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# AN ANALYSIS OF NEARFIELD NORMAL MODE AMPLITUDE ANOMALIES OF THE LANDERS EARTHQUAKE

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*Abstract*. The 1992 Landers earthquake ($M_W$=7.3) occurred in the middle of the TERRAscope network. Long-period Rayleigh waves recorded at the TERRAscope stations ($\Delta \leq 3°$) after traveling around the Earth show large amplitude anomalies, one order of magnitude larger than spherical Earth predictions up to a period of about 600 s. The ground motions over the epicentral region at and after the arrival of R4-5 are in phase at all stations. These observations are inconsistent with the nearly vertical strike slip mechanism of the Landers earthquake. Synthetic seismograms for a rotating, elliptic and laterally heterogeneous Earth model calculated by the variational method agree well with the observed waveforms. Calculations for various 3D Earth models demonstrate that the amplitudes are very sensitive to the large scale aspherical structure in the crust and the mantle. The anomalies for modes shorter than 300 s period can be explained by lateral heterogeneity shallower than the upper mantle. Rotation of the Earth and lower mantle heterogeneity are required to explain mode amplitudes at longer periods. Current whole mantle seismic tomographic models can fully explain the observed amplitudes longer than 300 s. To assess the effect of the high order lateral heterogeneity in the mantle more precise estimate of the crustal correction is required.

## Introduction

The 1992 Landers Earthquake (6/28/1992 $M_W$=7.3) occurred in the middle of the Caltech/USGS TERRAscope network. Figure 1 shows the epicenter, the source mechanism determined from teleseismic surface waves (Kanamori *et al.*, 1992) and nearby broadband stations in California. Since the mechanism is nearly vertical strike slip, we expect long-period Rayleigh waves, or spheroidal modes, to be nodal near the epicenter and antipode for a spherical non-rotating laterally homogeneous Earth model. However, the amplitudes of the Rayleigh waves observed at the TERRAscope stations are much larger than expected for a spherical Earth model. Figure 2 compares the observed long-period vertical component seismograms at one teleseismic station and four nearby stations with synthetic seismograms computed for a spherically symmetric non-rotating Earth model. Surface waves with frequency between 3 and 4 mHz dominate in these records. A spherical Earth model explains Rayleigh wave amplitudes at MAJO (distance $\Delta$=81°) and BKS ($\Delta$=6°) but not at TERRAscope stations ($\Delta \leq 3°$) where observed amplitudes are an order of magnitude larger than the spherical Earth predictions.

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## Observations

We take the Fourier spectra of the observed and synthetic seismograms for a spherical non-rotating Earth model at MAJO, BKS and PAS (Figure 3). At PAS the discrepancy of the amplitudes of the fundamental spheroidal modes is very large up to a period of about 600 s, or mode $_0S_{10}$. At BKS anomalous amplitudes are found around $_0S_{11}$ and $_0S_{19}$. At large epicentral distances (e.g. MAJO) no amplitude anomalies are observed. All TERRAscope stations are located within 300 km of the epicenter and show similar large amplitude spectra. We also observed that the ground motions at long periods, several hours after the origin time, become in phase over the entire epicentral region (Figure 4 top). This is not expected from the surface wave radiation pattern of the nearly vertical strike slip mechanism. The initial part of the long-period R2,3 packet recorded at the TERRAscope stations (not shown here) is as large as the R4,5 packet. Horizontal component records are too noisy to be used for the determination of the modal peaks in the Fourier spectra.

## The cause of the anomalies

The non-spherical nature of the Earth such as rotation, ellipticity and aspherical structure could cause the anomalies. Since the small amplitude of the spheroidal oscillations from a strike-slip source near the origin results from the destructive interference of waves radiating in the orthogonal directions from the source, the non-spherical nature of the Earth could reduce the degree of destructive interference, thereby

