

Estimation of Source Parameters of DPRK Nuclear Tests by Exploiting Regional Seismic Waves

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14. ABSTRACT In this report, we focus on (1) developing an iterative method to jointly invert for Lg source spectra, Q tomography and site response models using two-stations based tomographic Q models and relative site responses as <i>a priori</i> information; (2) measure Lg amplitudes using the 3 rd peak and RMS methods on WWSSN-SP simulated seismograms, (3) estimate hypothetical Lg amplitudes at 10km to the source by correcting geometric spreading, path attenuation and site responses, (4) calibrate constant C value for mb(Lg) estimation, and (5) estimate mb(Lg) for used earthquakes and explosions.					
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EXECUTIVE SUMMARY

We aim at improving the physical and empirical understanding of the source and regional propagation characteristics of the six DPRK nuclear explosions and earthquakes occurred near the Punggye-ri test site by exploiting the large volume of regional waveform data recorded in China. First, we propose to calibrate $m_b(\text{Lg})$ magnitude estimator for a broad area in Asia containing the Punggye-ri test site and estimate $m_b(\text{Lg})$ values for both the DPRK explosions and the crustal earthquakes in this area. Second, we will calibrate and estimate various parameters describing explosion and earthquake sources, and to establish scaling relationships for these source parameters. Accurate corrections for path attenuation and station site responses play important roles in the calibration of $m_b(\text{Lg})$ and source parameters. We develop an iterative method to jointly invert for Lg source spectra, high-resolution Q tomography and site responses, during which the two-station based Q tomographic models and relative site responses models that we have created are used as *a priori* knowledge to start the iteration. The refined Q and site responses models will lead to a significant improvement for the estimation of source amplitudes and thus $m_b(\text{Lg})$, seismic moment, explosion yield and corner frequency. Using the Lg source spectra of DPRK explosions and regional earthquakes, we will conduct source spectral modeling for the DPRK explosions using various explosion source models and for the regional earthquake using Brune's model, respectively. The scaling of the seismic moment (and yield) of the DPRK explosions with the depth of burial or depth-dependent media parameters will be established for various explosion source models. With our quantitative resolution and uncertainty assessment for the tomographic Lg Q models, the uncertainties of source spectral amplitudes and $m_b(\text{Lg})$ magnitudes can be formally addressed. Direct benefits of the study will provide enriching information for the capability of seismic discrimination using $m_b(\text{Lg})$ and source spectra and the refinement of yield estimation for the Punggye-ri test site.

The main achievements during the first-year technical progress period include:

1. *Joint Inversion of Lg Source Spectra, Q and Site Responses*: This is an iterative method to gradually update Lg source spectra, Q and site responses. Each iteration consists of the following steps: (1) The Lg source spectrum for an event is first estimated at all individual stations with corrections for path Q and site responses, and the average of all individual station estimates is regarded as the "actual" source spectrum for that event. The error in the source spectrum is assumed mainly owing to the coupled errors in path Q and site responses. (2) The errors in path Q and site responses are de-coupled by examining whose impact on source spectra is dominant. The term with dominant error will be updated while the other term is assumed acceptable. (3) The updated path Q are used to improve Lg Q tomographic maps. Step (1) will be repeated using the updated path Q and site responses to improve Lg source spectra. This iteration procedure starts with using the two-station Q tomographic maps and relative site responses as *a priori* information and ends when Lg source spectra, path Q or site responses can no longer be improved. The large volume of seismic events and stations used in this study facilitates the implementation of our methodology, and in turn, the Lg source spectra of these seismic events, site responses of these stations and all event-station path Q are obtained for the calibration of $m_b(\text{Lg})$ and source model parameters.
2. *Calibration of Constant C for $m_b(\text{Lg})$* : The broad-band seismogram is simulated to WWSSN-SP seismogram. On the vertical-component of WWSSN-SP simulated seismogram, the Lg

amplitude is measured as the 3rd peak and RMS amplitudes. A hypothetical Lg amplitude at 10km from the source, $A(10\text{km})$, is then estimated after geometric spreading, path attenuation and site response corrections. Linear regression between $A(10\text{km})$ in the logarithm domain and $m_b(P)$ is performed to obtain the constant C value. When Lg amplitudes are measured by the 3rd peak method, we calibrate $C = 283\mu\text{m}$ when only using earthquake data, $C = 45\mu\text{m}$ only when using DPRK explosion data, and $C = 268\mu\text{m}$ when using combined earthquake and explosion data, respectively. When Lg amplitudes are measured by the RMS method, the constant C is calibrated to $212\mu\text{m}$, $33\mu\text{m}$ and $199\mu\text{m}$ for the three cases, respectively.

3. *Estimation of $m_b(\text{Lg})$ for Earthquakes and Explosions:* The constant C values are used to estimate $m_b(\text{Lg})$ for earthquakes and explosions. For earthquakes, the $m_b(\text{Lg})$ estimated using $C = 283\mu\text{m}$ and $C = 268\mu\text{m}$ are of only 0.025 magnitude unit difference. For explosions, the $m_b(\text{Lg})$ estimated using $C = 45\mu\text{m}$ are quite different from using $C = 268\mu\text{m}$ or $283\mu\text{m}$. The magnitudes estimated using the 3rd peak method and RMS method are consistent without systematical bias.

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1 INTRODUCTION

1.1 Motivation

The Democratic People's Republic of Korea (DPRK) successively conducted six underground nuclear explosion tests from 2006 to 2017 at the Punggye-ri test site. These DPRK nuclear tests attracted much interest in the nuclear explosion monitoring (NEM) community because the scaling laws empirically established in Nevada test site and former USSR test sites turned to be marginally used or failed applied to DPRK tests for discrimination (e.g., m_b - M_s) and yield estimation (e.g., m_b -Y and M_s -Y). The Punggye-ri is an uncalibrated test site due to the lack of ground truth data, which prevents seismologists from establishing region-specific scaling laws. A more profound problem is that there is a lack of physical understanding on why those discriminants, such as the spectral ratios and differences among different types of magnitudes, empirically work for the otherwise test sites although some source physics mechanisms have been speculated based on synthetic simulations. Nevertheless, it is not practical to extensively verify these mechanisms until the effects of propagation paths and receiver sites can be properly removed from observed regional wave spectra to obtain the spectral characteristics of source excitation

The regional seismic waves are attractive to conduct such source studies. The regional studies rejuvenate the regional magnitudes, such as m_b (Lg) and m_b (Pn), as toolsets in discrimination. The m_b (Lg), originally defined in Nuttli [1973], has been proven a more stable and accurate measure for seismic event size than m_b (Pn) as Lg wave is typically the most prominent and stable short-period phase at regional distances. Moreover, Lg consists of a superposition of many higher-model surface waves, its radiation is more isotropic than that of P and S waves. This feature adds to its usefulness as a magnitude estimator for small events because reliable m_b (Lg) can be made from fewer stations than m_b (or m_b (Pn)) that should require full azimuthal coverage to suppress radiation pattern effects. Because m_b (Lg) explicitly makes use of the attenuation model to correct event-station path effect, precise m_b (Lg) determinations (for discrimination and yield estimation) critically depend on reliable knowledge of the regional attenuation structure. In the early era of m_b (Lg) determination, the rough regional averaged attenuation coefficient γ , which is proportional to $1/Q$, or quality factor Q based on Lg coda or Lg wave was usually applied to account for path correction [e.g., Nuttli, 1980; 1986ab; 1988; Patton 1988; Hansen *et al.*, 1990; Ringdal *et al.*, 1992; Patton and Walter, 1993; Priestley and Patton, 1997; Jih *et al.*, 1995; Patton, 2001; Zhao *et al.*, 2008]. Given the considerable lateral varying of Lg γ or Q over a continent, individual path Q values were estimated and used in later studies [e.g., Patton and Schlittenhardt, 2005; Chun *et al.*, 2007; 2009]. With the creations of 2D tomographic Lg Q models in the recent decade, the event-station path Q values predicted from the tomographic Q map have been used to improve m_b (Lg) estimation. For example, Zhao *et al.* [2012] calculated the m_b (Lg) of DPRK2009 nuclear explosion based on a tomographic Lg Q model in and around Northeast China generated in Zhao *et al.* [2010], in which the tomographic Q parameters and the source spectra were simultaneously inverted.

The transportability of m_b (Lg) not only depends on the calibration of Lg Q for the propagation paths as well as the correction of site responses but also on the regional invariance of the source calibration constant C (Equation 2). The m_b (Lg) magnitude scale defined by Nuttli is tied to the teleseismic m_b (P) using a calibration constant C , which was determined empirically equal to $110\mu\text{m}$ by Nuttli [1986a] in eastern North American so that an m_b (P) = 5.0 earthquake in eastern

North American has $m_b(\text{Lg}) = 5.0$. This constant C value has been directly used for NTS [Nuttli, 1986a, Patton, 1988], Semipalatinsk test site in Kazakhstan [Nuttli, 1986b], Novaya Zemlya test site in the Arctic region [Nuttli, 1988], and Punggye-ri test site as well [Zhao *et al.*, 2008; 2012]. For Iranian Plateau, Nuttli [1980] determined a constant $C = 270\mu\text{m}$ for Lg wave using a region-averaged attenuation coefficient $\gamma = 0.0045\text{km}^{-1}$, which is similar to the γ for California but much greater than that for eastern North America. To determine C , Nuttli originally measured the 3rd Lg amplitude peak on the vertical component of the WWSSN-SP recorded seismogram. If Lg amplitudes were measured as RMS amplitudes, Patton [1988] reported that the $m_b(\text{Lg})$ computed from the 3rd peaks were 0.22 magnitude unit larger than that based on RMS amplitudes when $C = 110\mu\text{m}$ was used. In order to compensate for this difference in magnitude, Patton and Schlittenhardt [2005] re-calibrated C to $90\mu\text{m}$ when Lg amplitudes were measured as RMS amplitudes.

The main problems involved in $m_b(\text{Lg})$ estimation for both earthquakes and explosions can be summarized as follows: (1) Inaccurate path attenuation correction. A region-average γ or Q could be the “best-effort” estimate for the crustal attenuation structure of the studied area in the earlier era. Such an average is highly unreliable and variable, particularly for an area with significant lateral attenuation variation. When the 2D Lg Q tomographic map for a study region becomes available, the correction for path attenuation is highly improved. The Lg Q tomographic methods can be divided into two groups based on the Lg spectral data used in the tomographic inversion. First, the Lg Q tomography can be inverted directly from Lg spectral amplitudes observed at individual stations, in which the source spectra and site responses are required to be simultaneously solved if their parameters are unknown [e.g., Pasyanos *et al.*, 2009; Pasyanos, 2013; Phillips *et al.*, 2000; 2005; Phillips and Stead, 2008; Zhao *et al.*, 2010; 2013; Zhao and Xie, 2016; Zhou *et al.*, 2011]. Such Q tomographic approach is usually called coupled or single-station tomography and suffers from a non-uniqueness of the Q model as a result of the inherent trade-off among the Q , source, and site parameters [Xie, 1998; Menke *et al.*, 2006]. Second, the Q data used for tomographic inversion can be measured using the standard two-station (TS) method [Xie and Mitchell, 1990] or the reverse two-station (RTS) method [Chun *et al.*, 1987], from which the source and/or site are eliminated from Lg spectral ratios [e.g., Xie 2002; Xie *et al.*, 2004; 2006; Zor *et al.*, 2007; Bao *et al.*, 2011; Gallegos *et al.*, 2014; 2017; Ranasinghe *et al.*, 2015; Chen and Xie, 2017]. Therefore, two-station based methods generate more accurate Q tomographic models than the single-station method. (2) A power law relationship, $Q(f) = Q_0 f^\eta$, is usually assumed for the frequency dependence of Lg Q , during which Q_0 and η are simultaneously inverted by least-squares regression for $Q(f)$ within a frequency range. The regression is performed in the logarithm domain as $\log[Q(f)] = \log(Q_0) + \eta \log(f)$. The estimate of frequency dependence, η , is generally unstable and poorly constrained. The uncertainty in η will consequently result in the uncertainty in Q_0 because a small change of slope η leads to a large change of intercept $\log(Q_0)$. More fundamental questions, such as what causes the power law frequency dependence for Lg Q , and whether the power law model follows a single frequency dependence η for the entire frequency range in which Lg wave dominantly appears, have never been systematically addressed. (3) The correction for station site responses was not explicitly involved in $m_b(\text{Lg})$ calibration in previous studies. The residual between the $m_b(\text{Lg})$ estimated at a given station and a reference $m_b(\text{Lg})$ value was usually used as site correction for the magnitude estimated at that station. The reference value was either the network average $m_b(\text{Lg})$ or the result at a stable station [e.g., Patton and Schlittenhardt, 2005]. In practice, the correction for site responses has the same importance as that

for path attenuation because at short epicentral distances the impact of site effect on seismic amplitudes very likely overwhelms the impact of attenuation.

The purpose of this study will target solving the issues described above. In this 1st year annual report, we focus on developing the iterative method to jointly invert for Lg source spectra, Q tomography, and site responses, calibrating constant C for Asia, and estimating $m_b(\text{Lg})$ for regional crustal earthquakes and DPNK explosions.

1.2 Previous Studies

The importance of generating laterally varying Lg Q maps across Asia results from the complex structure and evolution history of the crust in Asia. Unlike the continent of North America with uniform and stable cratonic nuclei, the tectonic configuration of Asia is comprised of several major terranes, including the Tarim-Sino-Korean craton, the Kazakhstan-Kyrgyzstan block, the Siberian craton, the Yangtze craton, the Cathaysia block, and the Tibetan plateau, as well as amalgamated microcontinents and island arcs, surrounded by Phanerozoic orogenic belts [e.g., Chen *et al.*, 2007; Zhai *et al.*, 2007; Pirajno, 2013]. Collectively, these tectonic elements and events represent a complex geologic history spanning more than 3 billion years. Values of the Lg Q may vary by several orders laterally because they are sensitive to the current temperature, fluid content, unconsolidated sediments, or partial melt of crustal rocks.

Using a large set of regional waveform data collected within and adjacent to China, we have measured inter-station (and inter-event) path Q values using various two-station based methods and tomographically mapped Lg Q at multiple frequency ranges for Asia using a novel SVD-based tomographic method. The results and the relative technical issues have been written in a manuscript titled “[Lateral variations of crustal Lg wave attenuation in Asia from two-station tomography](#)” that will be submitted to JGR soon. We attach this manuscript along with this annual report and cite it as Chen *et al.*, [2020] in this report. We briefly describe the main contents of the paper below. The Q and site responses models obtained from that study will be applied to our joint inversion of Lg source spectra, refined Lg Q tomography, and site responses as initial models.

1. We precisely inverted the relative site responses (SRs) of all individual stations from many SR ratios measured at the large number of stations in Asia. The resulting SRs were then used to correct non-unity SR ratios for the majority of stations involved in the standard two-station (TS) method. The site-corrected TS Q measurements thus possess the similar precision as those measured by the reverse two-station (RTS) and reverse two-event (RTE) methods, and significantly enhance the path coverage for Q tomography when they were combined with RTS and RTE Q measurements.
2. Chen and Xie [2017] verified that the error in the 1.0Hz Lg Q data measured in southeastern China could be modeled as a Gaussian random variable. This study justified that the Gaussian distribution of the error in Q measurements is a universal phenomenon for the Q measured at various frequencies and regions, and thereby the Q tomography can be solved as a least-squared problem. The combined Q data that are measured by the RTS, RTE, and site-corrected TS methods are input to our new SVD-based tomographic program [Chen and Xie, 2017] to invert for Lg Q tomographic models together with the model resolution and covariance matrices ([Figure 1](#)).
3. Guided by the quantified model resolution and error, we explored the relationship between various crustal structures of China and laterally varying Lg Q_0 (Q at 1.0Hz) map ([Figure 1](#)). In northeast China, Lg Q_0 are characterized by contrasting high Q_0 (~500-600) values in the

Greater Khingan Range and low Q_0 (~ 300) values in the Songliao Basin. The Lg Q_0 in NCC correspond to the stable western block with high Q_0 (~ 700) values and the active eastern block with dominantly low Q_0 (~ 220) values. The Yangtze craton also has a lower Q_0 ($\sim 250 - 300$) than a typical craton as a result of more recent tectono-thermal activities. The Cathaysia Block in the SCB exhibits a contrasting Q_0 pattern, with high Q_0 (≥ 800) in the Wuyishan terrane in the northeast and relatively low Q_0 ($\sim 250-300$) in the Nanling-Yunkai terrane in the southwest, supporting the distinct evolutionary history of the two terranes. The entire Tibetan plateau manifests persistently low Q_0 (< 180) extending to the Kunlun-Qaidam-Qilian terranes. These persistent low Q_0 values are very likely attributed to a hot Tibetan crust heated by the upwelling hot and buoyant asthenosphere during the Cenozoic deformation of the plateau caused by the India-Eurasia collision. The low Lg Q_0 values (~ 250) of the Tianshan and Eastern Kunlun Mountains are also related to the India-Eurasia collision. The basins in China can be generally classified as flexural basins and rift basins [Watson *et al.*, 1987]. It is interesting to note that flexural basins in response to compressional tectonics, such as the Tarim, Turpan, and Qaidam, have high Q_0 (≥ 700) basements, but these Q_0 values are often reduced by thick sedimentary layers. On the other hand, rift basins caused by extensional thinning of the lithosphere, such as the Songliao and Bohai basins, usually have low crustal Q_0 values (~ 300). Overall, our Lg Q_0 map exhibits a correlation with the last major tectonic-thermal events that modified the crustal blocks.

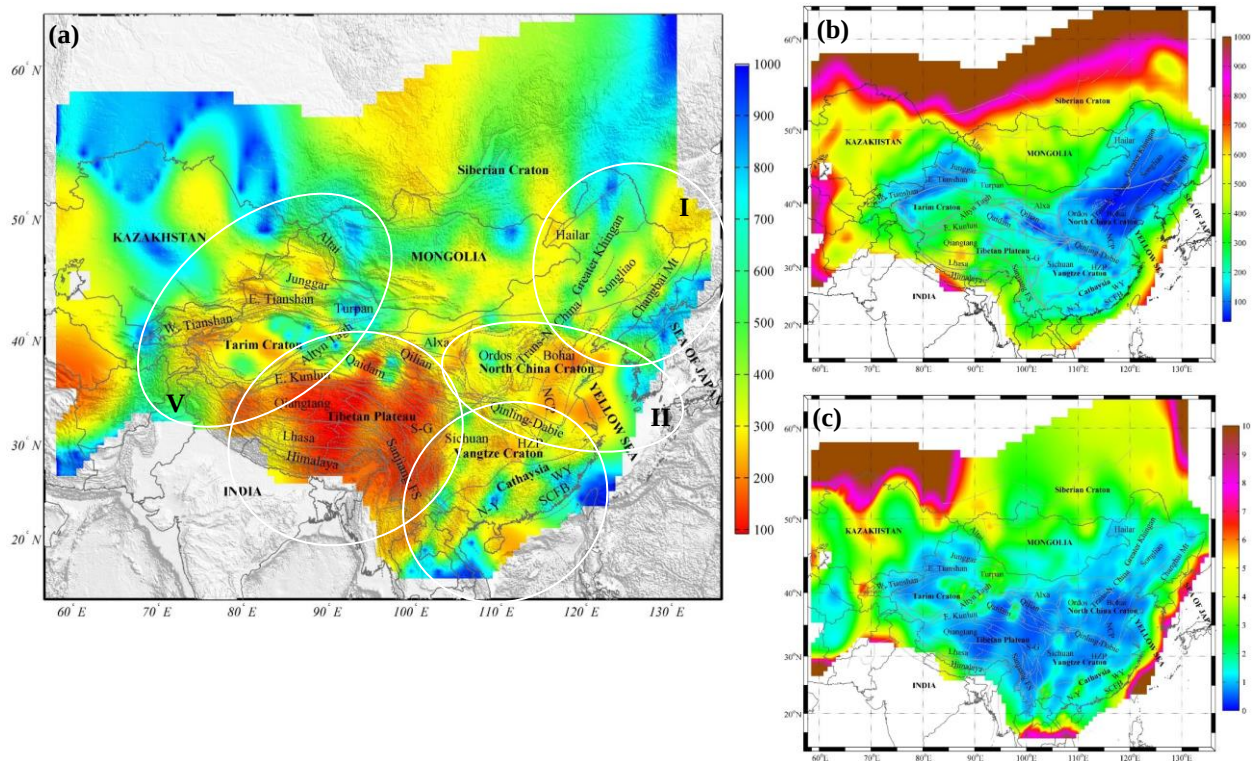


Figure 1. (a) Lg Q tomographic map at a central frequency of 1.0Hz. Areas of high attenuation (low Q) are shown in red and areas of low attenuation (high Q) are shown in blue. I. Northeast China; II. North China Craton; III. South China Block; IV. Tibetan Plateau; V. Tarim, Junggar, Turpan and Tianshan. (b) The resolution of the model represented by Backus-Gilbert spread function in kilometers calculated from the model resolution matrix. (c) The relative uncertainty of the model represented by $\delta Q/Q$ in percentage, where δQ is one standard deviation of Q calculated from the diagonal elements of the model covariance matrix.

