Supplementary Materials

Determination of Epicenters before Earthquakes Utilizing Far Seismic and GNSS Data: The Novel Common-Mode Ground Vibrations

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The methodology and data availability for the analysis in the ground vibrations during the 2004 Parkfield, 2010 Baja, 2014 Jinggu, 2014 Ludian, 2016 Meinong, 2018 Hualien earthquakes. The amplitude of the ground vibrations at the particular B770 seismic station after the Meinong earthquake is shown in Figure S1. The enhancements of the ground vibrations at the example stations, the spatial distribution of the enhancements, and the determination of the source locations are shown in Figures S2–S4 for the Parkfield earthquake, Figures S5–S7 for the Baja earthquake, Figures S8–S10 for the Jinggu earthquake, Figures S11–S13 for the Ludian earthquake, and Figures S14–S16 for the Hualien earthquake. The amplitudes computed from the magnetic data could be dominated by the ground vibrations before the Meinong earthquakes are shown in Figures S17–18. The amplitudes computed from the magnetic data could be dominated by the ground vibrations S19.

Methodology

The time series data of ground velocity retrieved from broadband seismometers and surface displacements obtained from ground-based GNSS receivers show significant enhancements of amplitude in a particular frequency band around 10–0 days before the six example earthquakes. We quantified the associated enhancements using a comparison method to examine the occurrence of long-term crustal

vibrations before the earthquakes. The retrieved vertical velocity was down-sampled with a sampling rate of 0.1 Hz. Meanwhile, data extrema were removed by considering thresholds given by the standard deviation in order to mitigate the influence of artificial noise and unwanted high-frequency interference.

We constructed the background amplitude in the particular frequency band with the Fourier transform using the vertical velocity within a time span of 60–0 days before the earthquakes as references for each station. The monitoring amplitude in the same frequency band was computed using the vertical velocity within a moving time span of a 5-day window during 25–0 days before the earthquakes. The amplification ratio of the ground velocity was calculated by dividing the monitoring amplitude by the background amplitude. Spatial distributions of amplification ratio changes were obtained by applying the gridding method for the amplification ratios of the entire stations. In contrast, the amplification ratios of surface displacements were computed using time-series data retrieved from ground-based GNSS receivers and were utilized to construct spatial distributions through the same method. Notably, surface displacements were derived from revived GNSS data with a time resolution of 30 seconds. The process of down-sampling was not applied on surface displacement data.

We investigated propagation azimuths of long-term crustal vibrations in a moving time span of a 5day window during 25-0 days before the earthquakes by using the ground velocity and surface displacement in the NS and EW components in the direction of the maximum horizontal amplitude, using the method proposed by Tanimoto et al. [1]. The recorded data were filtered using a band-pass filter between 8×10^{-5} Hz and 2×10^{-4} Hz via the Fourier transform. Note that the frequency band associated with the M7.2 Baja earthquake ranges between 6×10^{-5} Hz and 2×10^{-4} Hz. We summarized the values computed from the NS and EW component data in the associated frequency band projected on the orthogonal axes with clockwise rotation from 0° to 360° by following the method of Tanimoto et al. [1]. Propagation azimuths were determined using the directions of the maximum summarized values. Furthermore, we determined the locations of sources of crustal vibrations by using azimuths obtained from at least three stations with significant enhancements through an intersection method. Notably, potential areas that reveal the locations of sources of long-term crustal vibrations were defined using a sector centered at the propagation azimuth with an expansion angle of 15° on both sides. This suggests a resolution of 30° in the determination of the propagation azimuth. Furthermore, the radius of a sector was determined to be 300 km because enhancements of 10-20 percent were distributed in areas with an epicentral distance of approximately 300 km.

Data Availability:

Seismic and geomagnetic data for Taiwan

Seismic waveform data in Taiwan were provided by the Seismic Array of NCREE in Taiwan (SANTA), which is a multipurpose seismograph network operated by the National Center for Research on Earthquake Engineering (NCREE) since June 2012. SANTA includes thirty-seven seismograph stations uniformly distributed over the entire island of Taiwan. The broadband seismic waveforms recorded by a ground-velocity broadband seismometer (CMG-6TD, Guralp Systems Ltd.) were analyzed for the cases in Taiwan. Geomagnetic data associated with the Meinong earthquake were retrieved from the Institute of Earth Sciences, Academia Sinica, and the Central Weather Bureau, Taipei, Taiwan.