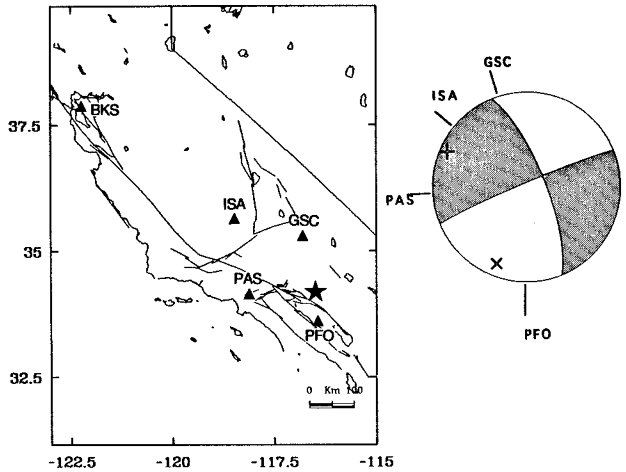

Fig. 1. The location of the Landers earthquake ($M_W$=7.3, June 28, 1992, 11h57m34s GMT, 34.20°N, 116.44°W) and the five broadband stations in California used in this study. The source mechanism (dip=74°, rake=-176°, strike=340°) is nearly vertical strike slip.

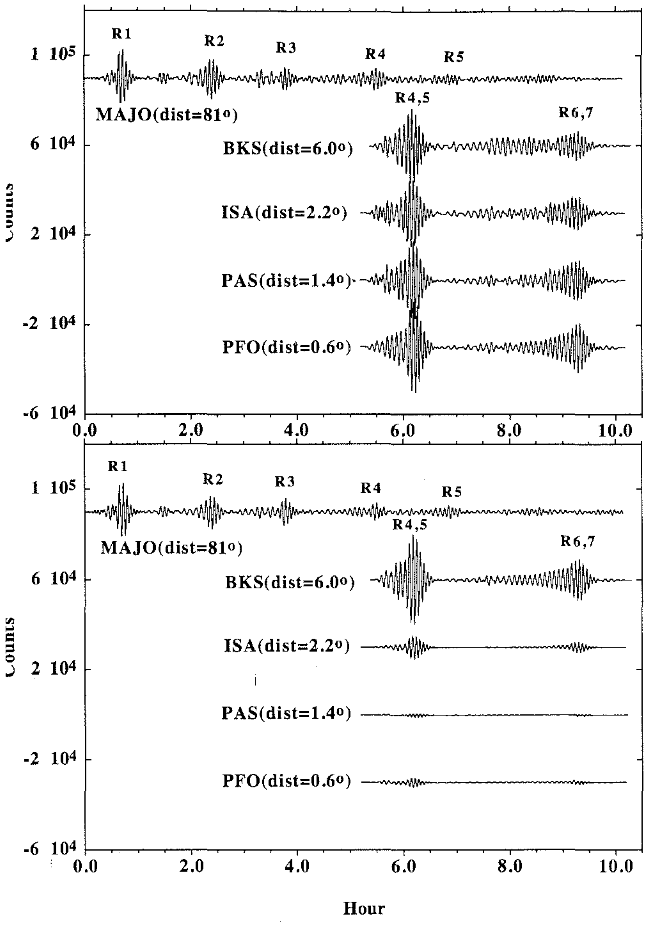

Fig. 2. VLP vertical channel records (upper traces) filtered between 1 and 4 mHz and synthetic (PREM model) seismograms (lower traces) of the Landers earthquake at one teleseismic station MAJO and four nearby stations BKS, ISA, PAS and PFO. At all nearby stations the initial part of the records up to R1 was clipped. R2 and R3 were also clipped by the signals from the Big Bear earthquake ($M_W$=6.4) which occurred about three hours after the Landers earthquake and are not shown here. BKS records are multiplied by a factor of four to make the response similar to TERRAscope stations.

increasing amplitudes at the origin. Several hours after the event the long-period waves may be disturbed enough to make the source region non-nodal.