4. To understand the frequency dependence of Lg Q , we simulated Lg wave as many high-mode high-frequency surface waves and inspect their behaviors to various typical 1D velocity profiles. The simulated dispersion curves of all modes show that they can be separated into two segments representing Lg phase and Sn phase, respectively. With the increase of frequency, more modes are trapped in the crust as Lg waves. The depth distribution of Lg wave energy, which is calculated as squares of the eigenfunctions of all individual crustal-trapped modes, grossly tends to concentrate more at shallow depths with increasing frequency. This means that the frequency dependence of Lg Q is not a result of the depth-varying Lg wave sampling pattern in the crust but is mainly caused by the inherent frequency dependence of layered Q_s .

2 SEISMIC DATA AND PROCESSING

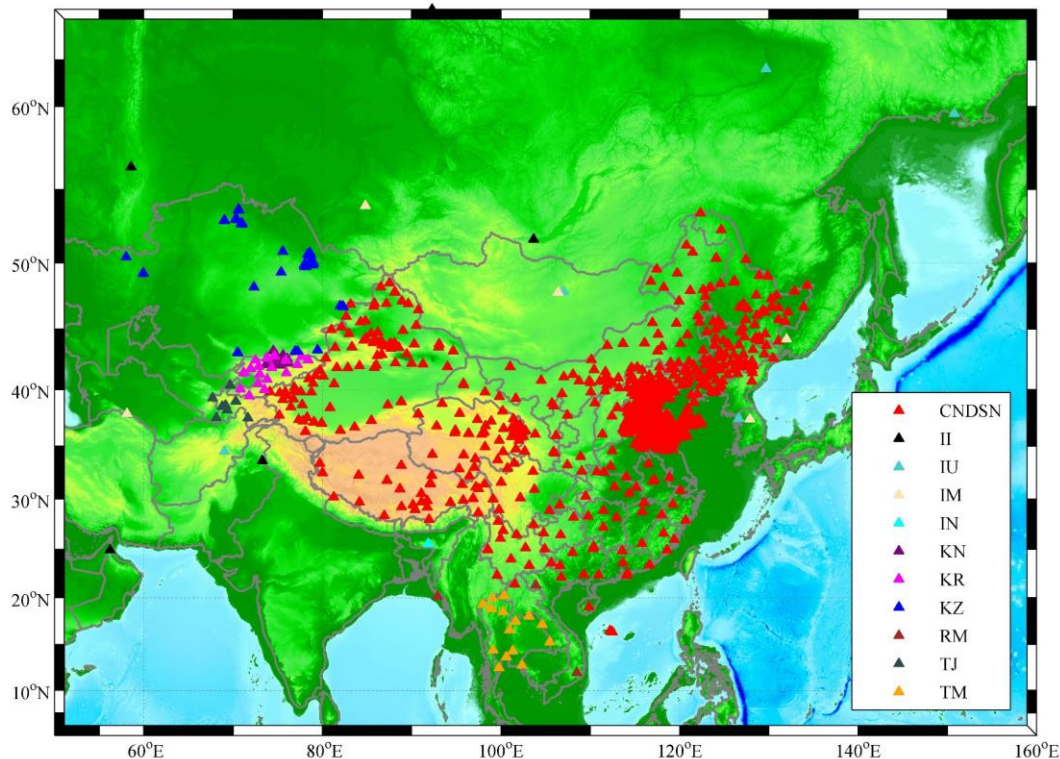


Figure 2. Distribution of seismic stations used in this study. The stations are shown as triangles, with various colors representing individual networks.

This study makes use of ~890 permanent broadband seismic stations which are comprised of the Chinese National Digital Seismic Network (CNDSN) in China and open-accessed IRIS stations deployed in Siberia, Mongolia, Kazakhstan, Kyrgyzstan, Tajikistan, Afghanistan, India, Thailand, and the Korean peninsula from various networks (e.g., II, IU, IM, IN, KN, KR, KZ, RM, TJ and TM) (Figure 2). The CNDSN consists of a backbone network of 144 stations and 31 regional networks in every province that add up to more than 1000 stations. We select the 144 backbone stations, most of which are densely and evenly distributed in the eastern part of China. We also select regional networks in western China and northern China: the three regional networks in western China are Xinjiang, Qinghai and Tibet and the eight regional networks in northern China are Helongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shandong and Beijing. These regional networks enhance coverage for western, northern and northeastern parts of China. The Chinese

stations are equipped with various broad-band and short-period instruments. The broad-band instruments include the Chinese BBVS-120, BBVS-60, CTS-1 and JCZ-1 serial systems, the KS-2000 series (Geotech Instruments, LLC), the CMG series (Güralp Systems Limited), and the standard GSN STS-1 and STS-2 systems, with flat responses to ground velocity from at least 0.1Hz to 30.0Hz (Figure 3a). Some regional stations are equipped with short-period instruments, such as the Chinese FSS and JDF serial systems and CMG-40T. These short-period seismometers have flat responses to ground velocity from ~1.0Hz to ~30.0Hz.

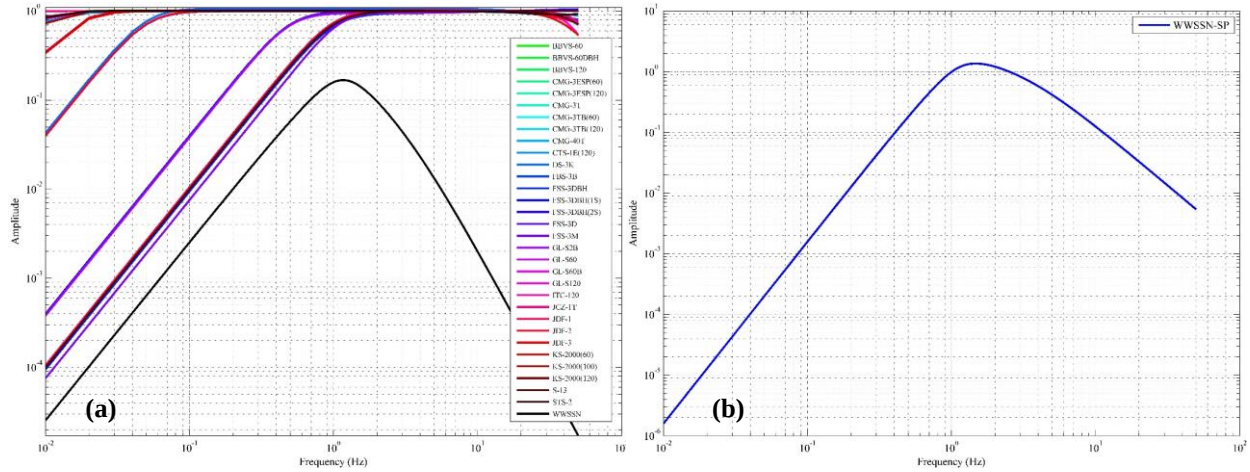


Figure 3. (a) Velocity response of the instruments equipped in the stations used for this study. The velocity response of WWSSN-SP is also plotted. (b) Displacement response of WWSSN-SP.

We have chosen 232 regional earthquakes with focal depths less than 40km and $M \geq 3.5$ occurring from 2009 – 2017 across Asia to ensure a relatively homogenous event distribution (Figure 4). Among the total earthquakes, 170 events have been used for Lg Q and site response analysis. The newly added events are mainly chosen from Northeast China as this is a region we want to specifically calibrate. The source data for the 232 crustal earthquakes are summarized in Table 1. The six DPRK nuclear explosions are also listed in Table 1 marked with “*”. The source parameters of the used events are taken from ISC bulletin. For one magnitude type, if more than one seismic agency reported results to ISC, we use their mean as the magnitude value that will be used in this study.

Table 1: Source Information of the Used Earthquakes and Explosions

Date	Time	Lat	Lon	Dep	mb	Ms	ML	Mw	Event ID
2006/10/ 9	1:35:27.63	41.31	129.05	0.0	4.17	-	3.90	-	2006.10.09_01.35.276*
2009/ 1/26	21:30:34.20	57.61	121.14	11.0	5.07	5.04	4.85	5.40	2009.01.26_21.30.342
2009/ 2/20	3:48:53.90	34.37	74.49	29.0	5.38	5.01	5.48	5.45	2009.02.20_03.48.539
2009/ 5/25	0:54:42.89	41.29	129.07	0.0	4.64	3.82	4.55	-	2009.05.25_00.54.428*
2009/ 6/13	17:17:38.20	44.78	79.02	21.0	5.62	5.11	5.57	5.37	2009.06.13_17.17.382
2009/ 6/29	18: 3:51.50	31.46	103.96	24.0	5.15	4.96	4.75	5.25	2009.06.29_18.03.515
2009/ 7/ 9	11:19:14.20	25.60	101.03	6.0	5.26	5.63	5.42	5.68	2009.07.09_11.19.142
2009/ 7/13	18: 4:58.00	24.09	122.23	6.0	5.85	6.44	6.06	6.26	2009.07.13_18.04.580
2009/ 7/16	10:48:12.40	24.03	122.32	32.0	5.23	5.07	5.00	5.43	2009.07.16_10.48.124
2009/ 7/24	3:11:56.60	31.25	86.05	13.0	5.61	5.48	5.40	5.50	2009.07.24_03.11.566
2009/ 8/28	1:52: 6.20	37.60	95.90	10.0	6.04	6.24	5.93	6.23	2009.08.28_01.52.062

2009/ 8/28	2:14:57.10	37.70	95.84	6.0	5.45	5.45	4.85	4.20	2009.08.28_02.14.571
2009/ 8/30	17:15:49.70	37.85	95.65	10.0	5.01	4.87	5.13	5.40	2009.08.30_17.15.497
2009/ 8/31	10:15:28.80	37.74	95.98	7.0	5.76	5.59	5.35	5.83	2009.08.31_10.15.288
2009/ 9/18	7: 2:13.00	37.68	95.68	7.0	4.79	4.60	4.75	-	2009.09.18_07.02.130
2009/ 9/21	8:53: 2.90	27.30	91.38	16.0	5.66	6.11	6.55	6.13	2009.09.21_08.53.029
2009/10/ 3	17:36: 3.20	23.76	121.57	5.0	5.72	5.83	5.92	5.96	2009.10.03_17.36.032
2009/11/ 4	21:56:10.60	37.59	95.77	5.0	5.36	4.70	5.27	5.20	2009.11.04_21.56.106
2009/11/ 5	9:32:53.50	23.84	120.70	10.0	5.34	5.33	5.58	5.60	2009.11.05_09.32.535
2009/11/ 5	11:34:18.10	23.82	120.75	17.0	4.97	4.71	5.40	5.15	2009.11.05_11.34.181
2009/11/ 7	20: 8:45.60	29.69	86.12	10.0	5.46	5.01	5.27	5.26	2009.11.07_20.08.456
2009/11/27	16: 4: 4.90	31.23	103.80	15.0	4.98	4.37	4.55	4.77	2009.11.27_16.04.049
2009/12/13	14:41:54.80	22.09	91.82	23.0	5.00	4.44	5.13	4.75	2009.12.13_14.41.548
2009/12/13	16: 3:58.50	41.89	94.50	5.0	5.15	4.11	5.10	5.10	2009.12.13_16.03.585
2009/12/20	21:31:12.30	44.49	123.01	8.0	4.61	3.88	5.00	-	2009.12.20_21.31.123
2009/12/21	5:15: 7.00	37.57	96.65	6.0	5.09	4.54	4.95	4.75	2009.12.21_05.15.070
2010/ 1/ 1	2:22:24.00	30.94	84.00	6.0	4.60	4.60	4.80	5.20	2010.01.01_02.22.240
2010/ 1/ 2	2:15:10.00	38.40	71.50	40.0	5.26	5.04	5.15	5.40	2010.01.02_02.15.100
2010/ 1/19	6: 9:23.70	23.95	121.57	6.0	4.64	4.06	4.80	4.90	2010.01.19_06.09.237
2010/ 1/24	2:36:11.60	35.57	110.76	8.0	4.81	4.27	4.40	-	2010.01.24_02.36.116
2010/ 2/12	2:42:36.80	23.93	121.13	11.0	4.74	4.45	5.06	4.67	2010.02.12_02.42.368
2010/ 2/22	5:21: 1.80	24.00	122.97	17.0	5.16	4.88	5.67	5.17	2010.02.22_05.21.018
2010/ 2/25	4:56:51.60	25.42	101.94	20.0	4.84	4.53	5.33	5.05	2010.02.25_04.56.516
2010/ 2/26	1: 7:55.40	23.84	122.73	12.0	5.41	4.94	5.72	5.43	2010.02.26_01.07.554
2010/ 3/ 8	9:26:19.50	23.44	120.56	7.0	4.11	3.83	4.95	4.60	2010.03.08_09.26.195
2010/ 3/10	14:32:19.90	36.60	86.70	7.0	4.56	4.56	-	5.10	2010.03.10_14.32.199
2010/ 3/24	2: 6: 9.60	32.36	93.05	7.0	5.38	5.47	4.50	5.60	2010.03.24_02.06.096
2010/ 3/24	2:44:47.70	32.71	92.75	10.0	5.30	5.08	5.10	5.50	2010.03.24_02.44.477
2010/ 4/ 9	22:23:57.40	41.27	78.97	13.0	3.74	-	-	-	2010.04.09_22.23.001
2010/ 4/ 9	22:51:18.50	32.76	105.86	5.0	3.60	4.07	3.75	-	2010.04.09_22.51.185
2010/ 4/11	4:57:27.60	23.40	122.02	7.0	5.04	4.67	5.26	5.23	2010.04.11_04.57.276
2010/ 4/13	20:49: 6.50	23.05	121.41	10.0	4.52	4.35	4.88	4.63	2010.04.13_20.49.065
2010/ 4/13	23:49:36.10	33.22	96.59	14.0	6.10	6.90	5.85	6.78	2010.04.13_23.49.407
2010/ 4/14	1:25:16.20	33.22	96.57	17.0	5.47	6.01	5.00	6.10	2010.04.14_01.25.178
2010/ 4/17	0:58:57.10	32.31	92.92	23.0	4.78	4.72	4.40	5.30	2010.04.17_00.58.571
2010/ 4/18	20:28:47.90	35.97	67.78	5.0	5.50	5.28	5.00	5.50	2010.04.18_20.28.479
2010/ 5/25	6:11:53.10	31.17	103.49	20.0	5.08	4.53	4.75	5.00	2010.05.25_06.11.531
2010/ 5/29	2:29:49.50	33.26	96.21	10.0	5.37	5.63	5.10	5.73	2010.05.29_02.29.495
2010/ 6/ 3	5:35:42.00	33.31	96.22	11.0	5.04	5.14	4.65	5.50	2010.06.03_05.35.420
2010/ 6/10	6:38: 2.20	39.89	74.70	9.0	5.37	4.74	4.95	5.15	2010.06.10_06.38.022
2010/ 6/15	0:31:16.20	24.06	121.65	16.0	4.95	4.93	5.07	5.14	2010.06.15_00.31.162
2010/ 6/18	1: 8:43.20	24.18	121.79	6.0	4.55	3.97	4.80	4.70	2010.06.18_01.08.432
2010/ 6/22	8:46: 1.00	38.27	106.20	6.0	4.30	3.78	4.30	-	2010.06.22_08.46.010
2010/ 6/27	20:33:25.00	25.03	122.34	8.0	4.68	4.13	5.13	4.63	2010.06.27_20.33.250
2010/ 9/ 7	15:41:39.30	39.51	73.90	30.0	5.51	5.09	4.90	5.30	2010.09.07_15.41.393
2010/ 9/27	15:49:21.90	25.04	123.54	33.0	4.97	4.68	5.60	5.10	2010.09.27_15.49.219
2011/ 1/ 1	1:56: 4.70	39.49	75.21	9.0	5.00	4.49	4.55	4.90	2011.01.01_01.56.047
2011/ 2/ 1	7:11:20.70	24.70	97.90	10.0	4.66	4.33	5.35	4.40	2011.02.01_07.11.207
2011/ 2/ 1	8:16:28.30	24.20	121.80	10.0	4.81	4.98	5.28	5.17	2011.02.01_08.16.283
2011/ 2/ 4	2:39:14.80	38.72	91.74	10.0	4.64	4.15	4.40	-	2011.02.04_02.39.148
2011/ 2/10	5:35:12.80	52.26	91.68	7.0	5.22	5.18	5.37	5.40	2011.02.10_05.35.128

2011/ 2/23	17:10:37.50	45.75	94.00	10.0	4.57	4.43	4.80	5.00	2011.02.23_17.10.375
2011/ 3/10	4:58:12.40	24.65	97.95	10.0	5.30	5.27	5.60	5.30	2011.03.10_04.58.124
2011/ 3/17	15:34:30.40	40.38	79.09	6.0	4.78	4.19	4.40	4.90	2011.03.17_15.34.304
2011/ 3/24	13:55:12.30	20.70	99.85	20.0	5.93	7.11	6.58	6.80	2011.03.24_13.55.123
2011/ 3/24	15:54:33.40	20.60	99.90	10.0	5.21	5.30	5.70	5.43	2011.03.24_15.54.334
2011/ 3/25	0:22:38.70	20.60	99.90	10.0	4.76	4.47	5.30	5.10	2011.03.25_00.22.387
2011/ 4/ 4	11:31:39.00	29.75	80.85	10.0	5.42	5.06	5.57	5.35	2011.04.04_11.31.390
2011/ 4/10	9: 2:42.40	31.28	100.80	10.0	4.88	5.03	4.90	5.40	2011.04.10_09.02.424
2011/ 5/22	1:34:13.30	24.15	121.60	10.0	4.57	4.70	4.86	4.90	2011.05.22_01.34.133
2011/ 6/ 8	1:53:23.40	42.95	88.30	10.0	5.09	4.70	5.20	5.10	2011.06.08_01.53.234
2011/ 6/20	10:16:49.60	25.05	98.69	10.0	5.14	4.55	5.17	5.10	2011.06.20_10.16.496
2011/ 6/26	7:48:15.40	32.40	96.05	20.0	5.10	4.70	4.80	5.30	2011.06.26_07.48.154
2011/ 7/12	11:17: 6.70	23.55	121.52	8.0	4.80	4.20	5.10	4.77	2011.07.12_11.17.067
2011/ 7/16	18:38:48.60	52.95	108.66	5.0	5.15	5.00	4.75	5.27	2011.07.16_18.38.486
2011/ 7/19	19:35:40.80	40.15	71.35	10.0	5.98	6.16	5.80	6.12	2011.07.19_19.35.408
2011/ 7/22	14:52:55.70	49.85	118.85	10.0	4.52	3.92	4.53	4.50	2011.07.22_14.52.557
2011/ 7/24	19: 5:28.10	46.01	90.36	8.0	4.71	4.97	4.83	-	2011.07.24_19.05.281
2011/ 8/ 1	19:40:52.00	33.90	87.80	10.0	4.98	4.73	3.90	5.30	2011.08.01_19.40.520
2011/ 8/ 9	11:50:17.30	25.00	98.70	11.0	4.68	4.55	5.15	4.85	2011.08.09_11.50.173
2011/ 8/11	10: 6:29.00	39.90	77.20	10.0	5.08	5.34	5.00	5.53	2011.08.11_10.06.290
2011/ 8/27	10:29:44.00	44.02	104.58	10.0	5.26	5.26	5.47	5.40	2011.08.27_10.29.440
2011/ 9/10	15:20:31.20	29.70	115.40	13.0	4.17	4.05	5.00	-	2011.09.10_15.20.312
2011/ 9/15	15:26:58.90	36.40	82.40	6.0	5.20	4.95	5.15	5.30	2011.09.15_15.26.589
2011/ 9/18	12:40:45.70	27.70	88.20	20.0	6.16	6.59	6.23	6.85	2011.09.18_12.40.457
2011/10/14	6:10:10.20	54.15	123.75	10.0	5.56	5.86	5.80	6.04	2011.10.14_06.10.102
2011/10/16	13:44:46.10	44.25	82.70	18.0	5.03	4.29	4.60	4.80	2011.10.16_13.44.461
2011/10/20	20:52:37.20	35.62	81.53	6.0	4.48	4.28	4.55	5.00	2011.10.20_20.52.372
2011/10/31	21:58:15.00	32.60	105.30	6.0	5.49	4.66	4.90	5.00	2011.10.31_21.58.150
2011/11/ 1	0:21:27.10	43.60	82.45	28.0	5.88	5.36	5.55	5.53	2011.11.01_00.21.271
2011/11/28	15: 6:48.00	25.15	97.60	10.0	4.87	4.57	5.27	4.90	2011.11.28_15.06.480
2011/12/ 1	3:50:56.30	31.73	83.85	6.0	4.85	4.43	4.77	5.10	2011.12.01_03.50.563
2011/12/ 1	12:48:19.80	38.40	77.00	30.0	5.02	4.50	5.33	4.90	2011.12.01_12.48.198
2011/12/25	16:46:51.70	31.37	103.79	20.0	4.63	4.00	4.40	-	2011.12.25_16.46.517
2011/12/27	15:21:54.80	51.80	95.80	10.0	5.75	6.68	5.55	6.63	2011.12.27_15.21.548
2013/ 1/18	12:42:50.10	30.95	99.40	15.0	5.15	5.24	5.10	5.47	2013.01.18_12.42.501
2013/ 1/23	4:18:15.10	41.50	123.20	10.0	4.69	4.63	5.30	4.90	2013.01.23_04.18.151
2013/ 1/28	16:38:52.00	42.55	79.75	15.0	5.96	6.04	5.75	6.17	2013.01.28_16.38.520
2013/ 1/30	9:27: 2.90	32.95	94.75	20.0	5.03	4.75	4.70	5.20	2013.01.30_09.27.029
2013/ 2/11	19:13: 0.10	38.50	92.45	8.0	5.23	4.37	4.60	5.00	2013.02.11_19.13.001
2013/ 2/12	2:57:50.96	41.31	129.09	0.0	5.03	4.02	4.50	-	2013.02.12_02.57.509*
2013/ 2/19	14:17:43.40	31.21	105.20	20.0	4.45	4.53	4.80	5.10	2013.02.19_14.17.434
2013/ 2/22	3:34:11.80	23.90	114.48	11.0	4.35	3.93	5.10	-	2013.02.22_03.34.118
2013/ 3/ 3	5:41:15.80	25.93	99.72	9.0	5.27	4.91	5.10	5.30	2013.03.03_05.41.158
2013/ 4/ 1	9:47:31.00	40.38	107.14	8.0	4.04	-	4.35	-	2013.04.01_09.47.310
2013/ 4/20	0: 2:47.50	30.30	102.99	17.0	6.05	6.77	5.85	6.64	2013.04.20_00.02.475
2013/ 4/20	3:34:16.80	30.24	102.94	15.0	4.81	4.75	4.95	5.40	2013.04.20_03.34.168
2013/ 4/20	20:53:44.40	30.35	103.05	26.0	4.92	4.27	4.70	4.80	2013.04.20_20.53.444
2013/ 4/21	9: 5:23.70	30.34	103.00	17.0	4.99	4.57	4.75	5.20	2013.04.21_09.05.237
2013/ 4/22	9:11:52.00	42.90	122.35	6.0	4.96	4.68	4.80	5.00	2013.04.22_09.11.520
2013/ 4/24	22:10:30.00	28.40	104.95	5.0	4.99	4.18	4.85	4.70	2013.04.24_22.10.300

