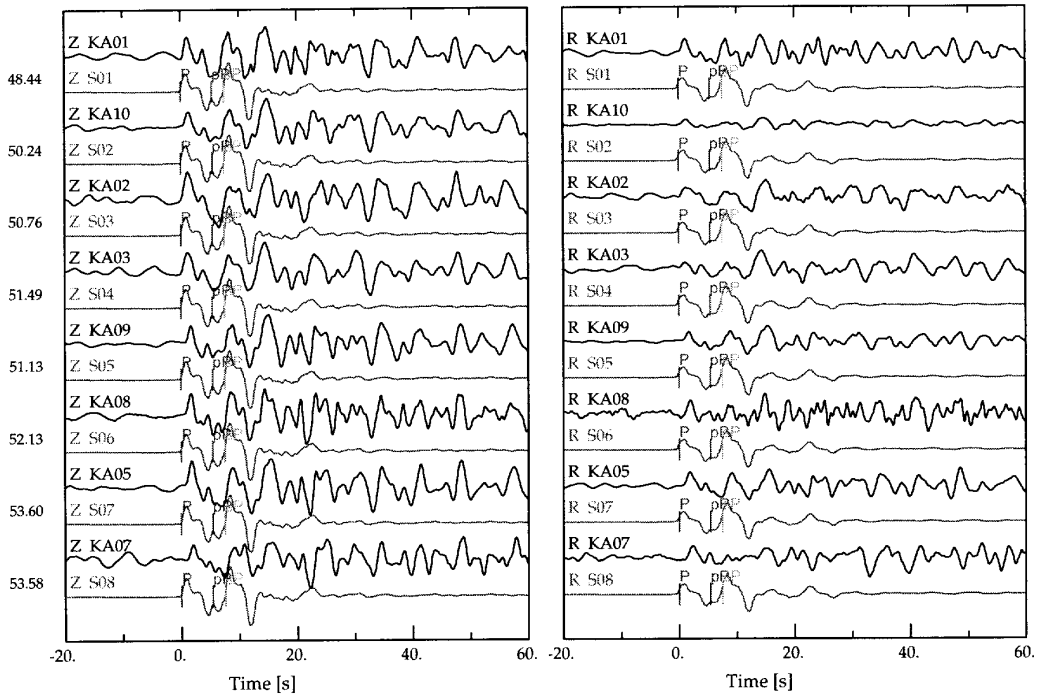

Figure 1. Comparison between observed and synthetic *P* wave seismograms for the Fiji event 1997 day 220, for the vertical (left) and radial (right) components. The black traces are the observed seismograms, and the grey traces are the synthetic seismograms in both cases. The traces are aligned on the theoretical *P* arrival, and the theoretical travel time curves are superimposed on the synthetic seismograms. The epicentral distances are indicated on the left-hand scale.

S arrival, at each frequency ω. In this way we can cover the surface multiples and crustal reverberations through the structure of the (ω, p) response without explicit calculations of the individual contributions.

For shallow events, most of the character of the interference packet comprising *P*, *pP* and *sP* can be reproduced by simpler approximations which are then suitable for use in a nonlinear inversion scheme.

Comparison with observations

As a illustration of the synthetic seismogram calculations at teleseismic distances, we synthesise the records of an event in the Fiji Islands region recorded in northwestern Australia, at epicentral distances of around 50°. The stations are fairly close together, therefore we can illustrate how the seismogram character varies over a small distance range. The source depth (17 km) and mechanism were taken from the Harvard CMT catalog. The event has an estimated moment magnitude of 6.6, and so the records have a noticeable long-period component.

Figure 1 compares the observed and synthetic seismograms for the vertical and radial components of the *P* wave. We have employed a trapezoidal far-field source-time function is used, with empirical time segments for the positive, zero and negative slopes of 1.25 s, 2.50 s and 1.25 s. The synthetics were calculated using the *ak135* velocity model, with the corresponding attenuation profile of Montagner and Kennett (1996). With a small time shift applied to the synthetics, to compenstae for the difference between the onset and centroid times, we can achieve a good fit for the first part of the *P* wave seismograms (*P*, *pP*, *sP*) in figure 1. The estimated source depth of 17 km, obtained from the Harvard CMT catalog, provides a good fit to the relative arrival times of the direct *P* wave and its surface reflections.

