GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 14, PAGES 1833-1836, JULY 1, 1996

On PP-P differential travel time measurements

Hanneke Paulssen and Eléonore Stutzmann[1]

Department of Geophysics, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, The Netherlands

Abstract. This study investigates the stability of PP-P travel time measurements using a waveform crosscorrelation method on both broadband and long-period data. This study finds correspondence between 50% of the PP-P travel times read from broadband and long-period data, but also finds 50% of the measurements differ more than 1.0 second. The inconsistent measurements are demonstrated to be due to two causes. (1) Diffraction near the core-mantle boundary causes dispersion of the P phase which yields an underestimate of the PP-P travel time determined from long-period data. This effect is identified at epicentral distances as small as 88°and may amount to several seconds. (2) Interference of the PP phase with secondary arrivals causes distortion of the PP waveform and produces a non-systematic measurement error. This effect are most clearly seen on broadband seismograms and may even hamper an unambiguous broadband PP-P travel time measurement. Although strong high-frequency effects associated with interference are filtered out on the long-period data, the long-period PP-waveform may still be contaminated. We conclude that the accuracy of PP-P travel time measurements is on the order of 1 s for both broadband and long-period seismograms.

Introduction

PP phases are important for determining upper mantle P-velocity structure in regions that are poorly sampled by direct P waves but well-sampled by PP ray paths. PP waveform modelling was therefore employed to determine the crustal and upper mantle structure of various tectonic regions [*LeFevre and Helmberger,* 1989; *Schwartz and Lay,* 1993]. At epicentral distances larger than 60° the PP phase is outside the upper mantle triplication region and a simple crosscorrelation technique should suffice to determine the PP-P travel time. This differential travel time is most sensitive to the P-velocity structure beneath the PP reflection point [*Girardin,* 1980; *Woodward and Masters,* 1991]. The crosscorrelation method is conventionally applied to long-period data, but more accurate measurements may be obtained from broadband instrumentation due to the shorter periods in the broadband data and the wider frequency band. Furthermore, broadband data are now becoming sufficiently abundant to obtain good coverage from such a data set.

[1]Now at: Laboratoire de Sismologie, Institute de Physique du Globe 4, place Jussieu, 75252 Paris Cedex 05, France

Paper number 96GL01598
0094-8534/96/96GL-01598$05.00

This study was initiated to determine PP-P differential travel times from long-period and broadband data by a semi-automatic procedure. However, it was soon apparent that waveform distortion affects the measurements, resulting in significantly different travel time measurements obtained from broadband and long-period data. In this paper we illustrate some of the P and PP waveform effects that complicate PP-P differential travel time measurements.

Data and analysis

Data We determined differential travel times from broadband and long-period stations in Europe to obtain a dense sampling of PP bounce points per event. Data available on CD-ROM (from the ORFEUS Data Center) were selected for the period 1983 to 1988 and epicentral distance range of 60° to 100°. We selected roughly 400 long-period and broadband seismograms with good signal-to-noise ratio.

Analysis Our semi-automatic procedure to determine differential travel times follows that of previous studies [e.g. *Butler,* 1979; *Woodward and Masters,* 1991]. It consists of the construction of a synthetic PP-waveform from the P waveform and its crosscorrelation with the seismogram to determine the differential travel time. More specifically, the synthetic PP waveform is obtained by (1) windowing of the P waveform, (2) application of the Hilbert transform to account for the $\pi/2$ phase shift of the PP phase, (3) multiplication by a factor of -1 to account for the reflection at the free surface, and (4) the application of a δt^* operator which accounts for the difference in attenuation along the P and PP ray paths. For shallow events the P waveform may include the pP- and sP-phase, depending on the depth of the event and the time window selected. The method was applied to raw broadband and long-period data, so without correction for instrument response.

Observations We checked the stability of the measurements by varying the length of the time window of the selected P waveform. In agreement with other (long-period) studies [*Woodward and Masters,* 1991; *Kuo et al.,* 1987] we found that stable measurements are obtained with an uncertainty of 0.5 – 1 seconds for seismograms with a clear maximum in the crosscorrelation. However, for a large portion of the broadband data it was not clear which extremum to select. Obviously, the given uncertainties are not appropriate for these data. Our observations indicate that the procedure described above in many cases does not adequately predict the measured broadband PP waveform.

