USE OF THE PP PHASE TO STUDY THE EARTHQUAKE SOURCE

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Abstract. The space-time history of the rupture process of a large earthquake can be determined from directivity analysis of source time functions deconvolved from long-period P waves. However, such analysis requires a good azimuthal distribution of stations, which is often difficult to obtain. We have developed a method for deconvolution of long-period PP waves which is useful for a distance range of 70° - 123° and 145° - 165°, thus increasing both the available data and the ray parameter aperture. The PP waveform is Hilbert transformed to remove the effect of the PP caustic and then deconvolved in the time domain. We tested the method on the 2 July 1974 Kermadec event (Ms=7.2) and obtained nearly identical source time functions from P and PP waves.

Introduction

Long-period P waves contain a great deal of information about the details of the rupture processes of large earthquakes. Deconvolution of the source time function from P waves yields the time-variant behavior of the earthquake (c.f., Ruff and Kanamori, 1983). Simultaneous deconvolution of several stations (Kikuchi and Kanamori, 1982) or deconvolutions coupled with directivity analysis (Beck and Ruff, 1984) or the Radon transform (Ruff, 1984) can define the spatial distribution of moment release. All three methods depend on the relative timing of source time function features as a function of the directivity parameter γ, where γ = p cos φ, p being the ray parameter and φ the difference of the fault and station azimuths. Thus, γ must be well sampled for adequate spatial resolution of the rupture process (e.g., Ruff, 1984). This condition is often difficult to meet, as when there are no stations in some azimuthal sector for teleseismic epicentral distances, particularly when the earthquake is too small to use stations further than 90° (i.e., diffracted P waves).

We have developed a method for deconvolving source time functions from PP waveforms; use of PP not only increases the amount of data available but can also improve azimuthal coverage by allowing the use of stations over a wider range of distances. The PP phase can be deconvolved at epicentral distances of 70° - 123° and 145° - 165°; closer than 70°, the PP phase is complicated by upper mantle structure; between 123° and 145°, the PKS phase interferes; and further than about 165°, the PP phase encounters the axial caustic. To deconvolve the PP waveform we must somehow account for the modifications of the direct P waveform introduced by the surface reflection and by the additional propagation. Although these modifications include greater attenuation and reverberations under the bounce point, the main change results from the internal caustic (Figure 1).

Jeffreys and Lapwood (1957) have shown that the caustic introduces a constant -π/2 phase shift at high frequencies, which, when combined with the π phase shift from the free-surface reflection, gives a π/2 phase shift. Choy and Richards (1975) give an intuitive discussion of how the phase shift arises at a caustic and show actual examples of this phase shift in the analogous SS phase. The π/2 phase shift transforms a function into its inverted allied function (or inverse Hilbert transform), an example of which is shown for the Dirac delta function δ(0) in Figure 1. The analytic form of the inverted allied function of δ(t) is 1/(πt) for t ≠ 0 and 0 for t=0; thus, there is energy arriving both before and after the geometric arrival time. For an actual seismogram, both the earth transfer function and instrument are band-limited, and the band-passed inverted allied function simply has a small precursor and coda. By applying the Hilbert transform, Butler (1982) successfully modelled these features in SS waveforms from the 1973 Hawaii earthquake. In a theoretical study of the PP phase, Hill (1974) has shown that in some cases, the phase shift may be frequency-dependent, tending toward π/2 at high frequency and toward 0 at low frequency due to interaction with the surface. At sufficient distance, however (i.e., Δ > 70°), even long-period PP waves should be free from this effect. Our technique for deconvolving the PP waveform consists simply of removing the π/2 phase shift introduced by the reflection at the surface and the internal caustic, and then deconvolving as we would a direct P waveform, allowing for differences in attenuation (i.e., doubling t*) and geometric spreading (g(Δ)).

Data and Discussion

For our test case, we chose the 2 July 1974 earthquake in the Kermadec Islands (Ms=7.2). The event occurred at 29.22° S, 175.94° W, with an origin time of 23:26:26.8 (ISC). Chapple and Forsyth (1979) show a first-motion focal mechanism with fault azimuth 65°, dip 22°, and slip angle 137° (Figure 2). Preliminary deconvolutions of the P and diffracted P waves indicate a shallow focal depth of 0-20 km (D. Christensen, pers. comm.), which is also implied by the absence of discernible

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Fig. 2. Equal area projection on the lower hemisphere of the focal mechanism for 2 July 1974 Kermadec event. The locations of the $P$ (circles) and $PP$ phases (crosses) used in this study are plotted on the focal sphere. Triangles are the pressure ($P$) and tension ($T$) axes.

Fig. 3. Distance profile of $P$ and $PP$ waveforms for eight stations. Station code, epicentral distance (deg.), and event-station azimuth (deg.) are listed to the left of each seismogram, with the maximum peak-to-peak amplitude (cm) to the right. While the amplitude of the $P$ wave decreases in the shadow zone, $PP$ maintains a relatively constant amplitude.

Fig. 4. Seismogram from LON plotted above its Hilbert transform at the same scale. Note the strong correspondence between the $P$ waveform and the transformed $PP$ waveform.
in the range 90° - 122°, which is consistent with the small variation in the observed amplitudes. Although all of the midpoints of the PP phases used in this study are oceanic, the effects of water bounces at the midpoint were neglected due to the long periods of the waveforms considered here.

The resulting source time functions are shown in Figure 5, with the source time functions from the transformed PP phase plotted aside those deconvolved from the P (or diffracted P) phase at the same station; the exceptions are SBA (Δ=49.4°) and KIP (Δ=53.2°), which are too close for PP, and VAL (Δ=154.9°) and PTO (Δ=164.2°), which are too far for diffracted P. The basic source time function as indicated by the diffracted and direct P waves is a single 18-second pulse, with an apparent seismic moment of about 8 x 10²¹ dyne-cm. As with the observed waveforms and their Hilbert transforms, the correspondence between the time functions from P and PP is quite remarkable. In fact, the PP-derived source time functions show no more noise than those from P and diffracted P, justifying the neglect of water bounces. Furthermore, the seismic moments derived from the PP deconvolutions are fairly consistent. The mean moment from the PP waveforms is 7.5 (±2.4) x 10²¹ dyne-cm, very close to the moment derived...
from the direct $P$ phases. Thus, it appears that the geometric spreading factors from simple geometric ray theory adequately predict both the relative and absolute amplitudes.

Conclusion

We have used a simple large earthquake to show that the long-period characteristics of the $PP$ phase are easily modeled, and that the source time function can be deconvolved from the $PP$ waveform. The chief advantages of the $PP$ phase are: 1) $PP$ phases arriving at all distances are undiffracted; and 2) the ray parameter of a given $PP$ phase is that of the $P$ phase at half the distance. The first feature allows both the reliable determination of seismic moments from seismograms recorded at stations greater than 90° from the source and the use of stations whose diffracted $P$ waves are too small. The second feature increases the range in ray parameter, and thus directivity parameter, which can be sampled. It may also help in the study of vertical strike-slip events (or dip-slip events with a steep plane), where stations corresponding to steep takeoff angles are near-nodal. Most importantly, perhaps, $PP$ deconvolution augments the available data set for a given earthquake. This is particularly crucial for earthquakes before 1963, where few seismograms are generally available for a given event.

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