2013/ 5/14	4:39:27.60	49.22	122.71	8.0	4.21	4.00	4.35	-	2013.05.14_04.39.276
2013/ 6/ 5	0:43:36.40	37.59	95.87	10.0	5.13	4.58	5.30	5.10	2013.06.05_00.43.364
2013/ 6/20	9: 5:11.70	49.75	125.20	10.0	4.34	4.04	5.15	-	2013.06.20_09.05.117
2013/ 7/21	23:45:56.50	34.54	104.21	15.0	5.84	6.07	5.80	5.93	2013.07.21_23.45.565
2013/ 7/22	1:12:36.00	34.56	104.21	14.0	5.40	5.01	5.25	5.40	2013.07.22_01.12.360
2013/ 7/26	16:25: 4.60	33.00	104.90	10.0	4.56	4.00	4.20	-	2013.07.26_16.25.046
2013/ 8/ 1	8:46:50.80	53.73	121.57	7.0	3.84	-	4.25	-	2013.08.01_08.46.508
2013/ 8/ 7	18:51:42.60	31.69	103.18	20.0	4.30	3.73	4.00	-	2013.08.07_18.51.426
2013/ 8/11	21:23:42.00	30.04	97.96	15.0	5.63	5.61	4.80	5.73	2013.08.11_21.23.420
2013/ 8/16	3:38:13.20	38.50	104.07	7.0	3.82	4.30	4.05	-	2013.08.16_03.38.132
2013/ 8/22	21: 2: 0.70	25.63	118.84	8.0	3.87	4.00	4.57	-	2013.08.22_21.02.007
2013/ 8/31	0: 4:16.80	28.15	99.35	10.0	5.33	5.41	5.60	5.63	2013.08.31_00.04.168
2013/ 9/ 3	22:23:26.00	25.64	118.75	10.0	4.09	4.80	4.77	-	2013.09.03_22.23.260
2013/ 9/16	22:43:38.50	39.50	100.67	10.0	4.69	4.06	4.60	-	2013.09.16_22.43.385
2013/ 9/19	21:37: 1.40	37.73	101.53	15.0	5.04	4.63	4.90	5.05	2013.09.19_21.37.014
2013/ 9/20	12:24:46.30	23.00	95.86	9.0	5.08	5.50	5.57	5.67	2013.09.20_12.24.463
2014/ 3/31	19:48:35.72	36.94	124.56	12.9	4.71	4.22	5.07	4.80	2014.03.31_19.48.357
2014/ 4/ 3	16:12:18.23	36.80	121.67	10.0	4.13	3.70	4.60	-	2014.04.03_16.12.182
2014/ 4/ 3	21:30: 2.40	42.82	121.81	0.0	-	-	3.60	-	2014.04.03_21.30.024
2014/ 4/ 4	17:37: 3.73	37.95	121.15	10.0	-	-	3.60	-	2014.04.04_17.37.037
2014/ 4/ 8	11: 7:42.50	40.54	122.29	0.0	-	-	3.50	-	2014.04.08_11.07.425
2014/ 4/12	21:22:44.57	44.90	133.69	10.0	4.17	5.03	4.10	-	2014.04.12_21.22.446
2014/ 4/14	2:27:58.59	41.75	124.08	10.0	3.64	-	-	-	2014.04.14_02.27.586
2014/ 4/17	8:19:40.50	40.59	122.85	0.0	-	-	3.50	-	2014.04.17_08.19.405
2014/ 4/18	1: 7:28.45	40.45	122.28	10.0	-	-	3.80	-	2014.04.18_01.07.285
2014/ 4/19	19:27:54.85	49.34	123.73	10.0	3.89	4.30	4.70	-	2014.04.19_19.27.549
2014/ 4/27	23:59:47.60	40.64	122.32	0.0	-	-	3.60	-	2014.04.27_23.59.476
2014/ 4/30	0:39: 0.11	46.16	129.18	0.0	3.80	-	-	-	2014.04.30_00.39.001
2014/ 5/22	0:24:43.22	40.32	122.02	10.0	3.70	3.55	3.50	-	2014.05.22_00.24.432
2014/ 5/25	20: 3: 5.88	38.51	120.91	10.0	3.70	-	3.80	-	2014.05.25_20.03.059
2014/ 5/27	7:49:14.60	44.86	123.42	0.0	-	-	3.80	-	2014.05.27_07.49.146
2014/ 5/27	7:52:22.71	44.68	124.25	10.0	4.04	4.10	4.33	-	2014.05.27_07.52.227
2014/ 6/17	0:33:42.06	44.58	124.20	10.0	4.20	-	3.90	-	2014.06.17_00.33.421
2014/ 6/25	20: 5:50.87	40.44	122.41	10.0	3.63	-	4.20	-	2014.06.25_20.05.509
2014/ 7/ 3	12:57:10.89	35.63	129.77	10.0	3.66	3.90	4.20	-	2014.07.03_12.57.109
2014/ 8/ 3	8:30:14.39	27.21	103.43	13.7	5.70	6.24	5.55	6.17	2014.08.03_08.30.144
2014/ 8/17	20:42: 6.50	47.18	121.36	6.0	-	-	3.80	-	2014.08.17_20.42.065
2014/ 8/21	23:54:44.09	40.46	122.21	10.0	3.82	3.90	4.25	-	2014.08.21_23.54.441
2014/ 9/ 3	1: 8:32.30	37.00	121.41	0.0	-	-	3.50	-	2014.09.03_01.08.323
2014/ 9/ 3	8:45:41.76	43.82	125.77	10.0	3.67	-	3.70	-	2014.09.03_08.45.418
2014/ 9/ 6	10:37:42.06	40.29	115.57	10.0	4.01	3.90	4.45	-	2014.09.06_10.37.421
2014/ 9/ 9	9:28:22.59	22.10	93.20	10.9	5.15	5.20	4.30	5.43	2014.09.09_09.28.226
2014/ 9/16	6:42:58.78	37.01	121.79	10.0	4.30	-	4.15	-	2014.09.16_06.42.588
2014/ 9/16	6:43:34.48	36.95	121.82	10.0	-	-	4.20	-	2014.09.16_06.43.345
2014/ 9/21	14:39:40.46	41.92	124.03	0.0	3.55	-	-	-	2014.09.21_14.39.405
2014/ 9/23	6:27:55.84	35.86	129.44	10.0	3.66	-	3.80	3.70	2014.09.23_06.27.558
2014/ 9/24	17:26:45.25	34.91	129.92	10.0	3.57	-	4.10	4.00	2014.09.24_17.26.453
2014/ 9/27	22:49: 4.06	36.41	69.81	30.8	5.05	4.53	4.95	5.05	2014.09.27_22.49.041
2014/10/14	9:27:27.62	39.48	118.75	10.0	-	-	3.85	-	2014.10.14_09.27.276
2014/11/14	1:24:16.03	42.11	77.19	12.7	5.44	5.08	5.30	5.27	2014.11.14_01.24.160

2014/11/22	8:55:26.49	30.31	101.80	2.0	5.60	6.13	5.60	6.02	2014.11.22_08.55.265
2015/ 2/ 8	17:32:18.59	44.73	124.06	10.0	4.19	4.30	4.60	-	2015.02.08_17.32.186
2015/ 2/10	7:21:55.43	44.72	124.05	0.0	3.73	-	3.60	-	2015.02.10_07.21.554
2015/ 2/16	22:28:47.09	44.63	124.05	10.0	3.94	-	4.20	-	2015.02.16_22.28.471
2015/ 4/ 1	3:12:23.73	42.70	123.41	10.0	3.62	3.50	-	-	2015.04.01_03.12.237
2015/ 4/ 3	17:39:18.12	41.92	123.84	10.0	3.58	4.20	-	-	2015.04.03_17.39.181
2015/ 4/15	7:39:27.18	39.73	106.38	8.2	5.00	5.13	5.20	5.45	2015.04.15_07.39.272
2015/ 4/25	6:11:26.63	28.13	84.71	13.4	6.56	7.77	6.43	7.80	2015.04.25_06.11.266
2015/ 4/25	8:55:55.00	27.87	85.77	10.0	5.20	5.45	5.30	-	2015.04.25_08.55.550
2015/ 4/25	12:44: 3.90	28.20	84.78	6.0	5.02	4.40	5.10	-	2015.04.25_12.44.039
2015/ 4/25	17:42:49.50	28.20	85.90	10.0	5.08	4.82	5.13	5.20	2015.04.25_17.42.495
2015/ 4/25	23:16:14.00	27.70	84.95	10.0	5.28	4.64	5.30	5.10	2015.04.25_23.16.140
2015/ 4/26	7: 9: 6.90	27.75	85.95	10.0	6.23	6.85	6.17	6.67	2015.04.26_07.09.069
2015/ 4/26	16:26: 2.30	27.65	85.80	10.0	5.36	4.82	5.30	5.10	2015.04.26_16.26.023
2015/ 5/10	2:27: 3.64	40.70	129.09	0.0	3.50	-	-	-	2015.05.10_02.27.036
2015/ 5/12	7: 5:18.83	27.80	86.12	12.3	6.45	7.53	6.05	7.28	2015.05.12_07.05.188
2015/ 5/16	11:34:10.10	27.79	86.38	11.0	5.51	5.15	5.40	5.40	2015.05.16_11.34.101
2015/ 5/21	16: 5:31.45	36.81	121.79	10.0	4.46	3.98	4.80	-	2015.05.21_16.05.315
2015/ 6/ 9	14:29: 8.40	37.01	121.82	10.0	-	-	3.70	-	2015.06.09_14.29.084
2015/ 6/12	6:40:34.77	41.58	115.01	10.0	3.58	-	4.00	-	2015.06.12_06.40.348
2015/ 6/15	18:26: 0.01	41.93	124.17	0.0	3.50	-	-	-	2015.06.15_18.26.000
2015/ 6/28	23: 3:23.01	38.60	120.76	10.0	3.79	3.80	4.07	-	2015.06.28_23.03.230
2015/ 6/29	11:37:55.41	46.18	119.11	10.0	3.72	3.80	4.40	-	2015.06.29_11.37.554
2015/ 7/ 3	1: 7:46.21	37.47	78.12	19.0	5.80	6.54	5.95	6.36	2015.07.03_01.07.462
2015/ 7/22	0:51:52.81	38.05	120.30	10.0	3.97	3.80	4.50	-	2015.07.22_00.51.528
2015/ 7/24	6:25:14.64	53.93	128.01	10.0	3.82	3.80	-	-	2015.07.24_06.25.146
2015/ 8/ 4	4:25:27.94	40.50	122.39	10.0	4.46	3.92	4.20	-	2015.08.04_04.25.279
2015/ 8/ 6	1:58:58.97	34.37	121.02	10.0	3.62	-	4.00	-	2015.08.06_01.58.590
2015/ 9/25	23:24:11.15	54.87	111.76	1.3	4.44	4.30	5.60	4.75	2015.09.25_23.24.112
2015/10/ 9	9:20:24.46	34.05	122.37	10.0	3.85	-	3.83	-	2015.10.09_09.20.245
2015/10/21	5:58:22.27	44.58	123.90	10.0	4.13	4.08	5.10	-	2015.10.21_05.58.223
2015/11/ 4	19:38:52.80	41.95	121.67	0.0	3.50	-	-	-	2015.11.04_19.38.528
2015/11/12	0:18:42.00	45.08	130.79	10.0	3.65	-	3.50	-	2015.11.12_00.18.420
2015/11/22	19:57:43.91	40.88	122.39	10.0	3.95	4.00	4.60	-	2015.11.22_19.57.439
2015/11/24	2:27:52.53	35.64	129.78	9.9	3.50	-	-	-	2015.11.24_02.27.525
2015/11/27	18:10:39.36	39.35	117.94	20.0	3.90	-	4.00	-	2015.11.27_18.10.394
2015/12/ 7	7:50: 4.54	38.12	72.88	14.2	6.25	7.40	4.70	7.15	2015.12.07_07.50.045
2015/12/ 7	8:30:54.94	41.70	74.56	14.3	5.31	5.83	4.77	-	2015.12.07_08.30.549
2015/12/18	22:16:57.00	29.50	81.80	18.0	5.15	4.75	5.05	5.20	2015.12.18_22.16.570
2015/12/21	19:31:24.59	36.03	126.95	11.6	4.13	3.90	4.20	3.90	2015.12.21_19.31.246
2015/12/24	23:56:14.68	35.58	117.79	10.0	3.83	-	-	-	2015.12.24_23.56.147
2016/ 1/ 6	1:30: 0.72	41.31	129.04	0.0	4.94	3.97	4.60	-	2016.01.06_01.30.007*
2016/ 1/20	1: 4:59.60	35.74	115.45	6.0	4.00	-	4.00	-	2016.01.20_01.04.596
2016/ 1/20	17:13:13.30	37.64	101.63	9.6	5.96	5.79	5.50	5.90	2016.01.20_17.13.133
2016/ 2/19	16:56:58.67	50.28	132.24	10.0	3.88	-	-	-	2016.02.19_16.56.587
2016/ 3/17	16:53:47.12	51.41	122.86	10.0	4.00	4.00	4.40	-	2016.03.17_16.53.471
2016/ 3/30	13:56:21.89	53.96	132.39	10.0	3.98	4.20	4.00	-	2016.03.30_13.56.219
2016/ 5/11	1:15:47.39	31.93	95.01	12.7	5.29	5.22	4.85	5.35	2016.05.11_01.15.474
2016/ 5/22	2: 5:55.29	28.44	87.42	12.7	5.03	4.67	5.00	5.20	2016.05.22_02.05.553
2016/ 5/22	9: 8: 5.25	41.64	120.18	15.4	4.52	4.17	4.77	-	2016.05.22_09.08.053

2016/ 6/11	16:30:55.93	51.09	135.49	10.0	4.16	3.70	3.95	-	2016.06.11_16.30.559
2016/ 6/23	0:37:35.17	40.98	114.25	10.0	4.02	3.80	3.90	-	2016.06.23_00.37.352
2016/ 6/26	11:17:11.22	39.39	73.51	8.6	6.11	6.57	5.60	6.38	2016.06.26_11.17.112
2016/ 6/28	21:38: 3.69	39.48	73.43	10.5	5.49	5.25	4.90	5.47	2016.06.28_21.38.037
2016/ 7/ 5	11:33: 3.74	35.51	129.91	7.8	4.45	4.27	4.60	4.80	2016.07.05_11.33.037
2016/ 9/ 9	0:30: 0.80	41.28	129.04	0.0	5.20	4.53	4.30	-	2016.09.09_00.30.008*
2016/ 9/10	10: 9:37.84	39.66	118.45	15.0	4.20	4.60	4.10	-	2016.09.10_10.09.378
2016/ 9/11	8: 7:43.02	53.51	127.18	10.0	4.18	3.97	4.70	-	2016.09.11_08.07.430
2016/ 9/12	10:44:32.81	35.78	129.17	10.0	4.72	4.70	5.60	5.07	2016.09.12_10.44.328
2016/ 9/12	11:32:54.95	35.76	129.15	12.2	5.22	5.32	5.95	5.47	2016.09.12_11.32.550
2016/ 9/19	11:33:58.45	35.73	129.18	9.1	4.02	3.83	4.80	4.45	2016.09.19_11.33.585
2016/10/17	7:14:49.09	32.85	94.87	25.2	5.90	5.96	5.55	5.95	2016.10.17_07.14.491
2016/10/28	18:58:11.06	41.20	119.76	10.0	4.05	-	4.30	-	2016.10.28_18.58.111
2016/11/25	14:24:30.37	39.20	74.07	12.4	6.20	6.67	5.65	6.57	2016.11.25_14.24.304
2016/11/27	23:35:20.78	27.71	86.50	14.8	5.29	4.92	5.53	5.20	2016.11.27_23.35.208
2017/ 1/ 2	2:10:10.57	40.84	114.34	13.0	3.50	-	4.10	-	2017.01.02_02.10.106
2017/ 1/ 3	9: 9: 2.29	24.10	91.98	34.6	5.33	5.20	5.20	5.60	2017.01.03_09.09.023
2017/ 1/17	8:53:47.03	49.81	118.71	10.0	3.78	-	-	-	2017.01.17_08.53.470
2017/ 1/21	3:22:24.81	44.53	132.32	10.0	4.03	-	-	-	2017.01.21_03.22.248
2017/ 1/21	16:43:34.26	51.94	120.02	10.0	3.72	4.00	4.05	-	2017.01.21_16.43.343
2017/ 2/ 6	17: 3: 5.81	30.57	79.07	14.6	5.49	4.92	5.25	5.20	2017.02.06_17.03.058
2017/ 2/25	20:34: 1.49	36.30	123.55	10.0	-	-	4.00	-	2017.02.25_20.34.015
2017/ 4/ 7	18: 8:35.08	38.06	120.79	0.0	3.60	-	4.00	-	2017.04.07_18.08.351
2017/ 4/10	2:56:47.60	53.07	135.53	10.0	4.25	-	-	-	2017.04.10_02.56.476
2017/ 5/ 3	4:47:13.38	39.49	71.44	11.0	5.82	6.17	5.55	5.93	2017.05.03_04.47.134
2017/ 5/ 5	5: 9:35.97	39.47	71.42	10.0	5.95	5.77	5.50	5.78	2017.05.05_05.09.360
2017/ 9/ 3	3:30: 1.76	41.33	129.03	0.0	6.23	5.10	5.85	5.85	2017.09.03_03.30.017*

We totally analyze more than 51,000 vertical-component seismograms recorded at the used stations for the 238 regional events. Given the stations operation time, occasional technical failure, and earthquake size, an earthquake may not be recorded by all stations. The Chinese waveform data are retrieved from the China Earthquake Networks Center (CENC) through the collaboration program between ARRAY and Chinese collaborators. The IRIS waveform data are downloaded from IRIS DMC.