## Synthetic Test

To test the asphericity hypothesis we compare long-period synthetic seismograms for a realistic Earth model with data. The epicentral and antipodal regions are the major caustics of seismic waves of a sphere. The raypath between the earthquake and seismic stations cannot be defined and conventional raypath approaches break down. We use the variational method (Park *et al.*, 1986, Tsuboi, 1992) which calculates synthetic seismograms from the eigenfunctions and eigenfrequencies of a rotating, elliptic Earth model with a three dimensional structure. The eigenfunctions and eigenfrequencies of non-spherical Earth are obtained by solving generalized eigenvalue problems of the form,

$$(V - \omega^2 T)\boldsymbol{x} = 0 \qquad (1)$$

where $V$ and $T$ are the potential and kinetic energy matrices respectively. $\omega$ is the eigenfrequency of a 3D eigenfunction $\boldsymbol{x}$. The rotational energy matrix $W$ is included in $V$ (Masters *et al.*, 1983). We use equivalent isotropic PREM (Dziewonski and Anderson, 1981) as a reference Earth model. Matrix elements of $V$, $W$ and $T$ are given in Woodhouse (1980) and Shibata *et al.* (1990). We include the crustal correction as velocity perturbations in the crust and boundary undulations based on the ocean function expanded up to the same order as that used for the mantle (appendix of Woodhouse and Dziewonski, 1984). The PREM spherical attenuation structure is included in $V$. Five nearby spheroidal and five toroidal fundamental mode multiplets are used as a basis set to calculate a hybrid eigenfunction and eigenfrequency up to 4 mHz to take into account the effects of self coupling, fundamental mode along-branch coupling and spheroidal-toroidal (S-T) coupling. Synthetic seismograms for a whole mantle model SH8U4L8 (up to degree $l$=8, Dziewonski and Woodward, 1992) are in good agreement with the observed records (Figure 4) and seem to explain the amplitude anomalies over a frequency range of 1.6 to at least 4 mHz (Figure 5a).

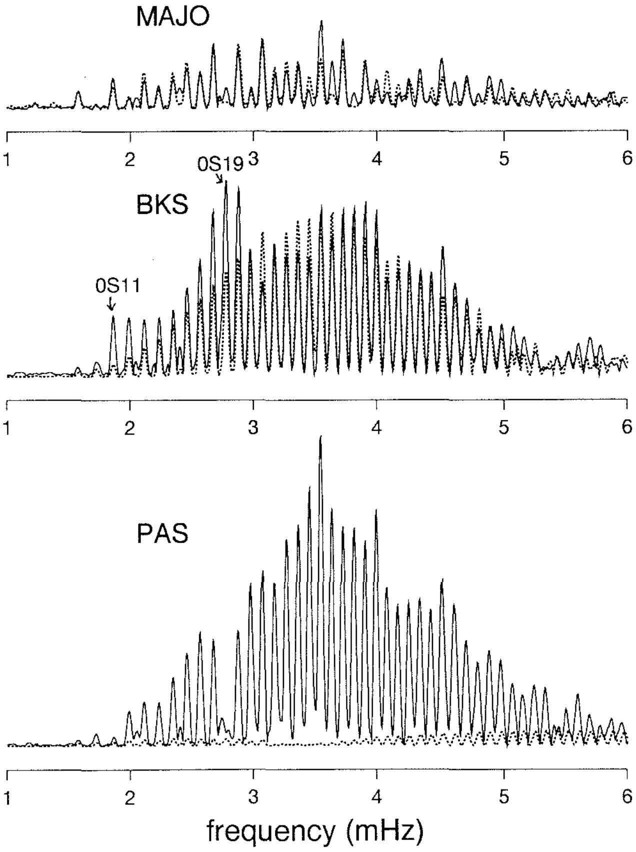

Fig. 3. The Fourier spectra of Hanning-tapered VLP vertical channel records (solid line) and spherical Earth synthetic seismograms (dashed line) at MAJO, BKS and PAS. Records start at 15000 s and end at 65000 s after the origin time. Vertical axes are linear and on the same scale for all the stations. BKS records are multiplied by a factor of four.