Seismic, GNSS, and geomagnetic data for the United States and Mexico

Seismic waveform data were taken from the Incorporated Research Institutions for Seismology (IRIS). We retrieved these waveform data from the Berkeley Digital Seismograph Network (BK), Caltech Regional Seismic Network (CI), and USArray Transportable Array (TA) of IRIS. The GNSS data of the United States were downloaded from the Scripps Orbit and Permanent Array Center, which processes and archives high-precision GPS data for the study of earthquake hazards, tectonic plate motion, crustal deformation, and meteorology. A total of sixty-four GNSS stations were selected and the CSRS-PPP online computation tool was utilized to calculate the 3D coordinates of the GNSS stations again. Geomagnetic data associated with the Parkfield earthquake were retrieved from the Northern California Earthquake Data Center [2].

Seismic and GNSS data for China

Seismic waveforms and GPS measurements associated with the earthquakes in China were retrieved from the China Earthquake Data Center (http://data.earthquake.cn/) and the Continental Tectonic Environment Monitoring Network of China, respectively. Seismic data were observed using a JCZ1 ultra

broadband digital seismograph with a frequency band of DC–50 Hz. The GPS data were recorded at a sampling frequency of 30 seconds by the Trimble NetR9 GNSS Reference Receiver, which was installed over December 2007 to 2012 and became operational in March 2012. The GIPSY/OASIS 6.0 software of JPL was adopted to process the GNSS data and the CSRS PPP tool was used to obtain daily solutions. Detailed procedures are listed in the previous studies [3, 4]. The QOCA software from JPL was applied to complete joint adjustment for the daily loosely constrained solutions of all stations and thus to obtain their coordinate time series and optimum estimations of velocity in ITRF2014. The a priori global pressure/temperature model and the global-mapping function were adopted, in which the correction for ocean tidal loading was made with the FES2004 model. To improve the solution accuracy, the Ambizap software was applied for resolving phase ambiguity, and various linear combinations of observational parameters were determined using the fixed-point theorems. Thus, the unique and self-consistent daily solutions with the phase ambiguity resolved were derived. Through the seven-parameter transform, the GPS time series were obtained.

Interpretation

The amplifications before the Meinong earthquake lasted for 10 days and became minimal within a few days after the earthquake occurrence (Figure S1). Notably, three M5 earthquakes occurred on February 16–18, 2016 (i.e., 10–12 days after the earthquake), which enhanced the amplitude in the associated frequency band mainly for 7–13 days after the earthquake.

The seismic and GNSS data associated with the other five earthquakes with magnitudes of 6–7 from world data centers for further examining whether the phenomena of the common-mode vibrations have typical characteristics (Figs. S2–S16). Selection of the earthquakes was based on available data and the existence of adequate observational networks. Enhancements in the relevant frequency band can consistently be found in both the seismic and GNSS data for a period of approximately 5–10 days before the earthquake events, except for the largest M7.2 Baja earthquake, which has an enhanced amplitude range in a wide frequency band of 6×10^{-5} to 2×10^{-4} Hz (i.e., a period of 1.5–4.5 hours) and tended to be low around 0–5 days before the earthquake. Significant enhancements can be observed from the seismic or GNSS stations near the epicenters. Amplitudes with 10–20% enhancements are roughly distributed in the areas with epicentral distances of less than 300 km. Intersection areas determined from the stations with amplitude enhancements suggest that the vibration sources are closer to the corresponding epicenters.

The common-mode vibrations can be potential sources of other pre-earthquake anomalous phenomena. Geomagnetic data show amplification enhancements in a particular frequency band (1.5–3.5 hour periods) for 5–15 days before the Meinong and Parkfield earthquakes (Figs. S17–S19). This generally agrees with the observations of amplification enhancements from ground velocity and surface displacements as shown in this study.

