

# Near-field deformation seen on distant broadband seismograms

John E. Vidale<sup>1</sup>

United States Geological Survey, Menlo Park, California

Saskia Goes

University of California, Santa Cruz, California

Paul G. Richards

Lamont-Doherty Earth Observatory, Palisades, New York

**Abstract.** Although far-field body waves and surface waves are widely recognized, the improvements in broadband networks now allow the measurement of "near-field" deformation of large earthquakes at great distances. Near-field motions have been recognized previously only in theory and in close-in recordings of earthquakes. We show examples from two recent events. For the large deep event on June 9, 1994 in Bolivia, there is a clear offset after the arrival of the P wave that has the amplitude expected for the near-field term. In the shallow September 2, 1992 Nicaragua earthquake, the very long-period motion observed between the P and S waves has roughly the amplitude expected from near-field terms. Such near-field terms are insensitive to earth structure, but supply information on long-period source processes, and their observation begins to close the gap between long-period seismology and geodesy.

## Background

The exact solution for the displacement field due to a point force acting in a solid uniform whole space was published by Stokes more than 150 years ago, and the double couple solution has been known for decades. Compressional and shear disturbances (P and S waves) are radiated, whose amplitudes are inversely proportional to distance traveled. In addition, the material is permanently strained as the P and S waves pass in a mostly compressional and a mixed shear and compressional sense, respectively. Finally, there is a component of progressive strain that appears most strongly just before the arrival of the S wave. This component may be thought of as the movement away from quadrants that have been compressed toward quadrants that have been dilated.

Although permanent tilt from the Great Alaskan earthquake of 1964 was consistent with that measured in

Hawaii [Press, 1965], in general, strain and tilt signals from distant earthquakes are difficult to identify [McHugh and Johnston, 1977]. On the other hand, near-field observations consistent with theory are routinely seen with instruments cemented into deep boreholes (see [Johnston et al., 1987] for summary).

Two examples are shown in Figure 1, calculated from the whole space solution at a distance of ten km [Aki and Richards, 1980]. Figure 1b shows a source duration of 0.1 s and the distance of 10 km, typical of a very close-in recording of a magnitude 2 or 3 earthquake. Figure 1a shows a source duration of 0.02 s, typical of a magnitude 1 earthquake. The near-field term is smaller in Figure 1a than in 1b because it depends, in the absence of background noise, on the ratio between the source duration and the P-wave travel time. Near-field terms such as those in Figure 1 have been recognized and modeled at local distances [Dreger and Helmberger, 1990; Johnston and Borchardt, 1986; Kanamori et al., 1990; Romanowicz et al., 1993]. Others have commented upon the phenomenon associated with near-field terms [e.g., Haskell, 1969; Grayzer, 1981].

Figure 1 is just as accurate when the distance and time scales are multiplied by  $10^3$ . So 20 and 100 sec duration earthquakes should produce near-field terms of the same magnitude at a distance of  $10^4$  km, or roughly  $100^\circ$ , with Figure 1 spanning 2000 rather than 2 s. In reality, different noise and instrumentation problems would be encountered, and a whole space solution is not an accurate approximation for the entire seismogram at teleseismic distances.

## The June 9, 1994 Bolivia earthquake

The Bolivia earthquake of June 9, 1994, provides a good opportunity to detect near-field deformation at great distance due to its large magnitude and great depth; and it occurred in the modern era when numerous broadband records can be promptly accessed. Its moment,  $3 \times 10^{28}$  dyne-cm (Ekström, pers. comm., 1994), is the largest moment ever measured for a deep event, an advantage since the amplitude of near-field terms is proportional to moment. The source duration is about 40 sec, which is normal for a deep event with moment  $3 \times 10^{28}$  dyne-cm [Vidale and Houston, 1993]. The depth of 660 km results in the arrival of the surface reflections pP and sP more than

<sup>1</sup> Also at Institute of Tectonics, University of California, Santa Cruz.