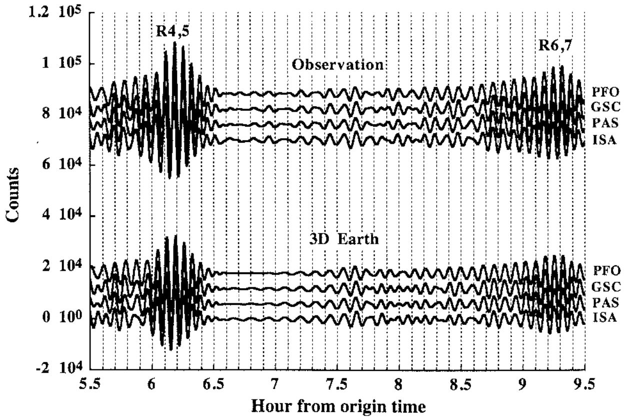

Fig. 4. top) Vertical component seismograms at the TERRAscope stations. bottom) Synthetic seismograms for rotating, elliptic and 3D earth model SH8U4L8 (Dziewonski and Woodward, 1992) at the TERRAscope stations. Both filtered between 1 and 4 mHz.

## Sensitivity to 3D Earth Models

To see the effects of the lateral heterogeneity in the mantle on the nearfield normal mode amplitudes we also calculated non-spherical Earth synthetics for 1) rotation + ellipticity only, 2) M84A (upper mantle $l \leq 8$) (Woodhouse and Dziewonski, 1984) + rotation + ellipticity, 3) MDLSH (whole mantle $l \leq 6$) (Tanimoto, 1990) + rotation + ellipticity, 4) upper mantle part of SH8U4L8 + rotation + ellipticity, 5) SH8U4L8 + one tenth of real rotation rate + ellipticity, 6) self coupling SH8U4L8 + rotation + ellipticity, 7) SH8U4L8 + rotation + ellipticity without crustal correction (Figure 5). All 3D Earth models include S velocity, P velocity and density perturbations scaled according to $d \ln v_p / d \ln v_s = 0.8$ and $d \ln \rho / d \ln v_s = 0.4$.

Rotation and ellipticity alone cannot explain the amplitude anomalies (Figure 5b). The crustal correction has large effect up to about 600 s (Figure 5h). Other than the crustal structure, the upper mantle lateral heterogeneity is mainly responsible for the large amplitude anomalies above 3 mHz (Figure 5e). As the frequency decreases the mode energy penetrates to the lower mantle whose aspherical structure can change the amplitude by a factor of two around ${}_0S_{14}$ (Figure 5e). Although self coupling explains most of the anomalies in the synthetics (Figure 5g), holes in the observed spectra around ${}_0S_{11}$ and ${}_0S_{19}$ (Figure 3 bottom) are probably caused by strong S-T coupling (Figure 5f). We also calculated normal-mode amplitude anomalies for other global seismic models, M84C (upper mantle $l \leq 8$) (Woodhouse and Dziewonski, 1984), SH8WM13 (whole mantle $l \leq 8$) (Dziewonski and Woodward, 1992) and SH12WM13 (whole mantle $l \leq 12$) ( Su *et al.*, 1992). M84C and both SH8WM13 and SH12WM13 predict synthetics similar to M84A and SH8U4L8, respectively. Amplitudes predicted by SH12WM13 are not larger than those by SH8U4L8.

## Discussion

The comparable amplitudes of the initial part of R2,3 (not shown) and R4,5 observed at the TERRAscope stations indicate that long-period surface waves, longer than 250 s, are already disturbed after the wave traveled around the Earth once. The change in the normal-mode amplitude with and without the crustal correction is about as large as that caused