Source inversion

Our major effort is now directed towards inversion for hypocentral parameters and source mechanism exploiting the Neighbourhood Algorithm of Sambridge (1998,1999) which we have already shown to be very effective for arrival

time location. This nonlinear inversion scheme provides a means of "zooming" in on the best fitting regions in a multi-dimensional parameter space.

We envisage the following steps in the procedure for source mechanism and source depth inversion:

(1) Invert for source location, given by the four parameters Δ, ϕ, h, t_o. The seismogram depends non-linearly on these parameters through the Green's tensor elements. We will use the Neighbourhood Algorithm as a non-linear location procedure with arrival time information to get an estimate of the hypocentral parameters

(2) Invert for the source mechanism using the hypocentral parameters obtained from step 1, and a range of source depths based around the estimated depth. A simple approach for calculating P, pP, sP and S, pS, sS will be best as we need to be able to perform calculations very rapidly in order to make inversion feasible. We will use a simplified synthetic seismogram scheme with an approximation to the interference packets produced by the direct waves and their surface reflections (similar to the approach adopted by Goldstein and Dodge, 1998). We intend to use a envelope matching procedure which will concentrate on relative amplitudes of arrivals, as well as using the cross-correlation between observed and synthetic seismograms to match the detail of waveforms. Inversion for source depth is non-linear and we will employ a full non-linear scheme with a moment tensor representation of the source.

For discrimination purposes it will be necessary to allow for an isotropic component in the source estimate. The source inversion could be done in two ways. Firstly, restricting the source mechanism to a shear dislocation (with no isotropic component), and secondly, with no restriction on the isotropic component (allowing for a moment tensor with non-zero trace). The fit of the two types of inversions can then be compared in order to estimate the significance of any isotropic component.

(3) Once the best fitting source depth and source mechanism have been obtained from the previous step we can try to relocate the event. The improved depth constraints can be fed back into the source location procedure in order to refine the estimate of the hypocentral parameters. If necessary these refined source location parameters could then be used again in step 2 again to obtain an updated estimate of the source mechanism.

(4) The final step will be to compute full synthetic seismograms using the best estimate of the hypocentral parameters and source mechanism. This will be used as a cross-check for the match to the full range of phases including the core reflections and core phases. These calculations would also provide a check in case of misidentification of phases, for example if crustal reverberations have been misidentified as a surface reflection.

Phase detection and characterisation

We have continued to develop techniques which are suitable for automated phase detection and characterisation of the detected arrivals. Many methods have been devised for event picking and each of these is based on the separation of signal and noise in a particular domain and so can not ensure consistent onset time picking under all source, receiver, path and noise conditions. However, a combination of four methods based on differing aspects of the seismic wavefield can be used to provide automated and consistent onset time picking and event location using a single three-component record. This approach is suitable for real-time use. For arrival detection, a combination of energy analysis, the differences in instantaneous frequency and the nature of the coefficients in an auto-regressive representation of the seismic record are used to develop an algorithm for robust picking of phase arrivals. The phase characterisation is aided by using a number of wavefield measures based on polarisation analysis using complex traces (based on Vidale 1986). These measures help to separate S and P wave phases.

The detection procedure is based on combining information on the changing amplitude of the seismic traces, the current frequency content of the trace and the correlation properties of the wavetrain. These three approaches are based on recognising the differing content of noise and signal in different domains, and we have further extracted three different measures from each method. For energy analysis, the three measures are the total energy (E_3), the vertical energy (Z_e) and the energy in the horizontal plane (H_e); for instantaneous frequency analysis, the three measures are FQ1, FQ2 and FQ3 based on different combinations of the 3-component records; for auto-regressive coefficient analysis (Leonard & Kennett, 1999), the three estimates are derived from the low order correlation coefficients (AR1), the medium order correlation (AR2) and the high order correlation coefficient (AR3).