The analysis performed and complications encountered are illustrated in fig. 1. Broadband data of the 1983 Nov 30 Chagos Archipelago event recorded at NARS station NE09 are shown along with the synthesized PP waveform and corresponding crosscorrelogram (fig. 1a). An unambiguous determination of the PP-P travel time from the crosscorrelogram

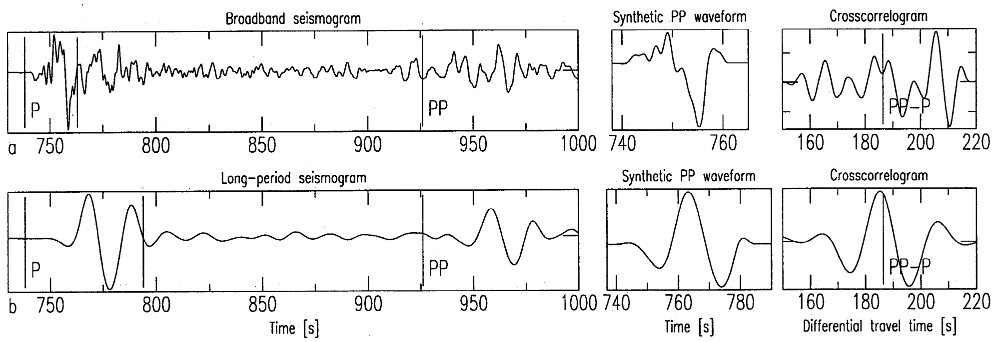

Figure 1. Broadband (a) and long-period (b) data, synthetic PP waveform, and crosscorrelogram of the 1983 Nov 30 Chagos Archipelago event (6.85S 72.04E, depth 10 km) of NARS station NE09 ($\Delta = 81.7°$). The tick marks indicate the theoretical P and PP travel times and the end of selected P time window. The PP-P tick marks on the crosscorrelograms indicate the theoretical PP-P travel time.

is obviously not possible. In contrast, fig. 1b shows the data converted to an SRO long-period response (by deconvolution of the broadband NARS response and convolution with the SRO response): the long-period crosscorrelogram has the expected clear maximum. The difference in the crosscorrelogram is due to the difference in frequency content of the data: the NARS instruments have a flat response to velocity between 0.01 and 1 Hz, whereas the SRO-response is strongly peaked at 25 sec.

Some waveform distortion is expected. Crustal layering at the bounce point would generate PP precursors (from underside reflections) and coda waves (from crustal reverberations). The largest effect on the PP-waveform is expected from Moho underside reflections which may have amplitudes of up to 20% of the surface reflected PP phase. Such phases may interfere with the PP phase and are expected to cause minor (< 1 s) perturbations in the travel time measurements.

Broadband versus long-period We analysed the data from individual events carefully, and compared the measurements from broadband data to those of simulated SRO long-period records. In about 50% of the cases we found discrepancies larger than 1.0 s between the broadband and long-period measurements. Such errors are rather large if PP-P differential travel times are to be used in tomographic studies of the upper mantle. In the following we show data of two events which illustrate some causes of waveform distortion.