For every seismogram where the Lg phase arrival can be readily identified, we select the arrival time by hand. Otherwise, a typical Lg group velocity window of 3.6-3.0 km/s is used as a reference. When picking these arrivals, we attempt to avoid the inclusion of Sn coda and the beginning of the fundamental mode Rayleigh wave. The Sn coda in particular is considered to be the pre-phase noise of Lg, with a group velocity window of 4.2-3.7 km/s. We also hand-select the first P arrival of every seismogram to account for errors in event origin time and hypocentral location. A window prior to the first P arrival with at least 10s duration is used as pre-event noise in our processing.

For Lg Q analysis, a Fast Fourier Transform (FFT) with a 10% cosine taper window [Xie, 1993] is applied to the three time-windows described above to obtain the spectra of the Lg phase, the pre-event noise, and the Sn coda, respectively. Instrument responses are removed from the raw spectra to obtain ground displacement spectra. Next, we compute the pre-event Signal-to-Noise Ratio (SNR) by dividing the Lg spectral amplitude by the pre-event spectral amplitude. We also calculate the pre-phase SNR by dividing the Lg spectral amplitude by the Sn coda amplitude. Only those Lg spectra whose pre-event SNR exceeds 3.0 and pre-phase SNR exceeds 1.3 are kept for

Lg Q analysis. Using the additional pre-phase SNR screening criterion not only ensures that all Lg amplitude measurements are actually from the Lg phase instead of the Sn coda, but it also has the benefit of removing blocked or partially blocked Lg measurements, which may otherwise be treated as high attenuation. Finally, we subtract the Lg power spectra by the pre-event noise power spectra to reduce the effects of ambient noise. To calibrate and estimate $m_b(\text{Lg})$, similar data quality control criteria using pre-event SNR and pre-phase SNR are also applied to screen Lg amplitudes in the time domain.

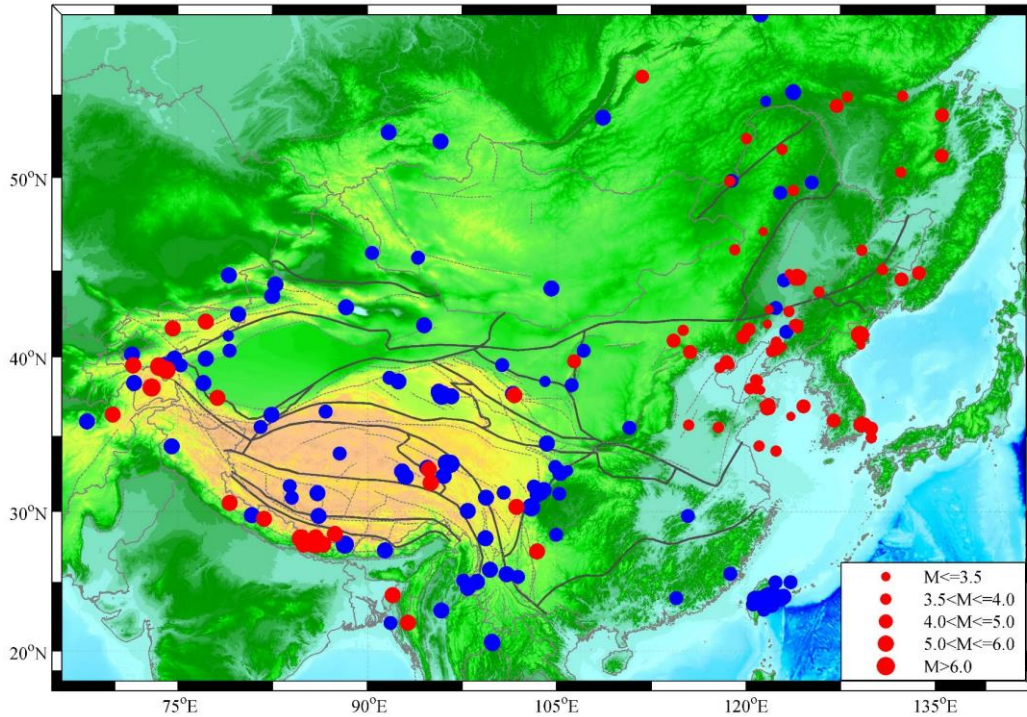


Figure 4. Distribution of seismic events used in this study including the six DPRK explosions. The events are shown as solid dots in different colors. The blue dots represent earthquakes used for generating two-station Lg Q tomographic models, and the red dots are newly added events for source parameters and $m_b(\text{Lg})$ scale calibration.

3 METHODOLOGY OF CALIBRATION OF $m_b(\text{Lg})$

3.1 Method of Estimation of $m_b(\text{Lg})$

The generalized formula of regional magnitude scale $m_b(\text{Lg})$ based on measurements of Lg wave amplitudes near 1.0Hz was originally proposed by Nuttli [1973; 1986a] and calibrated in eastern North American. Nuttli's formula for $m_b(\text{Lg})$ is expressed as:

$$A(10\text{km}) = A(\Delta) \left(\frac{\Delta}{10} \right)^{\frac{1}{3}} \left(\frac{\sin(\Delta/111.1)}{\sin(10/111.1)} \right)^{\frac{1}{2}} \exp(\gamma(\Delta - 10)) \quad (1)$$

$$m_b(\text{Lg}) = 5.0 + \log_{10}[A(10\text{km})/C] \quad (2)$$

where Δ is the epicentral distance in km and $A(\Delta)$ is sustained Lg amplitude observed at Δ . A “hypothetical” Lg amplitude at a distance of 10km from the source, $A(10\text{km})$, will be estimated with explicit corrections for Airy phase spreading and regional attenuation of Lg amplitude near 1.0Hz. In Equation (1), $\gamma = \frac{\pi f}{vQ(f)}$ is the attenuation coefficient tied to quality factor Q at frequency

f. Nuttli's $m_b(\text{Lg})$ scale is tied to the teleseismic $m_b(\text{P})$ using a calibration constant C (Equation (2)), which was determined empirically equal to $110\mu\text{m}$ [Nuttli, 1986a] so that an $m_b(\text{P}) = 5.0$ earthquake in eastern North American has $m_b(\text{Lg}) = 5.0$.

Equation (1) and (2) can be combined to a one-step formula by inputting Equation (2) into (1) and merging all constants into one constant [Jih and Lynnes, 1993; Jih and Baumstark, 1994; Jih *et al.*, 1995]:

$$m_b(\text{Lg}) = 4.0272 - \text{bias} + \log[A(\Delta)] + \frac{1}{3}\log(\Delta) + \frac{1}{2}\log[\sin(\Delta/111.1)] + \frac{\gamma(\Delta-10)}{\ln(10)} \quad (3)$$

where “bias” is a correction term if $C \neq 110\mu\text{m}$. In order to make $m_b(\text{Lg})$ a transportable magnitude scale on a region-to-region basis, determining the “bias” term is equivalent to calibrating C . Jih's concise formula is essentially equivalent to Nuttli's formulae and it facilitates inversion procedure for path correction and routine $m_b(\text{Lg})$ computation. Because we want to investigate the transportability of $m_b(\text{Lg})$, we keep using Nuttli's two-step formulae in this study.

When Nuttli's formulae are used to estimate $m_b(\text{Lg})$, the 3rd peak amplitude in μm is measured off a vertical-component, short-period (SP) seismogram with World-Wide Standard Seismogram Network (WWSSN) response in a prescribed group velocity window as the measure of sustained Lg ground motion, i.e., $A(\Delta)$ in Equation (1). On the other hand, as have been done in many previous studies [e.g., Patton 1988; Hansen *et al.*, 1990; Ringdal *et al.*, 1992; Priestly and Patton 1997; Patton and Schlittenhardt, 2005], the RMS amplitudes can be used as $A(\Delta)$ and it provides a more stable measure of sustained Lg ground motion than the 3rd-peak amplitudes. The $m_b(\text{Lg})$ formula using RMS amplitudes can be expressed as [e.g., Patton and Schlittenhardt, 2005]:

$$A_{rms}(10\text{km}) = A_{rms}(\Delta) \left(\frac{\Delta}{10}\right)^{1.0} \exp(\gamma(\Delta - 10)) \quad \text{for } \Delta < 1200\text{km}$$

$$A_{rms}(10\text{km}) = A_{rms}(\Delta) \left(\frac{\sin(\Delta/111.1)}{\sin(10/111.1)}\right)^{1.0} \exp(\gamma(\Delta - 10)) \quad \text{for } \Delta \geq 1200\text{km} \quad (4)$$

$$m_b(\text{Lg}; \text{rms}) = 5.0 + \log_{10}[A_{rms}(10\text{km}) / C_{rms}] \quad (5)$$

When $\Delta \geq 1200\text{km}$, the earth curvature is accounted for geometrical spreading (GS). As shown in Figure 5, when $\Delta < 1200\text{km}$, the difference between $\frac{\Delta}{10}$ and $\frac{\sin(\Delta/111.1)}{\sin(10/111.1)}$ is ignorable. When $\Delta \geq 1200\text{km}$, $\frac{\sin(\Delta/111.1)}{\sin(10/111.1)}$ deviates gradually from the linear relationship with Δ . The difference in geometrical spreading for RMS amplitudes and 3rd-peak amplitudes refers to the numerical synthetic study of Yang [2002] for Lg wave geometrical spreading, where the Lg amplitudes were measured by various methods including the RMS and the 3rd-peak. Furthermore, the calibration constant C for 3rd-peak amplitudes does not apply to RMS amplitudes. To distinguish between the two methods, we will add the subscript “3rd” and “rms” to the corresponding parameters in further analysis.

The main procedure to calibrate $m_b(\text{Lg})$ estimator includes the following steps: (1) measurements of $A(\Delta)$ in prescribed Lg window and associated wave frequency, and performance of data screening, (3) correction for the site response, (3) correction for GS and path attenuation from the source to the recording station, and (4) calibration of constant C . The previous studies usually did not involve explicit correction for site responses (SRs), but we will use the results of the joint inversion for source spectra, Q and SRs to correct site effects in this study.

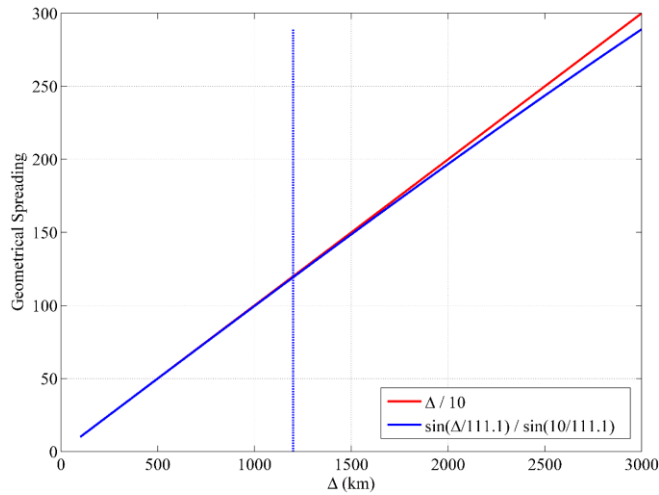


Figure 5. Comparison of the geometrical spreading term used by the RMS method in the different epicentral distances.

3.2 Measurement of Amplitude $A(\Delta)$

Measurement of 3rd peak amplitude

We process only the seismograms that have associated instrument responses. These seismograms are first deconvolved by their own broad-band or short-period responses and then convolved with WWSSN-SP response (Figure 3a) to obtain ground motions simulating WWSSN-SP records. Note that modern digital instruments are all equipped with velocity response seismometers. The poles-and-zeros normalization constant normalizes the velocity response to unity (Figure 3a). While WWSSN-SP is a displacement response instrument, and its normalization constant normalizes the displacement response to unity (Figure 3b). The 3rd-peak sustained amplitudes of Lg wave are picked on the vertical-component of WWSSN-SP simulated seismograms within the manually determined Lg window. The amplitudes and the associated arrival times of the 3rd-peak positive excursion and the 3rd-peak negative excursion of the Lg wave train are both found. The 3rd-peak amplitude used to compute $m_b(\text{Lg})$ is the mean zero-to-peak amplitude of the positive and negative peaks.

There is no explicit data quality control in the procedure of using the 3rd-peak Lg amplitude to measure $A_{3rd}(\Delta)$, but apparently, the analog seismograms substantially contaminated by background noise cannot be used to estimate $m_b(\text{Lg})$. In this study, we screen Lg data by performing a signal-to-noise (SNR) test. The waveform segment ending at the first P arrival is defined as pre-event noise N_e , and its maximum zero-to-peak amplitude is also found along with the 3rd-peak Lg amplitude. The pre-event SNR ratio is calculated by dividing the Lg 3rd-peak amplitude by the noise peak amplitude. A seismogram is rejected if the SNR is less than 3.0 [Rigsby *et al.*, 2014].

Measurement of RMS amplitude in the time domain

The RMS amplitudes have been used as a stable measure of sustained Lg ground motion compared to the 3rd-peak amplitudes. The modern digital waveform records facilitate the measurements of RMS amplitudes and correction for seismic noise. The RMS amplitudes for Lg ground motion are also measured on WWSSN-SP simulated seismograms within the manually picked Lg arrival windows. The waveform segment ending at the first P arrival is defined as pre-event noise N_e . Meanwhile, the Sn coda arriving within a group velocity window of 4.2-3.7 km/s is considered to be the pre-phase noise of Lg, N_c . If S is the RMS amplitude measured in Lg

window, the square SNR for pre-event noise, $\left(\frac{S}{N_e}\right)^2$ and pre-phase noise, $\left(\frac{S}{N_c}\right)^2$ will be both calculated. Patton and Schlittenhardt [2005] considered the pre-phase noise and rejected any Lg data from further analysis if their $\left(\frac{S}{N_c}\right)^2$ fell below a threshold value. They set the threshold initially to $\left(\frac{S}{N_c}\right)^2 = 1.12$ when calculating $m_b(\text{Lg})$ on individual stations and later increased it to 1.58 for the final network $m_b(\text{Lg})$. The RMS amplitude of Lg signal is estimated as $A_{rms} = \sqrt{S^2 - N_c^2}$.

For the RMS method, we add pre-event SNR as an additional criterion to screen out those seismograms with strong background noise. In processing Lg waveform data for Lg Q tomographic models, we used the pre-event and pre-phase SNRs to reject noisy or blocked Lg waves, where the SNRs were calculated using the spectra of Lg waves, pre-event noise and pre-phase noise, respectively [Chen and Xie, 2017]. In this study, the Lg data were rejected if their pre-event SNR fell below 3.0 or their pre-phase SNR fell below 1.3.

Measurement of RMS amplitude and spectrum in the frequency domain

We also attempt to calibrate $m_b(\text{Lg})$ in the frequency domain based on the following reasons: (1) Mathematically, the observed amplitudes of a regional wave in the time domain can be stochastically expressed as a convolution of source excursion, geometrical spreading, path attenuation, site response and instrument response. In the frequency domain the convolution is converted to the production of every term. The Q analysis is usually performed in the frequency domain. The production in Equation (1) to (5) is simply an approximation for the convolution procedure when it is applied in the time domain to measure magnitude. (2) We remove broadband instrument response and add WWSSN-SP response in the frequency domain and then simulate WWSSN-SP seismogram by performing inverse Fourier transform. As we have already calculated the spectrum of Lg wave in the above process, we can directly use Lg spectrum to measure $m_b(\text{Lg})$ and omit WWSSN-SP instrument simulation. (3) In a realistic situation when the original waveform data are no longer available, but the spectral data of the waveforms are stored, then they can be used to estimate $m_b(\text{Lg})$ without accessing the original waveforms.

There are two ways to use Lg spectral data to calibrate $m_b(\text{Lg})$. First, the RMS amplitudes of Lg wave can be converted from spectral amplitudes using Parseval's theorem (Equation (A4) in Appendix A). Equation (A4) can also be applied to pre-event noise and pre-phase noise. Taylor *et al.* [2002] used Parseval's theorem to convert the RMS measurements in the time domain into pseudo-spectra. Here, we simply invert Taylor *et al.* [2002] procedure for our work. The data quality control using pre-event SNR and pre-phase SNR can be used either in the spectral data or in the resulting "pseudo" RMS data.

Second, the spectral amplitudes are attempted to measure $m_b(\text{Lg})$, but the power in the GS term in Equation (4) shall be changed from 1.0 to 0.5. Yang [2002] demonstrated that the Lg GS estimated from RMS and spectral amplitudes is the most constant and stable among various source and path parameter simulations during the numerical investigation of Lg GS term. The relationship between the spreading exponent estimates of 1.0 for RMS amplitudes and the estimates of 0.5 for spectral amplitudes are in agreement with theoretical predictions.

3.3 Measurements of Wave Frequency

In estimating $m_b(\text{Lg})$, Nuttli [1986a] restricted wave frequencies f to be between 0.77 and 1.43Hz, and Patton and Schlittenhardt [2005] used a slightly wider range from 0.71 to 1.67Hz. In addition to screening measurements for acceptable period range, the instantaneous frequency f used in Equation (1) – (5) is needed for the calculation of frequency-dependent $\gamma(f)$ for the propagation paths. However, estimating a stable f is by no means a trivial task because it is difficult to measure consistently with automated techniques due to the relatively broad frequency content of WWSSN-SP signals. Following the procedure of Patton and Schlittenhardt [2005], we estimate f_{3rd} and f_{rms} separately, corresponding to A_{3rd} and A_{rms} , respectively.

Weighted average frequency for f_{3rd}

The “weighted average frequency” defined in Taner *et al.* [1979] is measured as the f_{3rd} (Appendix B). The algorithm for f_{3rd} associated with the 3rd-peak amplitude can be summarized as below:

- (1) The WWSSN seismic trace is high-pass filtered using a phaseless Butterworth filter with a corner frequency of 0.5Hz.
- (2) The weighted average frequency is computed for the filtered WWSSN trace using Equation (10) and denoted as $u(t)$.
- (3) Step (2) is repeated on the derivative of the WWSSN trace to obtain $v(t)$, and the geometric mean of $u(t)$ and $v(t)$ is computed.
- (4) Amplitudes (and associated arrival times) of the 3rd-peak positive excursion and negative excursion are found.
- (5) All excursions with amplitudes falling inside the limits set by the 3rd-peak amplitudes, including the next larger (positive) and next smaller (negative) excursion outside these limits are found and saved. These excursions give an assemble of sustained amplitudes making up Lg wave.
- (6) The frequencies computed in (3) for the excursions found in (5) are sorted, and the 3rd-peak frequency f_{3rd} is the median value.

Zero-crossing counting for f_{rms}

The RMS frequency f_{rms} is measured based on counting zero-crossings of the waveform portion for the Lg wave. The specific algorithm for f_{rms} is summarized as below:

- (1) The WWSSN seismic trace is high-pass filtered using a phaseless Butterworth filter with a corner frequency of 0.5Hz. The mean in the Lg window is removed.
- (2) In the Lg window with a length of L , zero crossings are counted and the period is computed as $T_1 = 2L/N$, where N is the number of zero crossings.
- (3) Step (2) is repeated on the derivative of the WWSSN trace to obtain T_2 .
- (4) A parameter α is defined as $\alpha = \log_{10}(T_1/T_2)$ and the resulting α value is tested against thresholds to determine two weight factors, w_1 and w_2 , for T_1 and T_2 , respectively. The RMS frequency $f_{rms} = 1/T_{rms}$, where T_{rms} is the weighted mean of T_1 and T_2 :

$$f_{rms} = \frac{1}{T_{rms}} = \frac{1}{w_1 T_1 + w_2 T_2} \quad (6)$$

where

$$w_1 = 0.8, w_2 = 0.2 \text{ when } \alpha < 0.05$$

$$w_1 = 0.6, w_2 = 0.4 \text{ when } 0.05 \leq \alpha < 0.01$$

$$w_1 = 0.4, w_2 = 0.6 \text{ when } \alpha \geq 0.05$$

The thresholds and weights were determined by experimentation by Patton and Schlittenhardt [2005].

In this study, we use the acceptable frequency range between 0.71 and 1.67Hz [Patton and Schlittenhardt, 2005]. If the measured f_{3rd} or f_{rms} falls outside the frequency range threshold, the corresponding Lg amplitude is rejected from further analysis. This acceptable frequency range is also used as the integral range in Equation (A4) to compute the pseudo RMS amplitude.

3.4 Path Attenuation and Site Corrections for Estimation of $A(10\text{km})$

The measured amplitude $A(\Delta)$ on WWSSN-SP simulated seismogram is first corrected for WWSSN-SP displacement response (Figure 3b) using the frequency estimate, f_{3rd} or f_{rms} , and then corrected for path attenuation and site effect at f_{3rd} or f_{rms} . The resulting $A(10\text{km})$ will then be used to calibrate the constant C value in Equation (2) and (5). In this study, we develop an iterative method to jointly invert for source spectra, Q and SRs for Lg wave. The resulting path Q and SRs are used to do site and path attenuation corrections in this study. We will describe this iterative method in the next section.