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Figure Caption



Figure S1. Amplitudes of the B770 (22.54°N, 120.39°E) seismic station varied with frequency computed from vertical seismic velocity for an interval of 1–26 days after the Meinong earthquake. The amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (**a**). The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancements. Changes of seismic raw data in vertical velocity motion for 1–26 days after the earthquake are shown in (**b**).



Figure S2. Locations of seismometers and ground-based GNSS receivers on a topographic map and the variations of the retrieved data in the vertical component from two example stations for an interval of 0-25 days before the 2004 Parkfield earthquake. Locations of seismometers and GNSS receivers are denoted by squares and triangles, respectively, in (a). The red star shows the epicenter. Seismic and GNSS data retrieved from the PKD (35.95°N, 120.54°W) and TBLP (35.91°N, 120.36°W) stations denoted by red symbols in (a) are shown in (b,c) and (d,e), respectively. Note that the stations are selected based on the short epicentral distance and the continuity of the recorded data. Seismic raw data showing changes in vertical velocity motion for an interval of 0–25 days before the earthquake are shown in (c). Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (b). In contrast, the vertical ground motion data retrieved from GNSS stations via the CSRS-PPP are shown in (d), while the variations of amplitudes of ground motion data with the frequency computed from the same moving temporal window of five days are also indicated by gray curves in (e). The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancements. Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S3. Spatial distribution of amplification ratios computed from seismic and GNSS data for an interval of 0–25 days before the Parkfield earthquake. The upper (a-e) and lower (f-j) panels denote amplification ratios obtained from seismic and GNSS data. Time intervals for (a)-(j) indicate distinct time spans until the occurrence of the earthquake during which the data were used for the analysis process. The red star denotes the epicenter. The red lines indicate portions of circles with a radius of 300 km from the epicenter of the earthquake.



Figure S4. Locations of the vibration sources determined using seismic and GNSS data for an interval of 0–25 days before the Parkfield earthquake. The upper and lower panels show locations obtained from seismic and GNSS data, respectively, in distinct time spans following (**a**–**j**). Black arrows lie on stations with significant amplitude enhancements, as shown in Figure S3, and point toward potential sources of crustal vibration excitation before the earthquake. The red star denotes the epicenter. Green areas on the map indicate the locations of potential crustal vibration sources, as determined by at least three stations showing significant enhancements.



Figure S5. Locations of seismometers and ground-based GNSS receivers on a topographic map and the variations of the retrieved data in the vertical component from two example stations for an interval of 0-25 days before the 2010 Baja earthquake. Locations of seismometers and GNSS receivers are denoted by squares and triangles, respectively, in (a). The red star shows the epicenter. Seismic and GNSS data retrieved from the DVT (32.66°N, 116.10°W) and PPBF (33.83°N, 117.18°W) stations denoted by red symbols in (a) are shown in (b,c) and (d,e), respectively. Note that the stations are selected based on the short epicentral distance and the continuity of the recorded data. Seismic raw data showing changes in vertical velocity motion for an interval of 0-25 days before the earthquake are shown in (c). Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (b). In contrast, the vertical ground motion data retrieved from GNSS stations via the CSRS-PPP are shown in (d), while the variations of amplitudes of ground motion data with the frequency computed from the same moving temporal window of five days are also indicated by gray curves in (e). The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancements. Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S6. Spatial distribution of amplification ratios computed from seismic and GNSS data for an interval of 0–25 days before the Baja earthquake. The upper (**a**–**e**) and lower (**f**–**j**) panels denote amplification ratios obtained from seismic and GNSS data. Time intervals for (a)–(j) indicate distinct time spans until the occurrence of the earthquake during which the data were used for the analysis process. The red star denotes the epicenter. The red lines indicate portions of circles with a radius of 300 km from the epicenter of the earthquake. Note that the frequency band associated with the Baja earthquake ranges between 6×10^{-5} Hz and 2×10^{-4} Hz.