P waveform distortion Figure 2a shows broadband

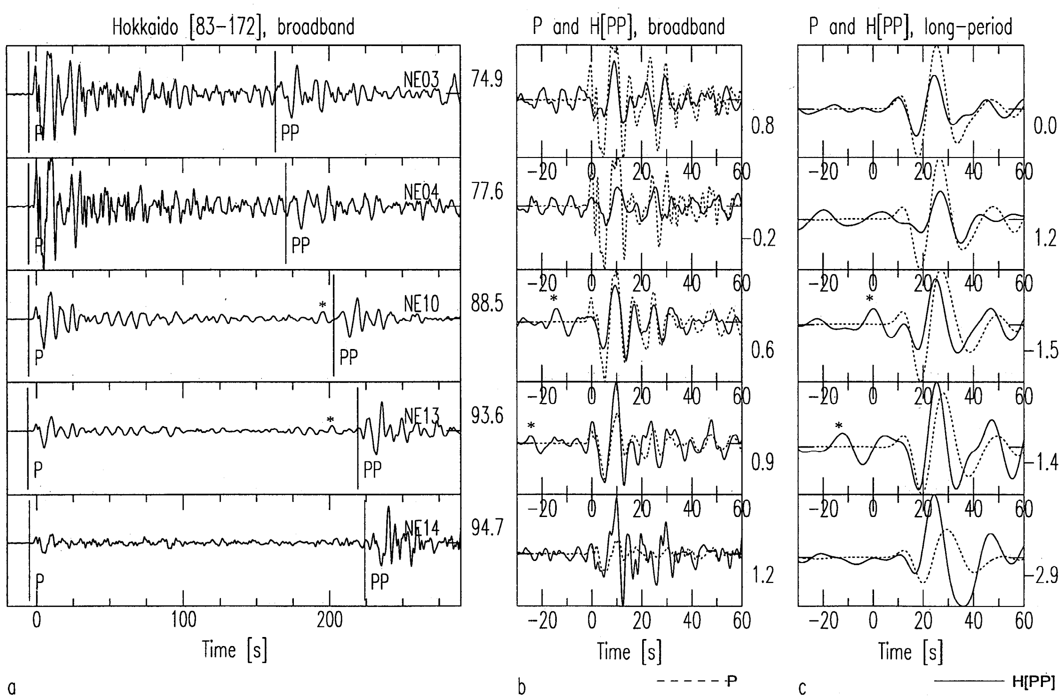

Figure 2. (a) Broadband data of the 1983 Jun 21 event (41.34N 139.10E, depth 6 km). The seismograms are aligned on the P arrival. (b) P waveforms (dashed) and Hilbert-transformed PP waveforms (solid) aligned on the first waveform maximum. The PP-P travel time anomalies from broadband crosscorrelation are shown to the right of each frame. (c) The data of panel b converted to a long-period response. The PP-P travel time anomalies from long-period crosscorrelation are shown to the right of each frame. Epicentral distances (degrees) are indicated between panels b and c. Asterisks indicate PP precursors.