The 9 attribute estimates from the three different methods are used construct an algorithm for phase recognition and onset time picks. Firstly, for for each of the attribute estimates from the different methods, we set a token equal to unity when the STA/LTA ratio surpasses a pre-set value, otherwise, the token is set equal to zero. Secondly, we declare a recognition or detection trigger when the combination of the nine attribute tokens exceeds a pre-specified value. We have used two different ways to combine such information and so follow the changes in the nature of the noise and signal. In the first approach (equal weighting – COM) we are only concerned with the sum of the tokens rather than the contributions of different methods. In the second (equal content – CM) we attempt to equalise the contribution from the different methods. Whichever process is used we specify two different pre-set thresholds for the combination. When the lower threshold is exceeded we represent the detection by a "small flag" and when the higher threshold is also reached we set a "big flag".

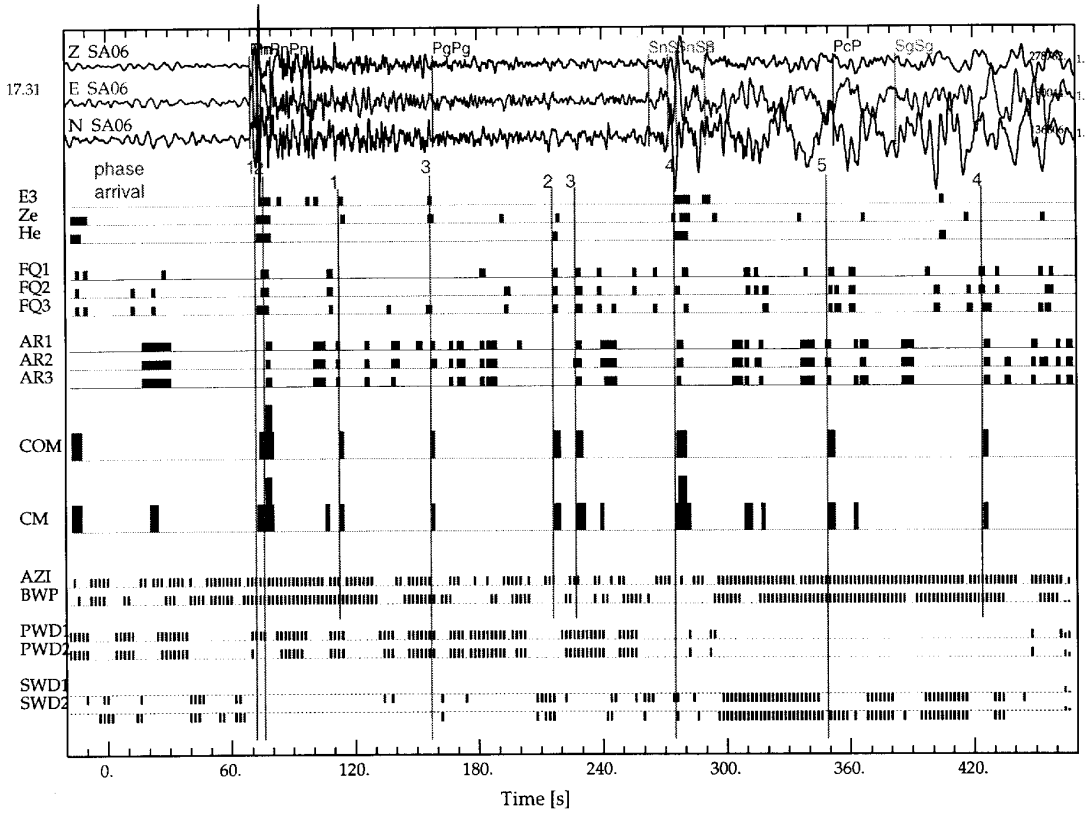

Figure 2. An example of the application of the multi-attribute algorithm to a far-regional record. The upper three traces represent the 3-component seismic records without rotation, with the superimposition of the predicted times of arrivals using the *iasp91* travel time tables for the event parameters. E_3, Z_e, H_e are the total, vertical and horizontal energy ratio of current value to long-term trend. FQ1, FQ2 and FQ3 represent different styles of detectors for instantaneous frequency. AR1, AR2 and AR3 are the detectors on the low-order, medium-order and high-order AR coefficients. COM and CM represents different styles of combining information from the detection processes. The measures AZI and BWP together provide a separation of body wave from background noise; PWD1 and PWD2 are detectors for *P* phases, and SWD1 and SWD2 are the detectors for *S* phases. The long vertical bar from the top to the bottom of the frame represents the case where both the *iasp91* travel times and the combination algorithm both indicate the arrivals, denoted as phases $1, 2, ...n$. A shorter vertical bar indicates where only the combination algorithm recognises the phases, denoted as arrivals $1, 2, ...n$.

In fig 2 we display the results of the multi-attribute analysis for an event at far-regional distance. From fig 1, it is clear that the performance of the combination algorithm is better than the performance of any single method.The energy attributes can only pick the strong seismic phases (*Pn*, *PgPg* and *SnSn*) by means of energy content if at least two attributes have a raised flag. The instantaneous frequency approach not only can pick strong phases (*Pn* and *SnSn*), but also can indicate weaker seismic phases (e.g. *PcP*) not indicated by the energy analysis. The use of the AR coefficients can indicate nearly all the phases (*Pn*, *PnPn*, *PgPg*, *SnSn* and *PcP*) which are indicated by using the *iasp91* travel time tables (Kennett and Engdahl, 1991). The combination algorithm can separate successive arrivals (such as *Pn* and *PnPn*).