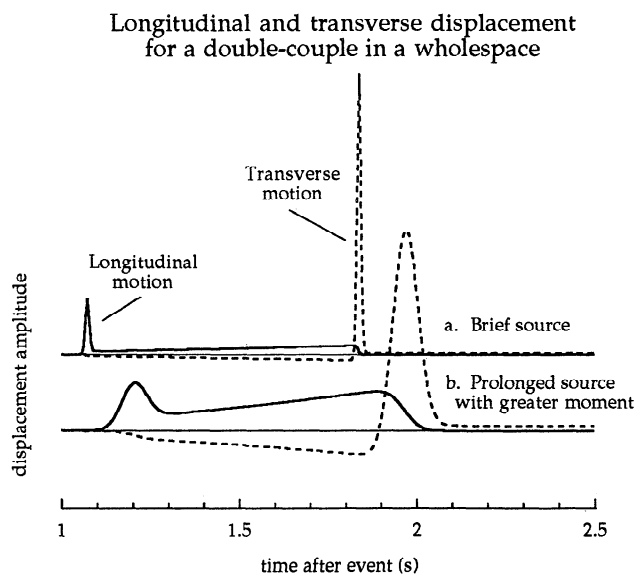


Figure 1. Longitudinal and transverse components of ground displacement 10 km away from fault. The amplitudes and particle motions of these components follow the far-field P and S radiation patterns. The earthquake durations are 0.02 s in Figure 1a and 0.1 s in Figure 1b. The compressional wave velocity is set to 10 km/s and the shear velocity to 5.78 km/s.

100 s after the P wave, late enough that they do not complicate our analysis of deformation coincident with the P wave. From the arrival time of pP on, our whole space solution is not expected to match the observations.

Since the P wave near-field term generally has the same polarity as the P transient wave, we can stack the P waves recorded at many seismic stations to cancel most of the scattered energy. Serendipitously, we did this in an unsuccessful attempt to search for anomalous source behavior. We aligned the beginnings of each P wave, so if there is significant spatial extent to the rupture, we may not have lined up the endings of the rupture, which will then be artificially smeared in the stack.

A stack of P waves from 22 stations in California is shown in Figure 2. None of the instruments seemed to clip. The stations span only a small range in distance and azimuth. Some of the energy up to 10 s behind the P wave may be the S to P conversion from the discontinuity near 660 km depth, and the underside reflection from the "410" may be 30 s later [Vidale and Benz, 1992; Zhang and Lay, 1993]. It is clear that the very high quality of the California stations, as well as the large size of the earthquake, are required to recover the long-period ground displacement.

The stack does not return to the same level after as before the P wave. The difference is about 10% of the peak amplitude. This corresponds to about 50 microns of displacement. A similar stack for the March 9, 1994 Tonga earthquake, which was also very large and deep, was less conclusive due to smaller moment by a factor of 10, greater epicentral distance, nodal P waves in North America, and perhaps core-grazing ray paths.

To appreciate the basic character of theory and observation in Figure 2, note from equation 4.32 [Aki and

Richards, 1980] that the pulse shape in the longitudinal direction near the P-wave arrival in a whole space is proportional to the sum of far-field and near-field terms, which reduces to a wavefront expansion,

$$\dot{M}(t-T) + \frac{4}{T} M(t-T) \quad (1)$$

where  $M$  is the moment release and  $T$  is the P wave travel time, which is about 600 s for the Bolivian event. Therefore, the amplitude of the near-field term compared to the P-wave pulse diminishes linearly with increasing travel time (i.e. distance); this is why it is called a "near-field" term. The simulated offset at 65° distance matches the stack of the observations, which range from 46° to 77°. We checked for similar near-field contributions at the S wave arrival time, but were stymied by greater signal-generated noise.

It is important to note that this offset at the time of the P wave is only one of the several terms whose amplitudes attenuate at the rate of the reciprocal of the distance squared, and the permanent offset due to the earthquake is not apparent until after the passage of the S wave, in the case of a whole space. These rapidly attenuating, long-period terms have been called both the near field and the intermediate field [Aki and Richards, 1980].

The modeling does not correctly incorporate the effect of the velocity gradients in the mantle, however the effects of the free surface are the same for a wavefront expansion of the far-field and near-field terms, and factor out. For the Bolivian event, whose duration of 40 s is about 5% of the P travel time, the ratio of near-field term amplitude to far-field term amplitude is intermediate between the traces in Figures 1a and 1b. Theory predicts an additional offset at the P-wave arrival time, resulting from analysis of the transverse displacement. However, this component is quite small for the vertical component data presented in the paper.