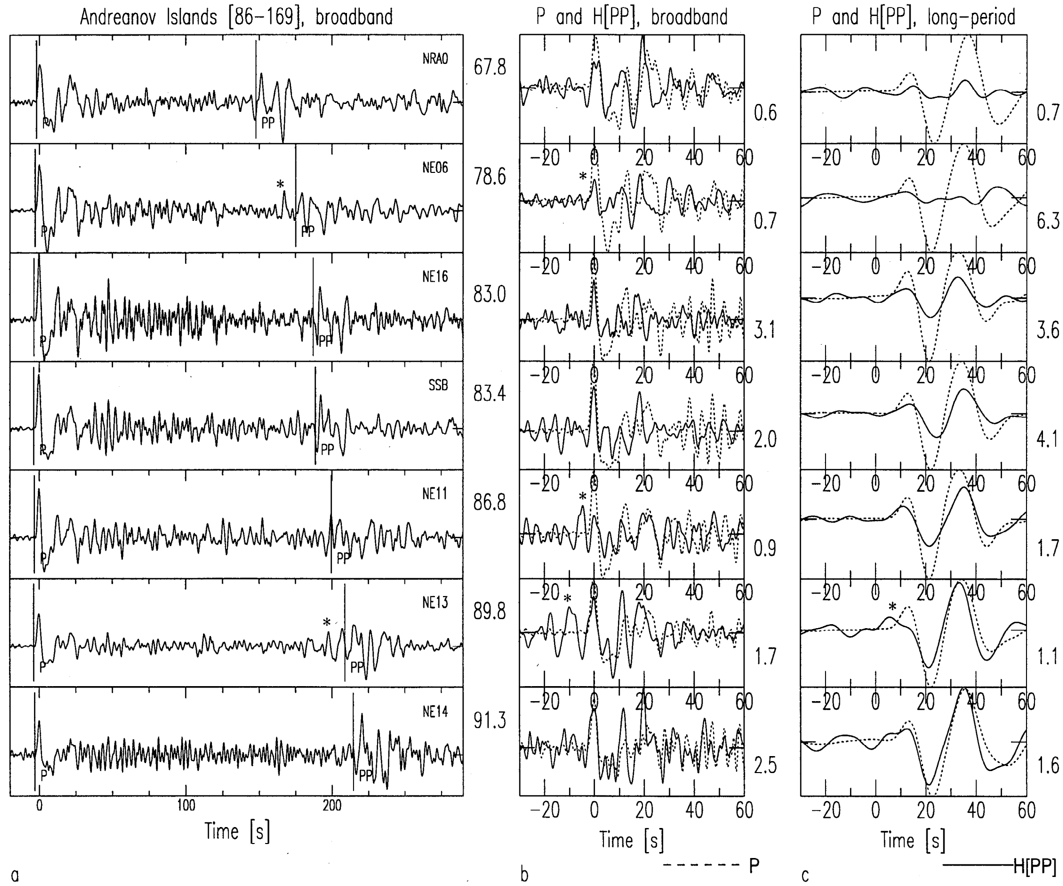

Figure 3. Similar as figure 2 for the 1986 Jun 18 event (51.66N 176.89W, depth 56 km).

NARS data of a Hokkaido event. We applied a Hilbert transform to the PP phase and compared this signal (solid) with the direct P wave (dashed). The first maximum of the P phase and Hilbert-transformed PP phase are manually aligned on the broadband data in fig. 2b to obtain the best waveform fit. In the absence of any complicating factors (e.g. attenuation, crustal reflections) the waveforms should match perfectly. Figure 2c shows these data converted to an SRO long-period response. Whereas the broadband data show a reasonable waveform match, the long-period data show an increase in mismatch with increasing epicentral distance due to broadening of the P waveform. For instance, the long-period P waveform of NE10 is not only broadened compared to the Hilbert-transformed PP waveform, but also to the P waveforms of NE04 and NE03. The reason for this progressive broadening of the P-waveform with epicentral distance due to is (low-frequency) diffraction along D" and the core-mantle boundary (CMB). Although CMB diffraction is well-known, it is usually investigated in the geometrical shadow of the core (> 95°). For the source-receiver configuration of fig. 2 P wave dispersion is already observed at 88°. Using the cross-correlation method the discrepancy between the broadband and long-period PP-P anomalies increases from 2 (NE10) to over 4 seconds (NE14). This discrepancy is systematic, and will lead to an underestimate of the PP-P travel time from long-period data. The increase in the PP-P travel time anomaly beyond 90° is also obvious in the data of *Woodward and Masters* [1991, their fig. 4]. Although their measurements could be explained by inaccuracies in the reference model, our observations clearly show a frequency dependent effect. It is important to acknowledge this dispersion effect otherwise biased travel times may be mapped along PP ray paths or to near-CMB structure.

Note that this effect seems to depend on the source-receiver configuration. For some events it is identified at epicentral distances as small as 88° (e.g. fig. 2) while for events from other source regions it is observable only at distances larger than 90° (e.g. fig. 3). To prevent possible contamination we suggest a conservative approach and limit the long-period PP-P measurements to epicentral distances smaller than 88°.

Interference of PcP with P has a negligible effect on the PP-P measurements as was synthetically tested and observationally checked. Moreover, its effect would decrease with decreasing PcP-P times (i.e. larger epicentral distances) whereas we observe broadening with epicentral distance.

PP waveform distortion Many seismograms show significant PP waveform variations. For example, station NE10 (fig. 2) shows an arrival approximately 15 s prior to PP, and station NE13 a PP precursor at approximately 25 s. Similar arrivals may affect the PP-P measurement, dependent on amplitude, timing and frequency content of the data. It is found that such interference effects explain most of the mismatches between broadband and long-period differential travel time measurements. In most cases, however, it is difficult to identify the origin of such secondary arrivals. For instance, the precursors at NE10 and NE13 cannot be explained by globally observed primary or secondary phases (see e.g. *Shearer*, 1991). Their timing corresponds to PP underside reflections from depths of roughly 50 and 100 km, respectively, but their amplitudes are difficult to explain by a 1-D model. Topography and/or heterogeneity near the PP bounce point is required to focus these arrivals.