4 JOINT INVERSION OF LG SOURCE SPECTRA, Q AND SITE RESPONSES

4.1 Initial Lg Q Tomographic Models and SR Models

In a previous ARRAY contract (SAQMMA17M1542), we processed more than 42,000 broad-band regional Lg waveforms recorded at the stations in Asia (Figure 2) for 170 crustal earthquakes and tomographically mapped the laterally varying Lg Q from 0.1 to 5.5Hz. We discretized frequency in very narrow bands at 45 central frequencies evenly distributed between 0.1 and 5.5Hz in logarithm. At each frequency, $f_i \in [f_1, f_2]$, f_1 and f_2 can be determined by $\log_{10}(f_i) - \log_{10}(f_1) = \log_{10}(f_2) - \log_{10}(f_i) = 0.02$ [Zhao *et al.*, 2010]. Setting the logarithm frequency difference to 0.02 makes neighboring frequency bands connected but barely overlapped. As the frequencies are evenly distributed in logarithm, the width of the frequency band increases with frequencies. Since we inverted 45 Lg Q tomographic models from 0.1 to 5.5Hz, we could directly use the $Q(f)$ at f falling in the corresponding narrow frequency band, without assuming the power law relationship between $Q(f)$ and f .

Using our 2D Q map we generated at each frequency band (e.g., Figure 1), we can predict Q (or $1/Q$) over any specific path covered by the Q map as:

$$\frac{1}{Q^t} = \frac{1}{\Delta} \sum \frac{\Delta_l}{Q_l} = \sum \frac{\Delta_l}{\Delta} \frac{1}{Q_l} = \sum a_l \frac{1}{Q_l} = \mathbf{a} \cdot \hat{\mathbf{m}} \quad (l = 1, 2, \dots, M) \quad (7)$$

where Q^t is the predicted value, $a_l = \frac{\Delta_l}{\Delta}$ is the weighted segment that the new path traverses in the l -th cell of the tomographic $1/Q$ model. Note that many a_l are zeros. The predicted $1/Q^t$ is a weighted linear summation of normal variables $1/Q_l$ and hence a normal variable itself.

An important practical usage of model covariance matrix of $1/Q$ tomography, $\mathbf{C}_m$, is that it enables a formal estimate of the uncertainties of the predicted $1/Q_i$ as the variance of normal variable $1/Q_i$ given by:

$$Var\left(\frac{1}{Q^t}\right) = Var[(\mathbf{a} \cdot \hat{\mathbf{m}})(\mathbf{a} \cdot \hat{\mathbf{m}})^T] = \mathbf{a}Var(\hat{\mathbf{m}}\hat{\mathbf{m}}^T)\mathbf{a}^T = \mathbf{a} \mathbf{C}_m \mathbf{a}^T \quad (8)$$

It is worth noting when $\mathbf{C}_m$ contains off-diagonal elements that are negative, Equation (16) predicts a smaller $Var(1/Q^t)$ than if $\mathbf{C}_m$ is simplified to be diagonal [Ballard *et al.*, 2016]. Note that the square-root of $Var(1/Q^t)$ gives $Std(1/Q^t)$, the standard deviation of the predicted $1/Q_i$ as a normal variable. Formal uncertainty estimates of predicted $1/Q^t$ can be expressed in terms of $n \times Std(1/Q^t)$, corresponding to confidence levels of 68% ($n = 1$), 95% ($n = 2$) and 99.7% ($n = 3$) in terms of the “68-95-99.7” rule in statistics.

Currently, we already have (1) the path Q predicted from the two-station based Q tomographic map and (2) the relative SRs of individual stations. However, there are some problems when they are applied directly to calibrate $m_b(\text{Lg})$ because: (1) the relative SRs may not be the true SRs but are “relative” values to the assumed unity-mean, which is a crucial assumption in our inversion for SRs. (2) The Q models only make use of Lg spectral ratios from station (or event) pairs that are aligned with sources (or stations). Unfortunately, the large amount of event-station spectral data in the study area have not yet been used. As a result, the current Q maps have a relatively limited spatial resolution, which means the long-wavelength features of the Q maps are more robust and reliable than the short-wavelength features. These limitations of our current Lg Q and SR models will bias $m_b(\text{Lg})$ estimates, particularly if the Lg wave data are mostly collected within 1000km.

We are developing an iterative method to jointly invert for Lg source spectra, high-resolution Lg Q tomographic models, actual station SRs. The two-station based Q tomographic models, hence the predicted path Q values (Equation 7), and the relative SR models will be used as *a priori* knowledge in this approach. We will first estimate the Lg source spectra from observed Lg spectral data using these *a priori* knowledge and analyze their errors in individual station estimates. By identifying the dominant sources of these errors, we attribute them to either the path-specific Q or the station SRs. The errors in the path Q and SRs will be corrected to obtain improved values of path Q and SRs, respectively. The improved event-station path Q will be combined with inter-station (and inter-event) Q as input data for new Lg Q tomographic models. The Lg source spectra will also be improved using the event-station path Q predicted from new Lg Q maps and the improved SRs. This procedure will be iterated until the source spectra, Q and SRs are no longer improved. A large amount of seismic data for Lg wave that we have collected motivate and facilitate the implementation of this method. Our method is illustrated in the flow-chart shown in Figure 6 and will be elaborated in the following steps.

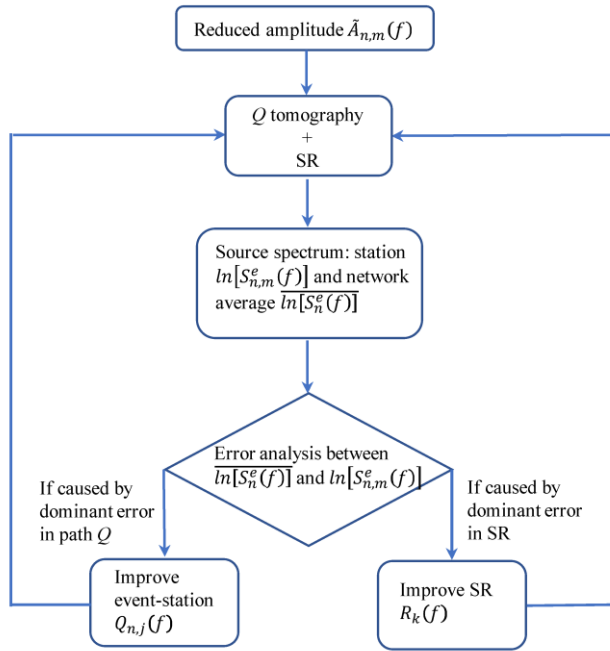


Figure 6. Flow chart illustrating the procedure of the iterative method of jointly inverting path Q , site responses and source spectra.

4.2 Estimation of Lg Source Spectrum and Error Analysis

When the Lg spectrum of an event is observed at a station, we estimate the source spectrum of this event by correcting path attenuation and site effects:

$$\ln[S_{n,m}^e(f)] = \ln[\tilde{A}_{n,m}(f)] + \frac{\pi f \Delta_{n,m}}{v Q_{n,m}^a(f)} - \ln[R_m^a(f)] \quad (9)$$

where $S_{n,m}^e(f)$ is the source spectrum estimate of event n using the observation at station m , $Q_{n,m}^a(f)$ is path Q value from event n to station m predicted from a Q tomographic map, and $R_m^a(f)$ is the SR estimate of station m . For parameters S , Q and R , the superscript “ e ” denotes estimated value and the superscript “ a ” means *a priori* value or the result from previous iterations. The corresponding symbols without superscript stand for parameters with true values. In the initial loop, $Q_{n,m}^a(f)$ is the path Q predicted from our two-station-based Q tomographic map and $R_m^a(f)$ is the relative SR for station m . The $\ln[\tilde{A}_{n,m}(f)] = \ln[A_{n,m}(f)] - \ln[G(\Delta_{n,m})]$ stands for the “reduced amplitude” of $A_{n,m}(f)$ corrected by GS term $G(\Delta_{n,m})$ in the logarithm domain.

When event n is recorded at M ($M > 1$) stations, we can thus take the average of $\ln[S_{n,m}^e(f)]$ over station m ($m = 1, 2, 3, \dots, M$) for event n :

$$\overline{\ln[S_n^e(f)]} = \overline{\ln[\tilde{A}_n(f)]} + \frac{\pi f}{v} \overline{\left[\frac{\Delta}{Q_n^a(f)} \right]} - \overline{\ln[R^a(f)]} \quad (10)$$

where the bar “ $\overline{}$ ” over each term means the average over M stations. Figure 7 shows the station $\ln[S_{n,m}^e(f)]$ and station average $\overline{\ln[S_n^e(f)]}$ of an example earthquake. The path-averaged Q is predicted over a large (typically in the order of 10^3 km) cumulative path length (i.e., $\left[\frac{\Delta}{Q_n^a(f)} \right] = \frac{1}{M} \sum_{m=1}^M \frac{\Delta_{n,m}}{Q_{n,m}^a(f)}$). This effect should be a good approximation of the true Q effect because the *a priori* Q model used in the prediction has reliable and robust long-wavelength (e.g., 10^3 km)

features. The SR correction of $\overline{\ln[R^a(f)]}$ is also done by averaging the individual SRs, hence a good approximation of the true SR. Therefore, the network average source spectrum is a good approximation of the true source spectrum, i.e., $\overline{\ln[S_n^e(f)]} \approx \ln[S_n(f)]$, where $S_n(f)$ stands for the true spectrum. In the above approximation, we also assume that the radiation pattern and/or occasional directivity effects caused by the azimuthal dependence of the source spectrum are sufficiently weak for the Lg wave such that they can be ignored.

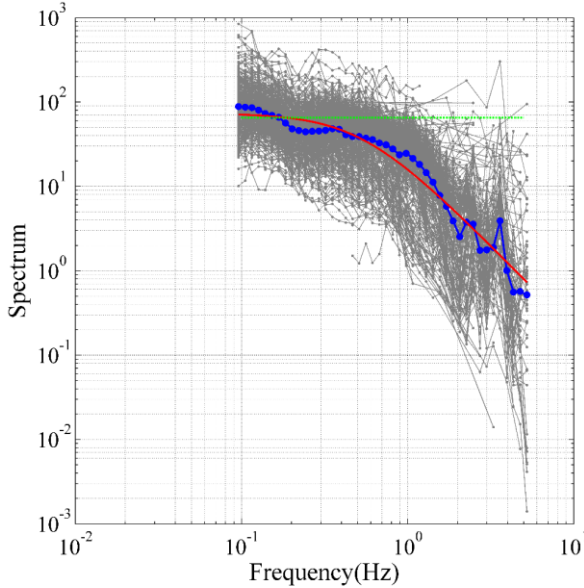


Figure 7. Lg source spectrum estimation of an example earthquake. The grey dotted lines are source spectra estimated at all individual stations. The blue dotted line is the station average spectrum. The red line is the theoretical source spectrum fitted by Brune's model. The green line indicates low-frequency spectral level estimated from GCMT M_0 .

When we gather N ($N > 1$) events in our study area, we can estimate the Lg source spectra of all N events using the above procedure. For any event n , we can define a differential source spectrum for the difference between the network-average estimate and individual station estimates as:

$$\delta\{\ln[S_{n,m}(f)]\} = \ln[S_{n,m}^e(f)] - \ln[S_n(f)] \approx \ln[S_{n,m}^e(f)] - \overline{\ln[S_n^e(f)]} \quad (11)$$

Generally, $\delta\{\ln[S_{n,m}(f)]\}$ does not vanish (Figure 7) because the estimate $\ln[S_{n,m}^e(f)]$ at individual stations contains a larger error as compared to the average $\overline{\ln[S_n^e(f)]}$. One cause of this error is that the $\frac{\Delta_{n,m}}{Q_{n,m}^a(f)}$ is predicted over path length $\Delta_{n,m}$. In the initial loop, $Q_{n,m}^a(f)$ is hence affected by the much shorter and less reliable wavelength feature of the two-station based Q map. Similarly, individual $\ln[R_m^a(f)]$ estimates are less reliable than the average $\overline{\ln[R^a(f)]}$. We denote the errors in $\frac{1}{Q_{n,m}^a(f)}$ and $\ln[R_m^a(f)]$ as:

$$\delta\left[\frac{1}{Q_{n,m}(f)}\right] = \frac{1}{Q_{n,m}^a(f)} - \frac{1}{Q_{n,m}(f)} \quad (12)$$

and

$$\delta\{\ln[R_m(f)]\} = \ln[R_m^a(f)] - \ln[R_m(f)] \quad (13)$$

respectively. Based on the above reasoning, we can assume that the errors $\delta\left[\frac{1}{Q_{n,m}(f)}\right]$ and $\delta\{\ln[R_m(f)]\}$ are the main error sources of $\delta\{\ln[S_{n,m}(f)]\}$. Spreading $\ln[S_{n,m}^e(f)]$ and

$\ln[S_n(f)]$ using *a priori* and true path Q and SR (Equation 9), respectively, and substituting into Equation (11), we have:

$$\delta\{\ln[S_{n,m}(f)]\} \approx \frac{\pi f \Delta_{n,m}}{v} \delta\left[\frac{1}{Q_{n,m}(f)}\right] - \delta\{\ln[R_m(f)]\} \quad (14)$$

4.3 Path Q Update If The *a priori* Path Q Contains Dominant Error

Since we assume that the radiation pattern and/or occasional source directivity effects are ignorable for Lg wave, Equation (14) demonstrates that the estimated error $\delta\{\ln[S_{n,m}(f)]\}$ is mainly related to the unknown errors $\delta\left[\frac{1}{Q_{n,m}(f)}\right]$ and $\delta\{\ln[R_m(f)]\}$. The reductions of the errors in path Q and SR are not straightforward because they are coupled in Equation (14). In order to de-couple the two types of errors, we first temporarily assume the effect of error in Q dominates the source error, during which we attempt to improve Q estimates. If we assume

$$\frac{\pi f \Delta_{n,m}}{v} \delta\left[\frac{1}{Q_{n,m}(f)}\right] \gg \delta\{\ln[R_m(f)]\} \approx 0 \quad (15)$$

the term $\delta\{\ln[R_m(f)]\}$ can be ignored in Equation (14):

$$\delta\{\ln[S_{n,m}(f)]\} \approx \frac{\pi f \Delta_{n,m}}{v} \delta\left[\frac{1}{Q_{n,m}(f)}\right] \quad (16)$$

Substituting Equation (9), (11) and (12) into Equation (16), we have:

$$\frac{\pi f \Delta_{n,m}}{v Q_{n,m}^I(f)} \approx \overline{\ln[S_n^e(f)]} - \ln[\tilde{A}_{n,m}(f)] + \ln[R_m^a(f)] \quad (17)$$

In an ideal case, a true path $Q_{n,m}(f)$ may be calculated using Equation (17). In practice, however, using known quantities in those equations can only yield an improved estimate of path Q . The superscript “ I ” used in Equation (17) specifically denotes that $Q_{n,m}^I(f)$ is an improved value from the *a priori* $Q_{n,m}^a(f)$, with a precision dependent on how good the temporal assumption of Equation (15) and (16) is. The *a priori* SR estimate $R_m^a(f)$ is considered acceptable for Equation (17).

Because the long-wavelength features of the *a priori* Q maps are robust and reliable, the predicted $Q_{n,m}^a(f)$ is not a “bad” approximation of true path Q . We do not expect that $Q_{n,m}^I(f)$ is of enormous difference from $Q_{n,m}^a(f)$. To detect if the new $Q_{n,m}^I(f)$ is a truly improved path Q or an erroneous estimate, we define the difference between $1/Q_{n,m}^I(f)$ and $1/Q_{n,m}^a(f)$ as:

$$q_{n,m}(f) = \frac{1}{Q_{n,m}^I(f)} - \frac{1}{Q_{n,m}^a(f)} \quad (18)$$

The relative change of $q_{n,m}(f)$, which is defined as $\epsilon = \left|q_{n,m}(f)/\left[\frac{1}{Q_{n,m}^a(f)}\right]\right|$, will be compared to a prescribed threshold c . If ϵ is less than the threshold c , we can consider $Q_{n,m}^I(f)$ a truly improved path Q . Tentatively, we set the threshold $c = 30\%$, and can adjust it in later loops.

Figure 8 shows the relative difference ϵ as a function of epicentral distance for an example event. If all ϵ are less than the threshold c , it means that the new $Q_{n,m}^I(f)$ from event n to all stations $m = 1, 2, 3, \dots, M$, are actually improved and acceptable to be used in re-estimating Lg source spectrum and inverting new Q tomography. However, as illustrated in Figure 8, some

$Q_{n,m}^I(f)$ significantly deviate from $Q_{n,m}^a(f)$. More importantly, the varying in ϵ is strongly dependent on the distance: the ϵ values at shorter epicentral distances are generally larger than those at longer distances. For the stations at long epicentral distances ($> \sim 1500\text{km}$), most ϵ values are less than 40%, while for those stations at short distances ($< \sim 1500\text{km}$), the ϵ values are so large that these $Q_{n,m}^I(f)$ are erroneous rather than truly improved. Therefore, we can only improve partial path Q estimates at this step, and we will seek the reason causing the erroneous $Q_{n,m}^I(f)$ at short distances in the next step.

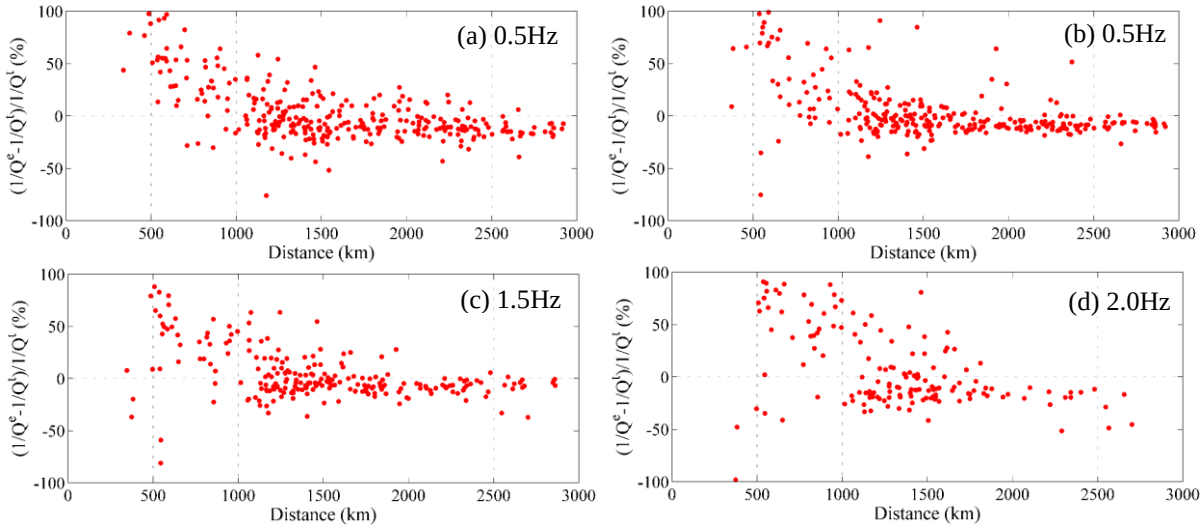


Figure 8. The relative difference ϵ between $1/Q_{n,m}^I(f)$ and $1/Q_{n,m}^a(f)$ as a function of epicentral distance for an example earthquake. The Q values are measured at 0.5-2.0Hz.

4.4 SR Update if The *a priori* SR Contains Dominant Error

The reduced amplitude of Lg wave is affected by path attenuation and the SR of the recording station. The effect of path attenuation overwhelms the effect of SR for long epicentral distances, while the path attenuation and SR have opposite effects on Lg amplitude for short distances. Because most erroneous $Q_{n,m}^I(f)$ occur in short epicentral distances, we suspect the assumption made by Equation (15) is incorrect for those Lg data recorded at near-source stations. Instead, the *a priori* SR estimates of those stations, $R_m^a(f)$, contain significant errors, such that for some or all events recorded by those stations, the opposite of assumption Equation (15) is true:

$$\delta\{\ln[R_m(f)]\} \gg \frac{\pi f \Delta_{n,m}}{v} \delta\left[\frac{1}{Q_{n,m}(f)}\right] \approx 0 \quad (19)$$

If this is the case, Equation (14) turns to:

$$\delta\{\ln[S_{n,m}(f)]\} \approx -\delta\{\ln[R_m(f)]\} \quad (20)$$

Substituting Equation (9), (11) and (13) into Equation (20), we have:

$$\ln[R_{n,m}^I(f)] \approx \frac{\pi f \Delta_{n,m}}{v Q_{n,m}^a(f)} - \overline{\ln[S_n^e(f)]} + \ln[\tilde{A}_{n,m}(f)] \quad (21)$$

Similar to our discussion for the derivation of Equation (17), the true SRs of these stations are only obtained in an ideal situation. In practice, using the known quantities in those equations can only yield an improved estimate of the true SRs, $R_{n,m}^I(f)$, by Equation (21). The subscript “ n ” in

$R_{n,m}^I(f)$ means that the SR of station m is calculated using event n . If station m records N' events satisfying the assumption of Equation (19) and (20), the final improved $R_m^I(f)$ is obtained by averaging the $R_{n,m}^I(f)$ over all N' event samples. The *a priori* path Q value $Q_{n,m}^a(f)$ is considered acceptable for Equation (21).