The offset observed in Figure 2, initiated by the P wave, is of the same order as the near-field offset induced at

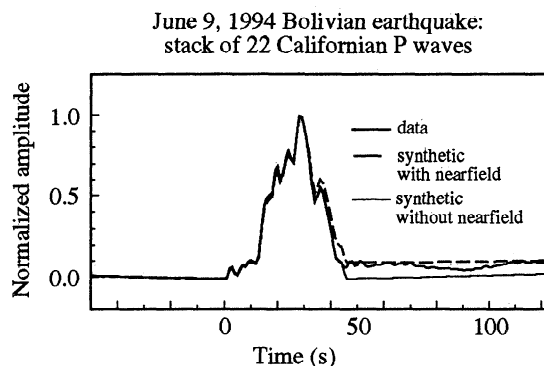


Figure 2. The heavy trace shows the stack of 22 Californian P-wave displacement records from the Bolivian event of June 9, 1994. Each trace was normalized to a common amplitude prior to stacking. The light trace shows the inferred moment rate function. The dashed line shows the moment rate function with the addition of the whole-space near-field displacement given by equation 1 in the text. All three traces are high-pass filtered with a corner of 500 sec period.

these distances by the Bolivian earthquake. We may also be seeing energy reflected from the velocity gradient above the source. However, this would require an almost constant gradient from 200 to 500 km depth, and would not be expected to add constructively in the stack. Reflections from the gradient would depend on the polarity of upgoing P and S radiation, not the downgoing P radiation that was used to set waveform polarity for our stack. Another unlikely possibility, which however cannot be absolutely rejected, is that the source continues to release moment at a constant rate for some time after most people would interpret the rupture to have stopped.

### The Sept. 2, 1992 Nicaraguan earthquake

It has recently been shown that long-period energy arriving between the P and S wave arrival times is simple to measure with broadband instruments, and carries valuable information about the long-period character of earthquakes [Kanamori, 1993]. The methods for calculating synthetic seismograms, while accurate and able to match the observations, do not allow the separate assessment of near-field terms and the more traditional surface and body waves. These long-period arrivals have been termed the W phase, and attributed to "whispering gallery" propagation paths [Saito, 1961] that multiply reflect from the Earth's layering [Kanamori, 1993].

An alternative and in some ways more elementary framework in which to appreciate the properties of the

long-period energy, observed to arrive between P and S, is to note its general correspondence with the near-field terms in an elastic-whole space.

Thus, Figure 3 shows vertical displacement from the P wave through the S waves to the onset of the Rayleigh waves at four North American stations. The data are high-pass filtered at 1000 s period. The horizontal motions are too noisy to add to this analysis. Whole space simulations are shown above and below the data. The simulations assume a moment of  $3.7 \times 10^{27}$  dyne-cm [Kanamori and Kikuchi, 1993]. Although more detailed models exist for this earthquake, the time function is chosen to be a Gaussian of duration about 60 seconds, since only the moment affects the near-field terms. The amplitude of the near-field terms are insensitive to the assumed duration of the earthquake.

There is no hope of matching the data in detail since the whole space simulation does not include the surface reflected and converted phases such as pP, sP, PP and SP. The simulation thus makes no effort to match the real mechanism of the Nicaraguan earthquake. However, it appears likely that there is sufficient amplitude in the near-field term to explain the very long-period constitution of the W phase. It is thus not necessary to invoke more complicated raypaths for the W phase than are currently used to model shorter-period body waves.

While the identification of the influence of near-field terms in long-period seismograms does not imply errors in current calculations done by modes [Gilbert and Dziewonski, 1975; Kanamori, 1993], it clarifies the factors that influence them. The role of permanent deformation in long-period seismograms may be considered a semantic question, however, if one uses complete solutions as a black box.

### Implications

The direct detection of near-field terms may allow the measurement of the permanent deformation resulting from faulting. These deformations are on the order of 0.1 mm for large earthquakes at distances of thousands of km. Near-field terms are sensitive to the depth and mechanism of faulting, but not to mantle structure, which mainly affects higher frequency waves. In the future, coupled broadband seismic recordings and geodetic measurements may allow the separation of coseismic slip and post-seismic relaxation where there are no close-in instruments.

For many shallow earthquakes, the interference of surface reflections and scattering with the direct wave will hinder the isolation and identification of near-field terms, but for long ruptures such as the Nicaraguan example above, such terms may present problems for long-period source inversions based on far-field modeling approaches. The acknowledgment of the presence of near-field terms improves our intuitive understanding of the contents of the seismic waves that we measure, and may affect the processing we choose to apply in measuring the earthquake source.