Effects of PP waveform distortion are also observed for other events. Figure 3a shows data from an event in the Andreanov Islands recorded by broadband NARS, GEOSCOPE (SSB) and NORESS (NRA0) stations. The P-waveform and Hilbert-transformed PP-waveform have been manually aligned to obtain the best waveform fit (fig. 3b). Figure 3c shows the data of fig. 3b converted to a long-period response. Apart from station NE14, the P and Hilbert-transformed PP waveform match on the broadband data is not very good. Visual inspection of the data shown in figure 3b and 3c suggests why the crosscorrelation method gives very different results when applied to broadband or to long-period data. For instance, the PP arrivals of stations NRA0 and NE06 are clear on the broadband seismograms but virtually absent on the long-period data. (Note that the manually aligned waveforms of NE06 show a 10 sec early PP arrival which matches the travel time of a Moho underside reflection.) The broadband data of station NE13 show a 20 s precursory wavetrain which is nearly filtered out by the long-period response. The broadband crosscorrelogram of this station (not shown) yields several extrema from which it is very difficult to select the best one.

Discussion and Conclusion

We have shown that P and PP waveform distortion affect the PP-P differential travel time measurement. Although half of the observations showed a 1 sec consistency between the broadband and long-period crosscorrelation measurement, the other half showed larger deviations. A systematic bias towards smaller PP-P travel times is obtained by P-wave diffraction along D" and CMB. This bias not only depends on the frequency content of the data but also on the region of the D" and CMB sampled by the data. P wave diffraction effects may be avoided by conservatively limiting the data set to epicentral distances smaller than 88°.

More important and less systematic are the PP waveform distortion effects. Some of these can be explained by PP interference with underside reflections from discontinuities near the bounce point, although in many cases focussing by topography is required to explain their high amplitudes. These interference effects are strongest on the broadband data and may even lead to misinterpretations of the PP arrival. The effects of precursors are partly filtered out on the long-period data. This means that these data are less affected, but also that the interference effects are not as easily recognized. To our knowledge, this is the first paper that addresses these PP-waveform complexities.

At this point it seems difficult to alleviate the problems with P and PP wave distortion due to the fact that their frequency-dependent effects are strongly regionally dependent.

The main conclusion from this study is that broadband data do not necessarily provide more accurate PP-P travel time measurements compared to those of long-period data. The 1-sec uncertainty estimated for long-period data [*Woodward and Masters* 1991] seems appropriate, and for many seismograms higher accuracy will not be obtained from broadband data. Thus, the uncertainty of PP-P differential travel times which can be obtained is an order of magnitude larger than the travel time accuracy of direct P waves.

Acknowledgments. We thank Bob Woodward and Arthur Rodgers for reviewing this manuscript. NARS is supported by the Earth Sciences branch of the Netherlands Organization for Scientific Research (GOA). This is Geodynamics Research Institute (Utrecht University) contribution nr 96.014.

References

Butler, R., Shear-wave travel times from SS, *Bull. Seismo. Soc. Am., 69,* 1715-1732, 1979.

Girardin, N., Travel-time residuals of PP waves reflected under oceanic and continental platform regions, *Phys. Earth Planet. Int., 23,* 199-206, 1980.

Kuo, B.-Y., D.W. Forsyth, and M. Wysession, Lateral heterogeneity and azimuthal anisotropy in the North Atlantic determined from SS-S differential travel times, *J. Geophys. Res., 92,* 6421-6436, 1987.

LeFevre, L., D.V. Helmberger, Upper mantle P velocity structure of the Canadian Shield *J. Geophys. Res., 94,* 17,749-17,765, 1989.

Schwartz, S.Y., T. Lay, Complete PP-waveform modelling for determining crust and upper mantle structure, *Geophys. J. Int., 112,* 210-224, 1993.

Shearer, P.M., Constraints on upper mantle discontinuities from observations of long-period reflected and converted phases, *J. Geophys. Res., 96,* 18,147-18,182, 1991.

Woodward, R.L., and G. Masters, Global upper mantle structure from long-period differential travel times, *J. Geophys. Res., 96,* 6351-6377, 1991.

(received October 30, 1995; accepted February 1, 1996.)