The above theoretical deduction states that some records can be classified into two groups: one with dominant error in path Q and the other with dominant error in SRs, during which the path Q and SRs will be updated respectively. The question we are facing now is how to efficiently identify a record that can be classified in any group. To do so, we will review the events recorded at every station m . As a matter of fact, Equation (17) can be applied to any Lg record. If the assumption made by Equation (15) and (16) is not satisfied, the derived $Q_{n,m}^I(f)$ is an erroneous Q estimate, but not a truly improved one. Similarly, Equation (21) can also be applied to any Lg record. We then sum Equation (17) and (21) together to obtain:

$$q_{n,m}(f) = \frac{1}{Q_{n,m}^I(f)} - \frac{1}{Q_{n,m}^a(f)} \approx \frac{V}{\pi f \Delta_{n,m}} \{ \ln[R_m^a(f)] - \ln[R_{n,m}^I(f)] \} \quad (22)$$

The above equation means that the error in SR, denoted as $\ln[R_m^a(f)] - \ln[R_{n,m}^I(f)]$, will be mapped to erroneous $Q_{n,m}^I(f)$. For a given station m , if it records multiple events $n = 1, 2, 3, \dots, N$, $q_{n,m}(f)$ is a reciprocal function of epicentral distance $\Delta_{n,m}$. Figure 9 shows $q_{n,m}(f)$ as a function of $\Delta_{n,m}$ at stations NM.DSM, QH.MEY, SC.BTA and NM.NIC, respectively. The red dots in each subplot in Figure 9 stand for the events with $\epsilon \leq 30\%$, while the blue and cyan dots stand for those with $\epsilon > 30\%$.

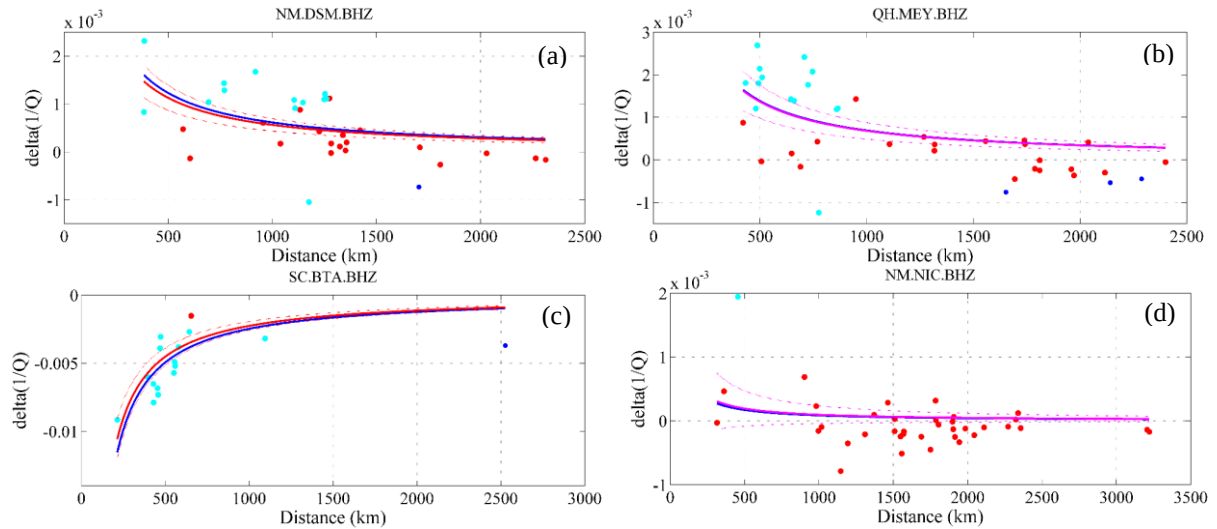


Figure 9. The distribution of $q_{n,m}(f)$ at $f = 1.0\text{Hz}$ with $\Delta_{n,m}$ for events observed at (a) NM.DSM, (b) QH.MEY, (c) SC.BTA and (d) NM.NIC. The red dots stand for samples with $\epsilon \leq 30\%$, and the cyan dots stand for samples with $\epsilon > 30\%$. The blue curve is predicted using a new SR calculated by Equation (21). The red curve (or the magenta curve) is the best-matched fitting of Equation (22) for the events. The dash curves indicate the range of best-fitting at 95% confidence level.

If the error in SR is large enough, $q_{n,m}(f)$ values at different distances form a clear curve that can be fitted by Equation (22). Therefore, Equation (22) provides an alternative approach to update the SR. At a given station m , when $q_{n,m}(f)$ samples are fitted by Equation (22), the SR value that

produces the minimal square-mean residue between theoretical and observed $q_{n,m}(f)$ is taken as the improved SR, $R_m^I(f)$. As shown in each subplot in Figure 9, the red or magenta curve shows the best-fitting for $q_{n,m}(f)$ using the fitted $R_m^I(f)$. The blue curve in Figure 9 shows the predicted $q_{n,m}(f)$ using the event-average $R_m^I(f)$ (Equation 18). In the examples shown in Figure 9a-c, because the SRs derived from the two methods are similar, we use their average as the final improved SR. The SR value for NM.DSM thus changes from $R_m^a(f) = 1.060$ to $R_m^I(f) = 0.632$, for QH.MEY changes from 1.431 to 0.783, and for SC.BTA changes from 0.244 to 1.954. Once we update the SR of one station, all events recorded by this station will be affected regardless of their distances to this station, but the effect on the events at long distances is insignificant.

There are also some stations on which the $q_{n,m}(f)$ values for all events show weak dependence on $\Delta_{n,m}$. Station NM.NIC is an example of such stations (Figure 9d). When the $q_{n,m}(f)$ values are fitted to Equation (22), the fitted curve is nearly flat with $\Delta_{n,m}$. This means that there is no major error in the *a priori* SR estimate, hence $\ln[R_m^I(f)] \approx \ln[R_m^a(f)]$, then all $q_{n,m}(f) \approx 0$. The *a priori* SR estimate of this station is acceptable for further process.

4.5 Identification of Records with Q and SR that Cannot Be Improved

The discussion in Section 4.3 and 4.4 focuses on de-coupling the errors in path Q and SRs. For the two extreme cases represented by Equation (15) and (19), we have identified some records that can be classified into two groups: one with dominant error in path Q (Group 1) and the other with dominant error in SRs (Group 2). The path Q and SRs can then be updated respectively. There should also exist a third group consisting of records whose source spectra, path Q and SRs have a more complicated relationship than those records in the first two groups. Possible causes of this phenomenon include (i) The errors in path Q and SR have comparable effects on the error in the source spectrum (Equation 14). If we try to update path Q using Equation (17), the trade-off of the unknown errors in path Q and SR result in a notable error in $Q_{n,m}^I(f)$, but the error contradicts the distance-dependence predicted by Equation (21). (ii) Some source spectra have no-vanishing radiation pattern or directivity. (iii) There are outlier data that cannot be modeled by Equation (9). Note that Cause (i) is fundamentally associated with data that carry no resolving power between Q and SR. With more iterations in later loops, the values of all Lg source spectra, path Q and SRs will be updated. Such updates may reduce the number of recordings in Group 3 by re-classifying them into the first two groups. We will also examine the behavior of the records in Group 3 to see whether we can identify any occurrences of Cause (ii) or (iii). Based on this examination, we will determine whether some $\delta \left[\frac{1}{Q_{n,m}(f)} \right]$ are still good and lead to acceptable $Q_{n,m}^I(f)$ estimates. Some updated $Q_{n,m}^I(f)$ will be deemed erroneous or uncertain, so we must set $Q_{n,m}^I(f)$ back to the *a priori* $Q_{n,m}^a(f)$. If we cannot successfully update SR by fitting Equation (22) or through Equation (21), we will keep using the *a priori* $R_m^a(f)$ as the estimate of SR.

4.6 Iterations of the Joint Inversion

The initial loop ends with the output path Q and SRs through the procedures discussed in Section 4.2 to 4.5, including the updated $Q^I(f)$ and $R^I(f)$ and the original $Q^a(f)$ and $R^a(f)$ if no updates are available. These event-station path Q values are combined with the original inter-station (and inter-event) Q values as new input data invert for updated Lg Q tomographic models at various frequencies. We then start a new loop using the path Q predicted from the new

tomographic Q models and updated SRs from Section 4.4 as *a priori* knowledge to update Lg source spectra.

Figure 10 shows the updating results for the SRs on the three stations shown in Figure 9a-c. Note that some events that have not been used in Figure 9 are now used in Figure 10. The SR value for NM.DSM is finally updated to $R_m^l(f) = 0.566$, for QH.MEY is updated to 0.545, and for SC.BTA is updated to 1.027. The updated SR values make more path Q values with errors less than 30% and the fitted $q_{n,m}(f)$ curve is nearly flat with $\Delta_{n,m}$ (Figure 10a and b). We can continue to improve SRs following the procedure described in Section 4.4 in further iterations (Figure 10c).

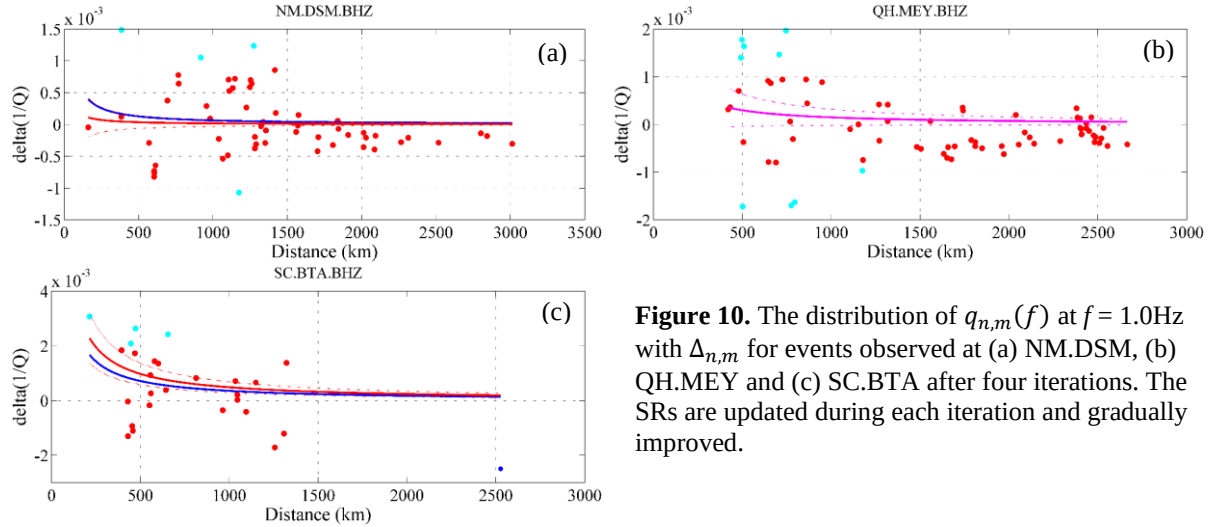


Figure 10. The distribution of $q_{n,m}(f)$ at $f = 1.0\text{Hz}$ with $\Delta_{n,m}$ for events observed at (a) NM.DSM, (b) QH.MEY and (c) SC.BTA after four iterations. The SRs are updated during each iteration and gradually improved.

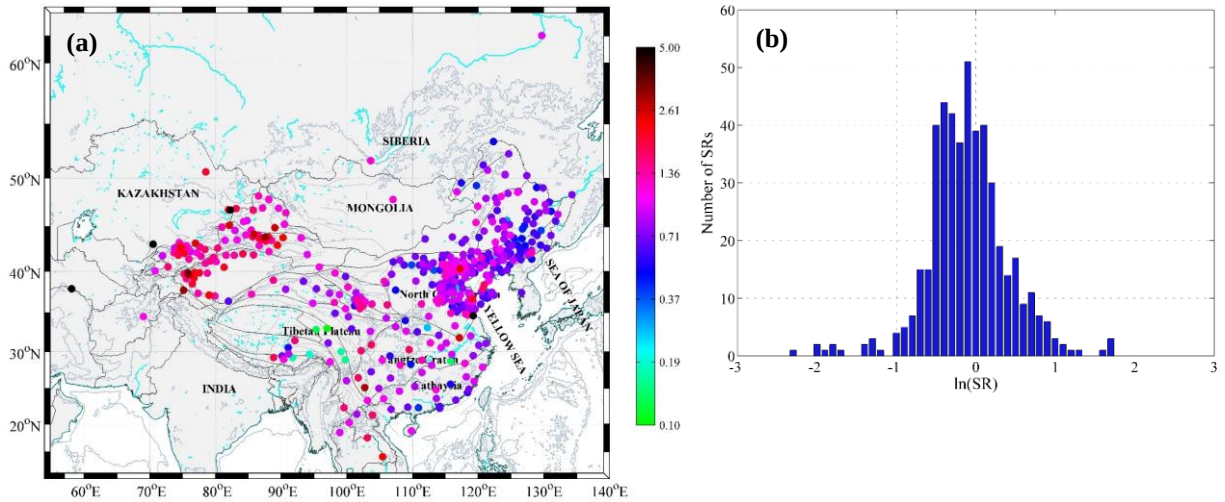


Figure 11. (a) Geographic distribution of SRs estimated for SR ratios measured using the RTS method at the central frequency of 1.0Hz. The colors stand for estimated SR values. (b) Histogram of SRs in logarithm domain.

Figure 11a and Figure 12a show the geographic distributions of relative SRs inverted by SR ratios and improved SRs after four iterations, respectively, at the central frequency of 1.0Hz. Because the SR is a physical quantity that characterizes the local structure beneath a receiver site, there is no regular pattern of SR variation with the tectonic environment that can be observed from either the relative SRs map or the improved SRs map, although a crude trend of SRs being higher than 1.0 within sedimentary areas or basins is observed. Note that there are more stations with SR

values in Figure 12a than in Figure 11a. This is because if one station is not involved in any RTS path, there is no SR ratio data to invert the SR for that station. However, we can set unity SR value to that station and use it as initial SR in our iterative procedure, during which this SR may be continuously improved to an appropriate value.

The SR values of the stations in Asia have a broad range, roughly extending from 0.1 to 5.0. This broad range is also observed in other regions in the world [e.g., Drouet *et al.*, 2008; Pasyanos *et al.*, 2009; Bao *et al.*, 2011]. Possible causes of this large SR range are: (1) a layered structure containing abnormally low and high velocities, (2) 3D crustal structure near a station, and (3) minor instrument miscalibrations. The distribution of relative SRs in logarithm (Figure 11b) roughly follows a Gaussian distribution with a mean centered at zero. This is caused by our zero-mean assumption for log-SRs in the inversion procedure. The distribution has a broad shape with most $\ln(\text{SR})$ values concentrating within $(-1, 1)$, corresponding to SR values within $(0.37, 2.72)$. After four times of iteration, the distribution of improved $\ln(\text{SR})$ (Figure 12b) turns to focus on zero with about 40% of total stations having unity SRs. In reality, the stations with large amplification or de-amplification impact for seismic waves should be much rarer than the normal stations.

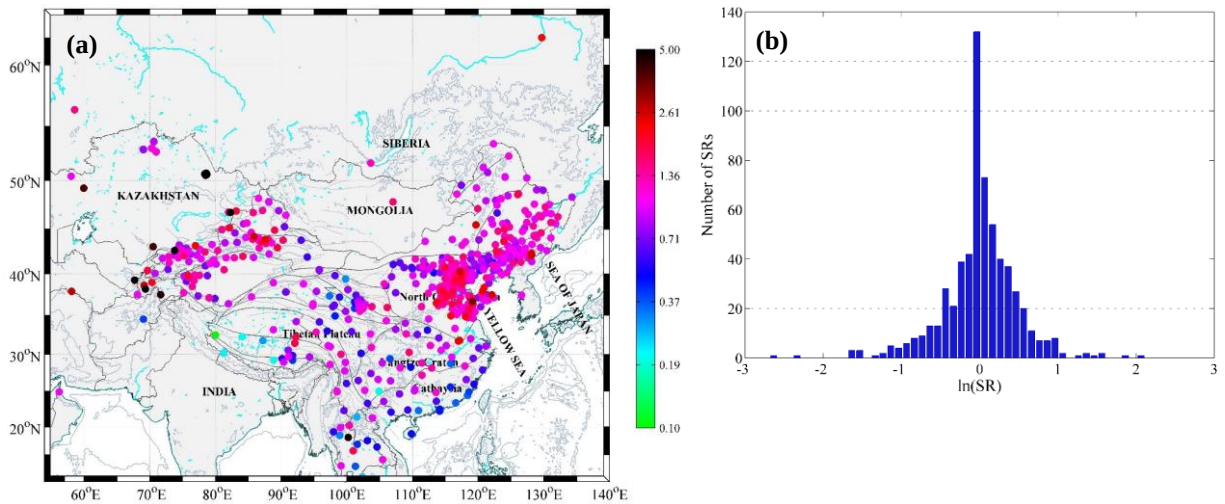


Figure 12. (a) Geographic distribution of SRs improved after four iterations at the central frequency of 1.0Hz. The colors stand for estimated SR values. (b) Histogram of SRs in logarithm domain.

Figure 13 shows Lg Q tomographic map at the central frequency of 1.0Hz obtained after four iterations. Comparing to the 1.0Hz Q map inverted by only two-station based Q measurements (Figure 1), we do not find significant changes in major features of lateral varying crustal attenuation. Some changes over small tectonic blocks are caused by denser ray-paths coverage in our new model. As a result, the model error is also reduced from $\sim 4\%$ (Figure 1c) to $\sim 1\%$ (Figure 13c) across China on average. The most notable change between the two models is that the model resolution in the northern part of China increases significantly because we use many regional earthquakes in this area. The resolvable scale, represented by Backus-Gilbert spread function, in the northern part of China is reduced from $\sim 200 - \sim 300\text{km}$ (Figure 1b) to $\sim 100\text{km}$ (Figure 13b).

Currently, the improved Lg Q and SR models obtained after four times iteration will be used for the performance of $m_b(\text{Lg})$ calibration in Section 5. We will continue the joint inversion iteration until either the differential source spectra $\delta\{\ln[S_{n,m}(f)]\}$, or $Q_{n,m}^I(f)$ and $R_m^I(f)$ stop

improving. The final output of this joint inversion procedure also includes Lg source spectra estimates $\ln[S_n^e(f)]$ for all used events. Lg source spectra of earthquakes and explosions will be used to estimate Mw, fit earthquake and explosion source model, respectively, and estimate the yield of explosions in future technical progress periods.

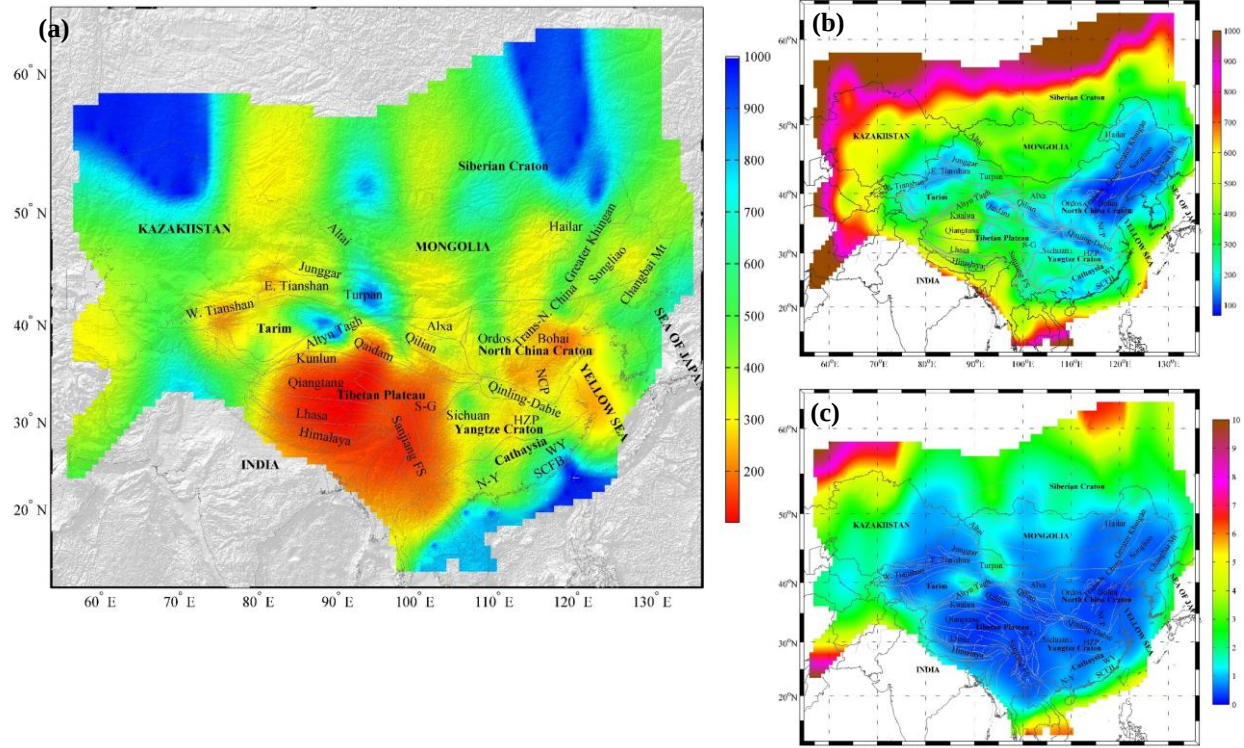


Figure 13. (a) Updated Lg Q tomographic map at a central frequency of 1.0Hz after four iterations. (b) The resolution of the model represented by Backus-Gilbert spread function in kilometers calculated from the model resolution matrix. (c) The relative uncertainty of the model represented by $\delta Q/Q$ in percentage, where δQ is one standard deviation of Q calculated from the diagonal elements of the model covariance matrix.