Figure S7. Locations of the vibration sources determined using seismic and GNSS data for an interval of 0–25 days before the Baja earthquake. The upper and lower panels show locations obtained from seismic and GNSS data, respectively, in distinct time spans following (**a**–**j**). Black arrows lie on stations with significant amplitude enhancements, as shown in Figure S6, and point toward potential sources of crustal vibration excitation before the earthquake. The red star denotes the epicenter. Green areas on the map indicate the locations of potential crustal vibration sources, as determined by at least three stations showing significant enhancements. Note that the frequency band associated with the Baja earthquake ranges between 6×10^{-5} Hz and 2×10^{-4} Hz.



Figure S8. Locations of seismometers and ground-based GNSS receivers on a topographic map and the variations of the retrieved data in the vertical component from two example stations for an interval of 0-25 days before the 2014 Jinggu earthquake. Locations of seismometers and GNSS receivers are denoted by squares and triangles, respectively, in (a). The red star shows the epicenter. Seismic and GNSS data retrieved from the YN.JIG (23.5°N, 100.7°E) and YNLC (23.9°N, 100.1°E) stations denoted by red symbols in (a) are shown in (\mathbf{b}, \mathbf{c}) and (\mathbf{d}, \mathbf{e}) , respectively. Note that the stations are selected based on the short epicentral distance and the continuity of the recorded data. Seismic raw data showing changes in vertical velocity motion for an interval of 0-25 days before the earthquake are shown in (c). Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (b). In contrast, the vertical ground motion data retrieved from GNSS stations via the CSRS-PPP are shown in (d), while the variations of amplitudes of ground motion data with the frequency computed from the same moving temporal window of five days are also indicated by gray curves in (e). The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancements. Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S9. Spatial distribution of amplification ratios computed from seismic and GNSS data for an interval of 0–25 days before the Jinggu earthquake. The upper (a-e) and lower (f-j) panels denote amplification ratios obtained from seismic and GNSS data. Time intervals for (a)-(j) indicate distinct time

spans until the occurrence of the earthquake during which the data were used for the analysis process. The red star denotes the epicenter. The red lines indicate circles with a radius of 300 km from the epicenter of the earthquake.



Figure S10. Locations of the vibration sources determined using seismic and GNSS data for an interval of 0–25 days before the Jinggu earthquake. The upper and lower panels show locations obtained from seismic and GNSS data, respectively, in distinct time spans following (**a**–**j**). Black arrows lie on stations with significant amplitude enhancements, as shown in Figure S9, and point toward potential sources of crustal vibration excitation before the earthquake. The red star denotes the epicenter. Green areas on the map indicate the locations of potential crustal vibration sources, as determined by at least three stations showing significant enhancements.



Figure S11. Locations of seismometers and ground-based GNSS receivers on a topographic map and the variations of the retrieved data in the vertical component from two example stations for an interval of 0–25 days before the 2014 Ludian earthquake. Locations of seismometers and GNSS receivers are denoted by squares and triangles, respectively, in (**a**). The red star shows the epicenter. Seismic and GNSS data retrieved from the YN.QIJ (26.9°N, 102.9°E) and SCNN (27.1°N, 102.7°E) stations denoted by red symbols in (**a**) are shown in (**b**,**c**) and (**d**,**e**), respectively. Note that the stations are selected based on the short epicentral distance and the continuity of the recorded data. Seismic raw data showing changes in vertical velocity motion for an interval of 0–25 days before the earthquake are shown in (c). Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in

(b). In contrast, the vertical ground motion data retrieved from GNSS stations via the CSRS-PPP are shown in (d), while the variations of amplitudes of ground motion data with the frequency computed from the same moving temporal window of five days are also indicated by gray curves in (e). The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancements. Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S12. Spatial distribution of amplification ratios computed from seismic and GNSS data for an interval of 0–25 days before the Ludain earthquake. The upper (a,e) and lower (f,j) panels denote amplification ratios obtained from seismic and GNSS data. Time intervals for (a)-(j) indicate distinct time spans until the occurrence of the earthquake during which the data were used for the analysis process. The red star denotes the epicenter. The red lines indicate circles with a radius of 300 km from the epicenter of the earthquake.