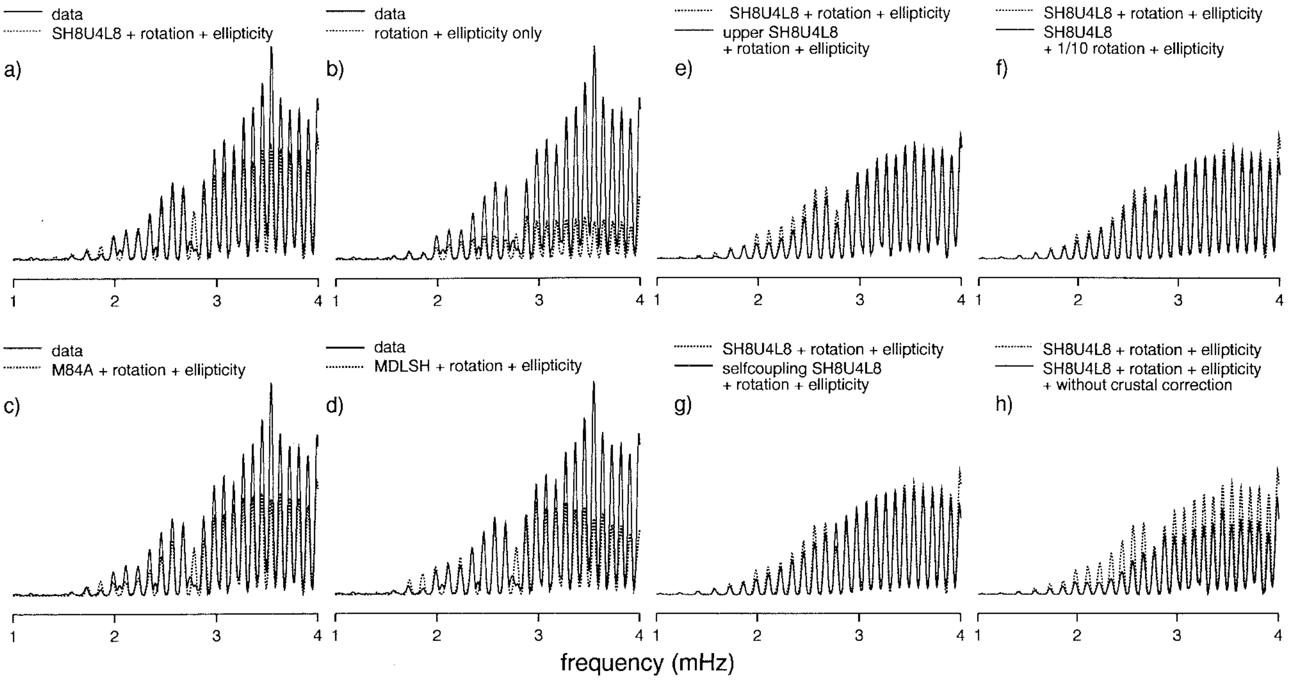

Fig. 5. Synthetic spectra at PAS for various non-spherical Earth models. The Fourier spectra are taken for Hanning-tapered records starting at 15000 s ending at 65000 s after the origin time. a) is the same case as Figure 4. b)-h) are the spectra for the cases 1)-7) described in the text respectively. Vertical axes indicate the linear amplitude on the same scale.

by the lateral heterogeneity in the mantle (Figure 5a, b and h) suggesting that the mantle structures in tomographic models without crustal correction are seriously contaminated by the crustal structure (e.g. M84A and MDLSH). Models with higher order lateral heterogeneity do not necessarily give better fits to the observed amplitude anomalies and phase. Synthetic test shows that observed anomalies are not sensitive to the truncation of spherical harmonics (e.g. SH8U4L8 and SH8WM13 extend to $l$=8, SH12WM13 extends to $l$=12) and parameterizations of Earth models (e.g. in SH8U4L8 the upper and lower mantles are parameterized separately; in SH8WM13 and SH12WM13 no boundary is pre-assumed in the mantle) indicating that short wave length heterogeneity ($8 \leq l \leq 12$) has little effects on this observation. The amplitude deficit in the synthetics compared to the observation around 3-4 mHz (Figure 5a) may be explained by the lateral heterogeneity higher than $l$=13 or by more realistic large scale crustal lateral heterogeneity.

Synthetic calculations (not shown) demonstrate that the amplitude anomalies observed at BKS are explained by strong rotational S-T coupling (Masters *et al.*, 1983).

## Conclusion

Anomalously large long-period Rayleigh waves observed at the TERRAscope stations of the Landers earthquake can be explained by the non-spherical nature of the Earth, such as rotation, ellipticity and large scale lateral heterogeneity. The observed long-period spheroidal mode amplitudes are very sensitive to the large scale structure in the crust and the mantle structure. Below 3 mHz the lower mantle structure and the rotation of the Earth can also change the amplitudes by a factor of two or more. To assess the effect of higher order lateral heterogeneity on the amplitude anomalies near the epicenter more precise knowledge of the large scale crustal structure is required.

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