5 CALIBRATION OF $m_b(\text{Lg})$ AND MAGNITUDE SCALING RELATIONSHIPS

5.1 Estimation of $A(10\text{km})$

The method described in Section 3 is applied to seismic waveform data of crustal earthquakes collected in Asia as well as of the six DPRK nuclear explosions (Table 1). After correcting path attenuation and site effect, we first estimate the hypothetical amplitude of the Lg wave at 10km from the source, $A(10\text{km})$. Using the earthquake 2009.12.20_21.31.123 (Table 1) as an example, we illustrate the procedure in Figure 14 and 15. Figure 14a shows the observed Lg amplitude at all used stations from ~200km to ~2000km to the source (Figure 14e). The Lg amplitude is measured as the 3rd peak of Lg wave excursions and is in displacement in unit μm corrected with the WWSSN-SP amplitude response. A seismogram is rejected for further process if the SNR of the 3rd peak to the maximum peak of pre-event noise is less than 3.0. An event is rejected for further process if it is recorded by less than five stations. The observed 3rd Lg amplitudes in the logarithm domain decrease linearly with the increasing epicentral distances. We first correct the SR for the Lg 3rd peak amplitude observed at each station, and the resulting amplitudes are plotted in Figure

14b as a function of distances. Some near-field Lg amplitudes deviate from the data population (Figure 14a). After SRs correction, the spreading of Lg amplitudes distribution is reduced.

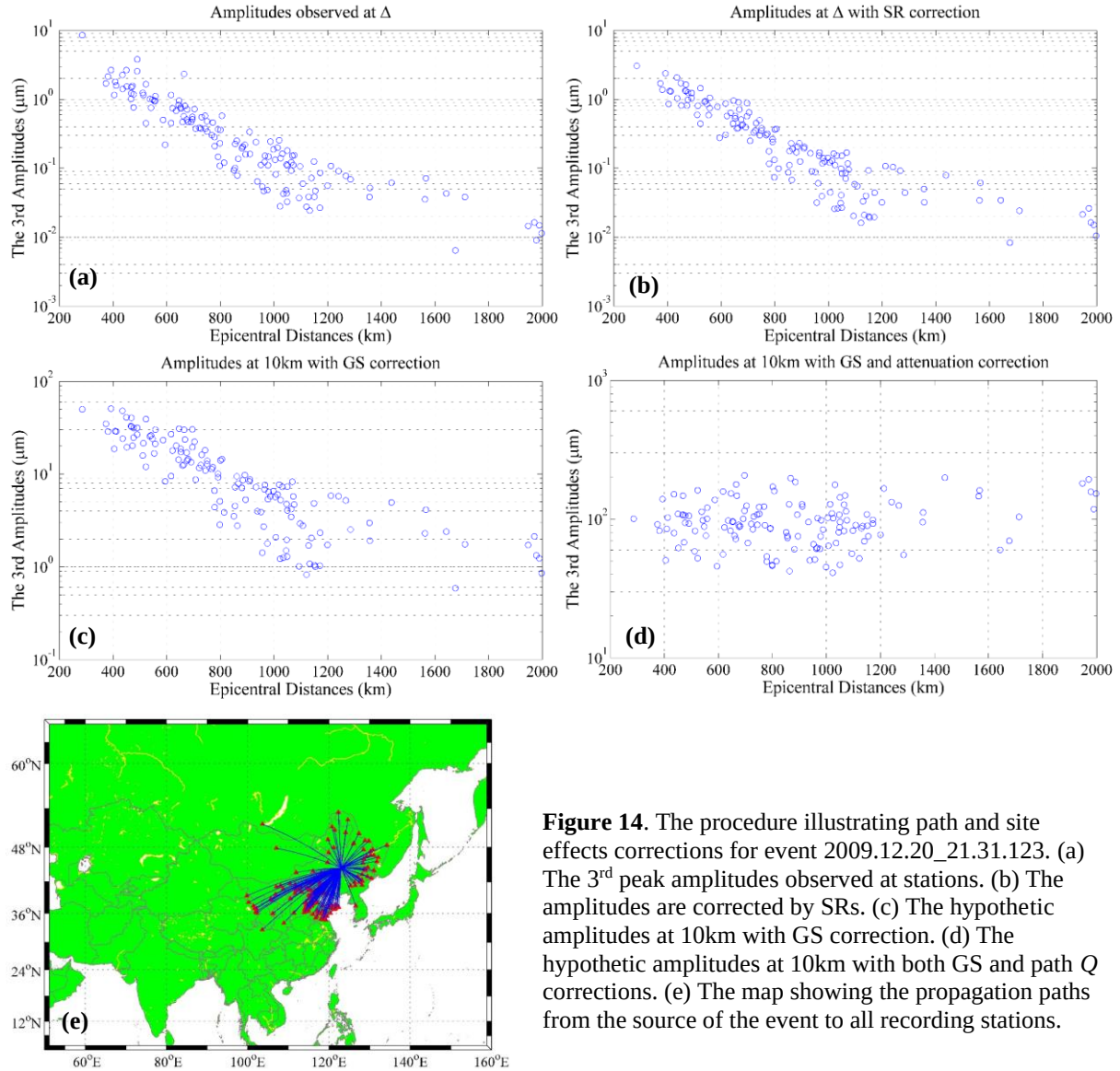


Figure 14. The procedure illustrating path and site effects corrections for event 2009.12.20_21.31.123. (a) The 3rd peak amplitudes observed at stations. (b) The amplitudes are corrected by SRs. (c) The hypothetic amplitudes at 10km with GS correction. (d) The hypothetic amplitudes at 10km with both GS and path Q corrections. (e) The map showing the propagation paths from the source of the event to all recording stations.

The hypothetical Lg amplitudes $A(10km)$ are calculated using Equation (1) by correcting GS term (Figure 14c) and attenuation over the path (Figure 14d). The resulting $A(10km)$ turn to be independent on the distance, which proves that the γ or Q and SRs used to correct Lg amplitudes are appropriate. In this study, we do not use a uniform γ or Q in Equation (1) to calculate $A(10km)$, instead, we calculate individual Q value from the event source to each station using our Lg Q tomographic models and apply it to each station. The Lg amplitudes data used for $m_b(Lg)$ are in the frequency range between 0.71 to 1.67Hz [Patton and Schlittenhardt, 2005]. As we mentioned in Section 4.1, we generate Lg Q tomographic models at 45 very narrow frequency bands from 0.1 to 5.5Hz, so that we do not assume the power law relationship to calculate $Q(f)$. Instead, if the f_{3rd} measured for one Lg amplitude falls in any one of the 45 frequency bands, we use the Lg Q model centered at that frequency band to predict path Q. Finally, the average

$A(10\text{km})$ over all stations is used as the hypothetical Lg amplitude at 10km for event 2009.12.20_21.31.123 in further process.

The same procedure is applied to Lg amplitudes measured using RMS method. Figure 15 illustrates the procedure by plotting the result in each step for event 2009.12.20_21.31.123. Besides the measurement methods for Lg amplitudes and frequencies, the other major differences between the 3rd peak and RMS methods are: (1) we use both pre-event SNR and pre-phase (pre-Lg) SNR to screen Lg amplitude data in RMS method. An Lg amplitude is rejected if its pre-event SNR fell below 3.0 or its pre-phase SNR fell below 1.2. (2) The RMS amplitude of Lg signal is estimated as $A_{rms} = \sqrt{S^2 - N_c^2}$, where S is the measured RMS Lg amplitudes and N_c is the measured RMS pre-phase amplitudes [Patton and Schlittenhardt, 2005]. (3) Due to the different screening criteria from the 3rd peak method, the station records that can be used for the RMS method extend to 3000km. The selected data are also of slight difference at other epicentral distances.

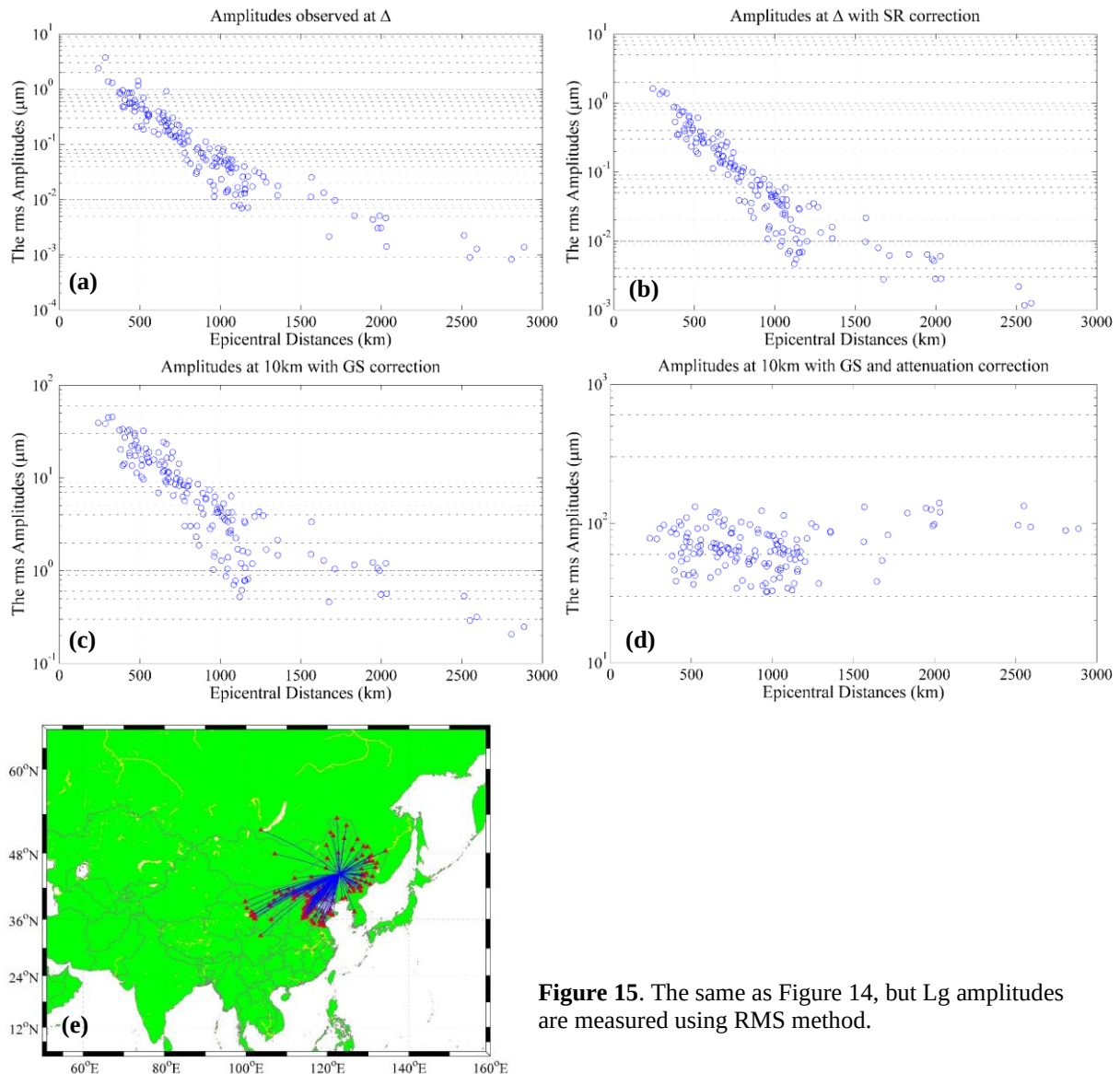


Figure 15. The same as Figure 14, but Lg amplitudes are measured using RMS method.

5.2 Calibration of Constant C

According to the definition of $m_b(\text{Lg})$ (Equation 2), if one or several $m_b(P) = 5.0$ events are found, the constant C in Equation (2) is simply equal to $A(10\text{km})$ for those $m_b(P) = 5.0$ events. The “bias” term in Equation (3) can then be determined by comparing $A(10\text{km})$ of these events to $110\mu\text{m}$. This method is usually impractical and suffers from large errors because (1) we may not be able to gather adequate $m_b(P) = 5.0$ earthquakes in our study area, particularly within the aseismic Korean Peninsula, and (2) the one-tenth unit error in the published magnitudes could correspond to a 33% error in amplitudes. In this study, we perform a linear regression to establish a relationship between $\log_{10}[A(10\text{km})]$ and $m_b(P)$ for all earthquakes. The constant C is then determined as the value of $A(10\text{km})$ corresponding to $m_b(P) = 5.0$ on the regression line.

We first use the 211 earthquake data (excluding the six DPNK explosions) to fit $\log_{10}[A(10\text{km})]$ and $m_b(P)$ (Figure 16a). For every earthquake, $A(10\text{km})$ is estimated using the 3rd peak method, and $m_b(P)$ is taken from ISC. The linear fitting line in Figure 16a is $\log_{10}[A(10\text{km})] = 1.0771m_b(P) - 2.9332$, resulting $C = 283\mu\text{m}$. The earthquakes used in this regression are distributed across Asia, most of which occurred in China (Figure 4). We do not purposely select earthquakes that only occurred in Northeast China to perform the regression because there are almost no crustal earthquakes larger than 5.0 occurred in Northeast China and Korean Peninsula. In order to confirm the regression result, we perform 100,000 times bootstrapping for the earthquake data. The randomly selected data using the bootstrapping method is linearly fitted and the process is repeated 100,000 times. The distribution of C values obtained from 100,000 bootstrapping re-samplings is shown by the histogram in Figure 16b. On average, the fitting result is $\log_{10}[A(10\text{km})] = 1.0760m_b(P) - 2.9285$, which is almost the same as that using all earthquake data. The 95% bootstrapped confidence interval of the mean $C = 283\mu\text{m}$ is [243, 329], meaning we can be 95% confident that the population mean falls with the range of [243, 329]. The calibration for Asia biases the constant C from $110\mu\text{m}$, leading to the “bias” term in Equation (3) equal to 0.4104. The regression results are summarized in Table 2.

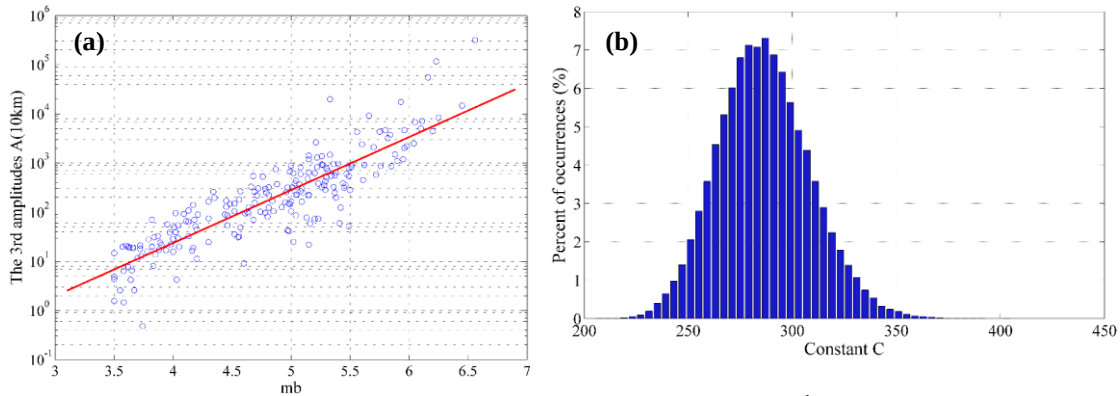


Figure 16. (a) The average $A(10\text{km})$ of earthquake data estimated using the 3rd peak method versus $m_b(P)$. The red line is the linear fitting for all data. (b) Histogram of constant C values derived by 100,000 bootstrapping simulations.

We next use the six DPNK explosions to fit $\log_{10}[A(10\text{km})]$, which is estimated using the 3rd peak method, versus $m_b(P)$ (Figure 17a). The linear fitting line is $\log_{10}[A(10\text{km})] = 0.9806m_b(P) - 3.2511$, resulting $C = 45\mu\text{m}$ (Table 2). A fact worth noting is that there are only six explosion samples used here. If we want to perform bootstrapping simulations to verify the

stability of the linear regression for DPNK explosions, we can only repeat bootstrapping $6^6 = 46,656$ times at maximum to avoid getting the same bootstrapping samples. In spite of this limit, we perform 40,000 times bootstrapping for the explosion data and obtain a mean $C = 51\mu\text{m}$ with 95% bootstrapped confidence interval of the mean in $[30, 80]$ (Table 2).

Table 2: Summary of Regression Results using Various Data and Methods

Data	Method	Fitting coefficients	Constant C	Mean C bootstrap	95% confidence interval	“bias”
Asia Eqs	3 rd peak	1.0771, -2.9332	283	283	243 – 329	0.4104
Explosions	3 rd peak	0.9806, -3.2511	45	51	30 – 80	-0.3882
Eqs+Exps	3 rd peak	1.0657, -2.9006	268	267	229 – 312	0.3867
Asia Eqs	RMS	1.0784, -3.0658	212	212	184 – 244	
Explosions	RMS	0.9605, -3.2887	33	37	24 – 55	
Eqs+Exps	RMS	1.0628, -3.0162	199	198	171 – 230	

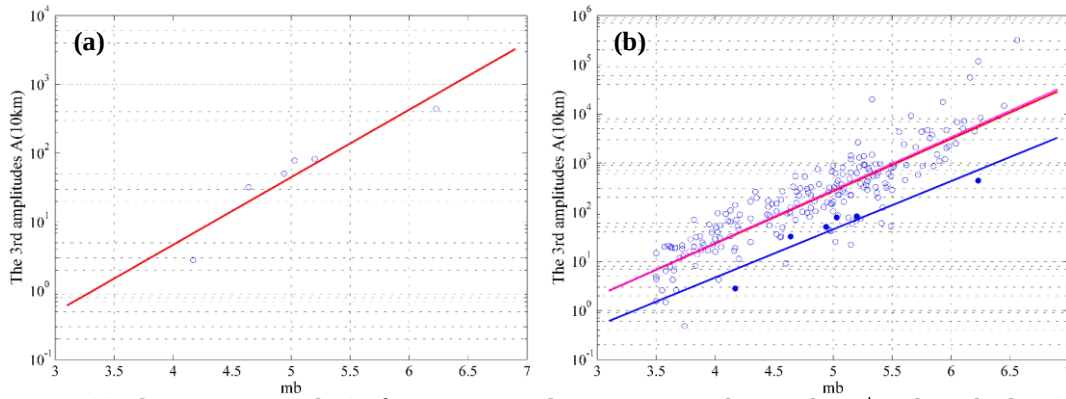


Figure 17. (a) The average $A(10\text{km})$ of six DPRK explosions estimated using the 3rd peak method versus $m_b(P)$. The red line is the linear fitting for all data. (b) The $A(10\text{km})$ of both earthquakes (open circle) and explosions (solid circle) and the linear fitting results.