For those detections that are indicated by the travel time tables, phases 1,2,3 can be distinguished as *P* wave arrivals with the linear polarisation property of body wave; phase 4 can not be definitely identified as an *S* wave phase due to uncertainty in the polarisation features of the body wave. Phase 5 has also uncertain style of P or S wave, because it is immersed in the S wave segment. However the *P* and *S* wave segments of the record can be clearly separated from the behaviour of the measures PWD1, PWD2 and SWD1, SWD2. Besides these five main phases, there are 4 other detections ('arrivals') which do not correspond to phases expected from the *iasp91* travel time tables using the event parameters.

The multi-attribute approach works well with unfiltered broad-band records even with relatively high noise levels

and such a display could present an analyst with a useful complement to more traditional methods of phase detection and recognition.

CONCLUSIONS AND RECOMMENDATIONS

A computational scheme for synthetic seismograms at teleseismic distances in which separate allowances are made for the crustal and upper mantle structure beneath source and receiver can be made both efficient and flexible. By using a representation in terms of the reflection and transmission properties of portions of the media it is possible to control the class of propagation processes included in the seismogram. The crustal reverberations and surface multiples can be calculated with correct relative amplitudes with a slowness bundle approach. A limited integration in slowness about the geometric slowness for the primary arival is undertaken at each frequency, so that the expense of a full reflectivity treatment is avoided by concentrating attention on the specific expected arrivals. Such an approach can be linked closely to any form of travel time corrections and should incorporate all available information about the structure beneath individual stations.

The full response can be used to calibrate approximate methods with shorter computation time, which can be employed in non-linear waveform inversion for source mechanism and depth. A very fast and effective non-linear location scheme has been developed for arrival time location using the Neighbourhood Algorithm and this same approach is now being developed to handle source parameter inversion by fitting the onset of P and, possibly, S waveforms.

The quality of location procedures depends heavily on the arrival time picks and for a sparse network of stations will be much enhanced if multi-phase information can be employed. Often even moderate quality later phase data can place strong constraints on an event location. With the combination of a number of different styles of phase detection we are able to provide an aid to analysts which not only flags potential phase arrivals but also provides an indication of their character. The multi-attribute approach works quite well even in the presence of significant noise and could be usefully employed in combination with selective filtering.

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