Figure S13. Locations of the vibration sources determined using seismic and GNSS data for an interval of 0–25 days before the Ludain earthquake. The upper and lower panels show locations obtained from seismic and GNSS data, respectively, in distinct time spans following (**a**,**j**). Black arrows lie on stations with significant amplitude enhancements, as shown in Figure S12, and point toward potential sources of crustal vibration excitation before the earthquake. The red star denotes the epicenter. Green areas on the map indicate the locations of potential crustal vibration sources, as determined by at least three stations showing significant enhancements.



Figure S14. Locations of seismometers and ground-based GNSS receivers on a topographic map and the variations of the retrieved data in the vertical component from two example stations for an interval of 0-25 days before the 2018 Hualien earthquake. Locations of seismometers and GNSS receivers are denoted by squares and triangles, respectively, in (a). The red star shows the epicenter. Seismic and GNSS data retrieved from the B210 (24.00°N, 121.55°E) and HUAL (23.97°N, 121.61°E) stations denoted by red symbols in (a) are shown in (b,c) and (d,e), respectively. Note that the stations are selected based on the short epicentral distance and the continuity of the recorded data. Seismic raw data showing changes in vertical velocity motion for an interval of 0-25 days before the earthquake are shown in (c). Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (b). In contrast, the vertical ground motion data retrieved from GNSS stations via the CSRS-PPP are shown in (d), while the variations of amplitudes of ground motion data with the frequency computed from the same moving temporal window of five days are also indicated by gray curves in (e). The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancements. Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S15. Spatial distribution of amplification ratios computed from seismic and GNSS data for an interval of 0–25 days before the Hualien earthquake. The upper (**a**,**e**) and lower (**f**,**j**) panels denote amplification ratios obtained from seismic and GNSS data. Time intervals for (a)–(j) indicate distinct time

spans until the occurrence of the earthquake during which the data were used for the analysis process. The red star denotes the epicenter. The red lines indicate portions of circles with a radius of 300 km from the epicenter of the earthquake.



Figure S16. Locations of the vibration sources determined using seismic and GNSS data for an interval of 0–25 days before the Hualien earthquake. The upper and lower panels show locations obtained from seismic and GNSS data, respectively, in distinct time spans following (**a**–**j**). Black arrows lie on stations with significant amplitude enhancements, as shown in Figure S15, and point toward potential sources of crustal vibration excitation before the earthquake. The red star denotes the epicenter. Green areas on the map indicate the locations of potential crustal vibration sources, as determined by at least three stations showing significant enhancements.



Figure S17. Amplitudes varied with frequency computed from the vertical component of the geomagnetic data for an interval of 0–25 days before the Meinong earthquake. Geomagnetic data are retrieved from the TCD station (24.33° N, 120.62° E) with epicentral distance of approximately 60 km. Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (**a**). Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancement. The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Changes of the geomagnetic total intensity data in the vertical component for 0–25 days before the earthquake are shown in (**b**). Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S18. Amplitudes varied with frequency computed from the geomagnetic total intensity data for an interval of 0–25 days before the Meinong earthquake. Geomagnetic data are retrieved from the TW station (23.25° N, 120.52° E) with epicentral distance of approximately 35 km. Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (a). Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancement. The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Changes of the geomagnetic total intensity data for 0–25 days before the earthquake are shown in (b). Vertical dashed lines indicate the frequency at 8×10^{-5} Hz (a period of 3.5 hours) and 2×10^{-4} Hz (a period of 1.5 hours).



Figure S19. Amplitudes varied with frequency computed from the geomagnetic data for an interval of 0–25 days before the Parkfield earthquake. Geomagnetic data are retrieved from the PKD station (35.95° N, 120.54° W) with epicentral distance of approximately 20 km. Amplitude variations with the frequency computed from a moving temporal window of five days are shown by gray curves in (**a**). Black curves show the smoothing results for the gray curves through a 5-point moving average along the frequencies to expose amplitude enhancement. The date marked at the end of each amplitude curve indicates the center time of the moving temporal window. Changes of the geomagnetic data for 0–25 days before the earthquake are shown in (**b**). Vertical dashed lines indicate the frequency at 8 × 10⁻⁵ Hz (a period of 3.5 hours) and 2 × 10⁻⁴Hz (a period of 1.5 hours).