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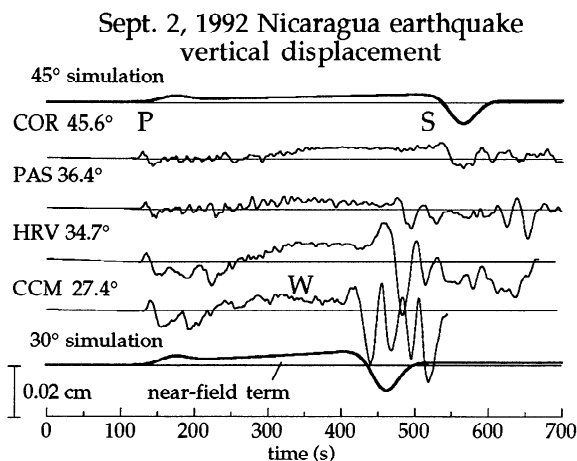


Figure 3. Four vertical displacement traces are from the Nicaraguan earthquake of September 2, 1992. The station name and distance in degrees is listed to the left of each trace. The data is bracketed by whole space simulations at 30° and 45° distances. The simulations assume a moment of  $3.7 \times 10^{27}$  dyne-cm, P wave velocity of 7 km/s, S wave velocity of 4 km/s, and density of 3 g/cm<sup>3</sup>. The mechanism and component chosen for the near-field simulation are arbitrary, but have typical amplitudes that appeared for P, S, and near-field terms in a suite of calculations. The details of the simulations are as follows: the mechanism is strike-slip in a wholespace, and the near receiver is placed at a depth of 2000 km, and 1500 km east and 1000 km north of a source with one nodal plane striking north. The far receiver is 50% farther away in the same direction.

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## References

- Aki, K., and P.G. Richards, *Quantitative Seismology: Theory and Methods*, vol. 1 and 2, 932 pp., W.H. Freeman, San Francisco, 1980.
- Dreger, D.S., and D.V. Helmberger, Broadband modeling of local earthquakes, *Bull. Seism. Soc. Am.*, **80**, 1162-1179, 1990.
- Gilbert, F., and A.M. Dziewonski, An application of normal mode theory to the retrieval of structural parameters and source mechanism from seismic spectra, *Philos. Trans. R. Soc. London*, **278**, 187-209, 1975.
- Grayzer, V.M., Some features of the fluctuations in the epicentral zone of earthquakes, *Solid Earth Geophysics (English trans.)*, **17**, 662-666, 1981.
- Haskell, N.A., Elastic displacements in the near-field of a propagating fault, *Bull. Seism. Soc. Am.*, **59**, 865-908, 1969.
- Johnston, M.J.S., and R.D. Borchardt, Short-period strain (0.1-100,000 s): Near-source strain field for an earthquake (ML 3.2) near San Juan Batista California, *J. Geophys. Res.*, **91**, 11497-11502, 1986.
- Johnston, M.J.S., A.T. Linde, M.T. Gladwin, and R.D. Borchardt, Fault failure with moderate earthquakes, *Tectonophysics*, **144**, 189-206, 1987.
- Kanamori, H., W-phase, *Geophys. Res. Lett.*, **20**, 1691-1694, 1993.
- Kanamori, H., and M. Kikuchi, The 1992 Nicaragua earthquake - a slow tsunami earthquake associated with subducted sediments, *Nature*, **361**, 714-716, 1993.
- Kanamori, H., J. Mori, and T.H. Heaton, The 3 December 1988 Pasadena earthquake (ML=4.9) recorded with the very broadband system in Pasadena, *Bull. Seism. Soc. Am.*, **80**, 483-487, 1990.
- McHugh, S., and M.J.S. Johnston, An analysis of coseismic tilt changes from an array in Central California, *J. Geophys. Res.*, **82**, 5692-5698, 1977.
- Press, F., Displacements, strains, and tilts at teleseismic distances, *J. Geophys. Res.*, **70**, 2395-2412, 1965.
- Romanowicz, B., D. Dreger, M. Pasyanos, and R. Uhrhammer, Monitoring strain release in central and northern California using broadband data, *Geophys. Res. Lett.*, **20**, 1643-1646, 1993.
- Saito, Y., Normal mode interpretation of the sound propagation in Whispering Galleries, *Nature*, **189**, 475-476, 1961.
- Vidale, J.E., and H.M. Benz, Upper mantle seismic discontinuities and the thermal structure of subduction zones, *Nature*, **356**, 678-683, 1992.
- Vidale, J.E., and H. Houston, The depth dependence of earthquake duration and implications for rupture mechanisms, *Nature*, **365**, 45-47, 1993.
- Zhang, Z., and T. Lay, Investigation of upper mantle discontinuities near northwestern pacific subduction zones using precursors to sSH, *J. Geophys. Res.*, **98**, 4389-4405, 1993.

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J. E. Vidale, MS 977, United States Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025

S. Goes, Institute of Tectonics, University of California, Santa Cruz, CA 94065

P. G. Richards, Lamont-Doherty Earth Observatory, Palisades, NY 10964

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