The constant C for DPNK explosions is much different from that for Asian earthquakes. Is this difference purely caused by too few explosion samples comparing the number of earthquakes (total 211 earthquakes are used), or is there a systematic bias? In the linear regression, the fitted slopes for explosions and earthquakes are similar (0.9806 vs 1.0771, Table 2), but the Y-intercept for explosions is quite lower than for earthquakes (-3.2511 vs -2.9332, Table 2). Finally, we perform linear regression using the combined earthquake and explosion data. The linear fitting line (Figure 17b) is $\log_{10}[A(10\text{km})] = 1.0657m_b(P) - 2.9006$, resulting $C = 268\mu\text{m}$. In Figure 17b, all the explosion data (solid blue circles) are located at the lower margin of the samples but are still buried in the earthquake population. The fitting linear using combined data is almost the same as that using only earthquake data, but the explosion data slightly lower C value from $283\mu\text{m}$ to $268\mu\text{m}$. The 95% bootstrapped confidence interval for combined earthquake and explosion data is $[229, 312]$ (Table 2). This confidence interval is slightly left-shifted but most of it is overlapped with the confidence interval of earthquake data. Calculating $m_b(\text{Lg})$ using $C = 283\mu\text{m}$ and $C = 268\mu\text{m}$ causes only 0.025 magnitude unit difference for earthquakes, but the difference will increase to 0.74 unit if $m_b(\text{Lg})$ is calculated using $C = 51\mu\text{m}$ and $C = 268\mu\text{m}$ respectively for explosions.

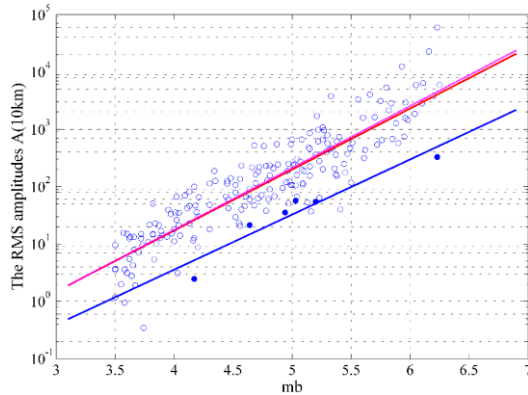


Figure 18. The average $A(10\text{km})$ of both earthquakes (open circle) and explosions (solid circle) estimated using RMS method versus $mb(P)$. The magenta line is the linear fitting for earthquake data, the blue line is the linear fitting for explosion data, and the red line is the linear fitting for both types of data.

The same calibration procedure is also applied to the $A(10\text{km})$ that are measured using RMS method for both earthquakes and explosions. The results are shown in Table 2 and Figure 18. It is not surprising that the constant C derived by RMS method is systematically lower than that by the 3rd peak method. The constant C for DPNK explosions is also much different from that for Asian earthquakes due to the large deviation of the Y-intercept for explosions from that for earthquakes (Figure 18).

5.3 Estimation of $m_b(\text{Lg})$

For each earthquake, the amplitudes $A(10\text{km})$ measured at all recording stations using the 3rd peak and RMS method, respectively, are used to estimate $m_b(\text{Lg})$. A 25% trimmed mean is employed to determine a network-average magnitude for an earthquake. In the 25% trimmed mean method, estimated magnitudes are sorted in an ascending order, and the top 25% and the bottom 25% of values are discarded. The final magnitude for the earthquake is calculated as the mean of the remaining station magnitudes with equal weight. The network-average $m_b(\text{Lg})$ for all earthquakes with sufficient $A(10\text{km})$ measurements are listed in Table 3 and 4 along with other information. In Table 3 the $A(10\text{km})$ is measured using the 3rd peak method, while the $A(10\text{km})$ is measured using RMS method in Table 4. Because of the different data screening used in the 3rd peak and RMS methods, some earthquakes may have only one type of $m_b(\text{Lg})$, either from the 3rd peak or from RMS method. The network-average instantaneous frequency, f_{3rd} and f_{rms} , path Q , SR and $A(10\text{km})$ for one earthquake are also listed in Table 3 and 4.

Table 3: Earthquakes $m_b(\text{Lg})$ Estimated using the 3rd Peak Method

Event ID	$mb(P)$	M_s	M_L	M_w	$mb(\text{Lg})$ $C=110$	$mb(\text{Lg})$ $C=268$	f_{3rd}	Q	SR	$A(10\text{km})$
2009.01.26_21.30.342	5.07	5.04	4.85	5.40	5.53	5.15	1.015	510.2	1.085E+00	3.694E+02
2009.02.20_03.48.539	5.38	5.01	5.48	5.45	5.24	4.85	1.180	411.3	1.216E+00	1.980E+02
2009.06.13_17.17.382	5.62	5.11	5.57	5.37	5.94	5.56	1.049	387.2	8.427E-01	9.138E+02
2009.06.29_18.03.515	5.15	4.96	4.75	5.25	6.02	5.63	1.054	333.6	1.072E+00	1.190E+03
2009.07.09_11.19.142	5.26	5.63	5.42	5.68	6.10	5.71	1.036	249.6	9.110E-01	1.385E+03
2009.07.13_18.04.580	5.85	6.44	6.06	6.26	5.90	5.51	1.008	422.8	8.960E-01	8.650E+02
2009.07.16_10.48.124	5.23	5.07	5.00	5.43	4.83	4.45	1.130	513.6	8.905E-01	7.336E+01
2009.07.24_03.11.566	5.61	5.48	5.40	5.50	5.63	5.24	1.070	236.3	3.216E+00	4.526E+02
2009.08.28_01.52.062	6.04	6.24	5.93	6.23	6.36	5.98	1.094	342.0	1.055E+00	2.506E+03
2009.08.28_02.14.571	5.45	5.45	4.85	4.20	5.45	5.07	1.236	332.6	9.580E-01	3.160E+02
2009.08.30_17.15.497	5.01	4.87	5.13	5.40	5.48	5.09	1.193	346.3	1.039E+00	3.217E+02
2009.08.31_10.15.288	5.76	5.59	5.35	5.83	5.90	5.51	1.025	324.8	1.083E+00	8.768E+02

2009.09.18_07.02.130	4.79	4.60	4.75	-	5.36	4.97	1.255	329.6	8.056E-01	2.492E+02
2009.09.21_08.53.029	5.66	6.11	6.55	6.13	6.89	6.51	1.083	193.2	4.757E+00	9.200E+03
2009.10.03_17.36.032	5.72	5.83	5.92	5.96	5.73	5.34	1.006	410.8	9.013E-01	5.833E+02
2009.11.04_21.56.106	5.36	4.70	5.27	5.20	5.47	5.09	1.161	346.5	1.057E+00	3.260E+02
2009.11.05_09.32.535	5.34	5.33	5.58	5.60	5.72	5.33	1.052	422.5	8.733E-01	5.469E+02
2009.11.05_11.34.181	4.97	4.71	5.40	5.15	5.48	5.09	1.132	439.0	8.743E-01	3.202E+02
2009.11.07_20.08.456	5.46	5.01	5.27	5.26	5.55	5.16	1.059	199.9	1.411E+00	3.556E+02
2009.11.27_16.04.049	4.98	4.37	4.55	4.77	5.14	4.76	1.159	335.8	9.921E-01	1.520E+02
2009.12.13_14.41.548	5.00	4.44	5.13	4.75	5.04	4.66	1.105	201.3	6.833E-01	1.044E+02
2009.12.13_16.03.585	5.15	4.11	5.10	5.10	5.29	4.90	1.266	470.9	1.074E+00	2.182E+02
2009.12.20_21.31.123	4.61	3.88	5.00	-	4.93	4.55	1.385	413.3	1.261E+00	9.508E+01
2009.12.21_05.15.070	5.09	4.54	4.95	4.75	5.17	4.78	1.142	349.7	1.030E+00	1.639E+02
2010.01.02_02.15.100	5.26	5.04	5.15	5.40	5.47	5.08	1.136	346.8	1.069E+00	3.210E+02
2010.01.19_06.09.237	4.64	4.06	4.80	4.90	4.92	4.54	1.269	527.5	8.597E-01	9.366E+01
2010.01.24_02.36.116	4.81	4.27	4.40	-	5.31	4.92	1.270	347.2	1.061E+00	2.248E+02
2010.02.12_02.42.368	4.74	4.45	5.06	4.67	4.97	4.58	1.152	486.4	9.042E-01	1.024E+02
2010.02.22_05.21.018	5.16	4.88	5.67	5.17	4.70	4.32	1.164	596.6	8.265E-01	5.869E+01
2010.02.25_04.56.516	4.84	4.53	5.33	5.05	5.17	4.79	1.176	269.5	8.300E-01	1.702E+02
2010.02.26_01.07.554	5.41	4.94	5.72	5.43	4.74	4.36	1.177	555.0	9.603E-01	5.972E+01
2010.03.08_09.26.195	4.11	3.83	4.95	4.60	4.74	4.36	1.261	554.4	9.546E-01	6.635E+01
2010.03.10_14.32.199	4.56	4.56	-	5.10	4.46	4.07	1.129	357.4	1.090E+00	3.220E+01
2010.03.24_02.06.096	5.38	5.47	4.50	5.60	5.77	5.38	1.010	167.0	8.503E-01	6.333E+02
2010.03.24_02.44.477	5.30	5.08	5.10	5.50	5.68	5.29	0.980	158.1	8.398E-01	5.057E+02
2010.04.09_22.23.001	3.74	-	-	-	2.65	2.26	1.325	384.8	2.144E+02	4.844E-01
2010.04.11_04.57.276	5.04	4.67	5.26	5.23	4.88	4.50	1.128	551.1	7.872E-01	8.642E+01
2010.04.13_20.49.065	4.52	4.35	4.88	4.63	4.51	4.13	1.203	595.7	9.411E-01	3.558E+01
2010.04.13_23.49.407	6.10	6.90	5.85	6.78	6.64	6.25	0.950	207.7	1.016E+00	5.068E+03
2010.04.14_01.25.178	5.47	6.01	5.00	6.10	5.73	5.34	0.943	189.7	8.860E-01	6.048E+02
2010.04.17_00.58.571	4.78	4.72	4.40	5.30	5.43	5.04	1.146	163.7	7.064E-01	3.009E+02
2010.04.18_20.28.479	5.50	5.28	5.00	5.50	5.42	5.04	1.128	396.3	1.119E+00	2.837E+02
2010.05.25_06.11.531	5.08	4.53	4.75	5.00	5.39	5.01	1.204	352.6	9.913E-01	2.693E+02
2010.05.29_02.29.495	5.37	5.63	5.10	5.73	5.70	5.31	1.037	212.6	9.715E-01	5.616E+02
2010.06.03_05.35.420	5.04	5.14	4.65	5.50	5.29	4.90	1.083	205.8	8.577E-01	2.249E+02
2010.06.10_06.38.022	5.37	4.74	4.95	5.15	5.35	4.97	1.228	326.8	1.212E+00	2.472E+02
2010.06.15_00.31.162	4.95	4.93	5.07	5.14	5.16	4.78	1.087	488.6	8.346E-01	1.611E+02
2010.06.18_01.08.432	4.55	3.97	4.80	4.70	4.48	4.09	1.256	546.1	9.241E-01	3.108E+01
2010.06.22_08.46.010	4.30	3.78	4.30	-	5.17	4.79	1.319	401.5	1.096E+00	1.647E+02
2010.06.27_20.33.250	4.68	4.13	5.13	4.63	4.81	4.42	1.208	495.2	9.153E-01	7.018E+01
2010.09.07_15.41.393	5.51	5.09	4.90	5.30	5.88	5.50	1.164	321.4	1.111E+00	8.307E+02
2010.09.27_15.49.219	4.97	4.68	5.60	5.10	4.59	4.21	1.106	500.4	9.596E-01	4.277E+01
2011.01.01_01.56.047	5.00	4.49	4.55	4.90	5.18	4.79	1.247	333.5	1.112E+00	1.639E+02
2011.02.01_07.11.207	4.66	4.33	5.35	4.40	5.47	5.08	1.080	176.2	7.976E-01	3.316E+02
2011.02.01_08.16.283	4.81	4.98	5.28	5.17	5.04	4.66	1.174	496.4	8.706E-01	1.236E+02
2011.02.04_02.39.148	4.64	4.15	4.40	-	5.09	4.70	1.266	415.2	1.035E+00	1.259E+02
2011.02.10_05.35.128	5.22	5.18	5.37	5.40	5.89	5.50	1.043	448.7	1.089E+00	8.335E+02
2011.02.23_17.10.375	4.57	4.43	4.80	5.00	5.38	4.99	1.201	426.7	1.069E+00	2.658E+02
2011.03.10_04.58.124	5.30	5.27	5.60	5.30	5.82	5.44	1.036	182.2	7.366E-01	7.801E+02
2011.03.17_15.34.304	4.78	4.19	4.40	4.90	4.94	4.56	1.275	366.4	2.210E+00	9.774E+01
2011.03.24_13.55.123	5.93	7.11	6.58	6.80	7.18	6.80	0.953	251.3	7.574E-01	1.750E+04
2011.03.24_15.54.334	5.21	5.30	5.70	5.43	6.37	5.99	1.029	230.1	8.036E-01	2.636E+03
2011.03.25_00.22.387	4.76	4.47	5.30	5.10	5.70	5.31	1.147	228.3	8.576E-01	5.305E+02
2011.04.04_11.31.390	5.42	5.06	5.57	5.35	5.05	4.67	1.260	431.6	1.102E+00	1.242E+02

2011.04.10_09.02.424	4.88	5.03	4.90	5.40	5.53	5.15	1.139	278.5	9.407E-01	3.733E+02
2011.05.22_01.34.133	4.57	4.70	4.86	4.90	4.62	4.24	1.152	517.4	8.911E-01	4.899E+01
2011.06.08_01.53.234	5.09	4.70	5.20	5.10	5.44	5.05	1.342	438.7	8.695E-01	3.035E+02
2011.06.20_10.16.496	5.14	4.55	5.17	5.10	5.63	5.24	1.117	198.3	7.491E-01	4.799E+02
2011.06.26_07.48.154	5.10	4.70	4.80	5.30	5.37	4.98	1.045	195.1	8.776E-01	2.500E+02
2011.07.12_11.17.067	4.80	4.20	5.10	4.77	4.86	4.48	1.264	551.3	8.944E-01	8.165E+01
2011.07.16_18.38.486	5.15	5.00	4.75	5.27	5.76	5.37	1.058	436.3	1.104E+00	6.460E+02
2011.07.19_19.35.408	5.98	6.16	5.80	6.12	6.32	5.94	1.180	346.1	1.068E+00	2.208E+03
2011.07.22_14.52.557	4.52	3.92	4.53	4.50	4.98	4.60	1.245	426.1	1.197E+00	1.043E+02
2011.07.24_19.05.281	4.71	4.97	4.83	-	5.29	4.90	1.353	436.9	9.857E-01	2.192E+02
2011.08.01_19.40.520	4.98	4.73	3.90	5.30	4.57	4.18	1.017	261.5	1.200E+00	4.153E+01
2011.08.09_11.50.173	4.68	4.55	5.15	4.85	5.68	5.30	1.075	198.5	8.536E-01	5.436E+02
2011.08.11_10.06.290	5.08	5.34	5.00	5.53	5.90	5.51	1.179	348.2	1.057E+00	8.211E+02
2011.08.27_10.29.440	5.26	5.26	5.47	5.40	5.93	5.54	1.140	401.1	1.145E+00	9.364E+02
2011.09.10_15.20.312	4.17	4.05	5.00	-	5.11	4.72	1.338	353.6	1.122E+00	1.407E+02
2011.09.15_15.26.589	5.20	4.95	5.15	5.30	5.76	5.37	1.376	385.1	9.786E-01	6.244E+02
2011.09.18_12.40.457	6.16	6.59	6.23	6.85	7.75	7.37	1.093	199.1	1.791E+00	5.521E+04
2011.10.14_06.10.102	5.56	5.86	5.80	6.04	6.60	6.21	0.974	453.1	1.099E+00	4.302E+03
2011.10.16_13.44.461	5.03	4.29	4.60	4.80	5.38	4.99	1.320	391.9	8.974E-01	2.645E+02
2011.10.20_20.52.372	4.48	4.28	4.55	5.00	5.12	4.73	1.273	400.7	1.043E+00	1.480E+02
2011.10.31_21.58.150	5.49	4.66	4.90	5.00	5.71	5.32	1.180	349.1	1.055E+00	5.414E+02
2011.11.01_00.21.271	5.88	5.36	5.55	5.53	6.13	5.75	1.197	380.9	9.450E-01	1.500E+03
2011.11.28_15.06.480	4.87	4.57	5.27	4.90	5.86	5.47	1.031	174.7	7.222E-01	7.489E+02
2011.12.01_03.50.563	4.85	4.43	4.77	5.10	4.99	4.60	1.034	205.8	1.018E+00	1.046E+02
2011.12.01_12.48.198	5.02	4.50	5.33	4.90	5.75	5.36	1.319	382.7	1.135E+00	6.183E+02
2011.12.25_16.46.517	4.63	4.00	4.40	-	4.95	4.57	1.250	349.8	1.008E+00	1.009E+02
2011.12.27_15.21.548	5.75	6.68	5.55	6.63	6.60	6.21	0.917	407.4	1.143E+00	4.333E+03
2013.01.23_04.18.151	4.69	4.63	5.30	4.90	5.15	4.77	1.317	401.0	1.187E+00	1.546E+02
2013.01.28_16.38.520	5.96	6.04	5.75	6.17	6.63	6.24	0.950	386.8	1.009E+00	4.666E+03
2013.02.11_19.13.001	5.23	4.37	4.60	5.00	5.55	5.17	1.049	362.4	1.106E+00	3.849E+02
2013.02.19_14.17.434	4.45	4.53	4.80	5.10	5.07	4.69	1.089	355.9	1.127E+00	1.293E+02
2013.02.22_03.34.118	4.35	3.93	5.10	-	5.21	4.82	1.173	365.8	1.455E+00	1.952E+02
2013.04.01_09.47.310	4.04	-	4.35	-	4.68	4.30	1.454	420.3	1.233E+00	5.414E+01
2013.04.20_00.02.475	6.05	6.77	5.85	6.64	6.81	6.42	0.925	311.0	1.183E+00	6.786E+03
2013.04.20_03.34.168	4.81	4.75	4.95	5.40	5.46	5.07	1.113	337.3	1.278E+00	3.229E+02
2013.04.20_20.53.444	4.92	4.27	4.70	4.80	5.06	4.68	1.174	350.1	1.296E+00	1.267E+02
2013.04.21_09.05.237	4.99	4.57	4.75	5.20	5.80	5.41	1.112	332.5	1.258E+00	6.769E+02
2013.04.22_09.11.520	4.96	4.68	4.80	5.00	5.37	4.98	1.409	406.3	1.245E+00	2.558E+02
2013.04.24_22.10.300	4.99	4.18	4.85	4.70	5.12	4.74	1.183	370.2	1.289E+00	1.461E+02
2013.05.14_04.39.276	4.21	4.00	4.35	-	4.88	4.49	1.284	463.4	1.035E+00	8.976E+01
2013.06.05_00.43.364	5.13	4.58	5.30	5.10	4.82	4.44	1.179	375.4	1.320E+00	7.766E+01
2013.06.20_09.05.117	4.34	4.04	5.15	-	5.38	4.99	1.316	450.9	1.178E+00	2.602E+02
2013.07.21_23.45.565	5.84	6.07	5.80	5.93	6.53	6.14	0.935	319.2	1.138E+00	3.746E+03
2013.07.22_01.12.360	5.40	5.01	5.25	5.40	5.94	5.56	1.054	331.5	1.161E+00	9.762E+02
2013.07.26_16.25.046	4.56	4.00	4.20	-	5.22	4.83	1.232	351.1	1.256E+00	1.809E+02
2013.08.01_08.46.508	3.84	-	4.25	-	4.47	4.08	1.478	510.1	1.161E+00	3.125E+01
2013.08.07_18.51.426	4.30	3.73	4.00	-	4.85	4.47	1.265	365.6	1.278E+00	7.493E+01
2013.08.16_03.38.132	3.82	4.30	4.05	-	4.79	4.40	1.444	369.3	1.365E+00	7.026E+01
2013.08.22_21.02.007	3.87	4.00	4.57	-	4.45	4.06	1.277	400.6	1.478E+00	3.306E+01
2013.08.31_00.04.168	5.33	5.41	5.60	5.63	7.22	6.83	1.509	331.3	1.261E+00	1.989E+04
2013.09.03_22.23.260	4.09	4.80	4.77	-	4.93	4.54	1.224	388.4	1.437E+00	9.237E+01
2013.09.16_22.43.385	4.69	4.06	4.60	-	5.36	4.97	1.250	383.3	1.199E+00	2.606E+02

2013.09.19_21.37.014	5.04	4.63	4.90	5.05	5.59	5.21	1.199	375.2	1.177E+00	4.376E+02
2014.03.31_19.48.357	4.71	4.22	5.07	4.80	5.31	4.92	1.301	479.2	1.165E+00	2.214E+02
2014.04.03_16.12.182	4.13	3.70	4.60	-	4.76	4.37	1.348	405.8	1.187E+00	6.389E+01
2014.04.04_17.37.037	-	-	3.60	-	3.58	3.19	1.463	515.5	1.380E+00	4.223E+00
2014.04.12_21.22.446	4.17	5.03	4.10	-	4.24	3.86	1.375	590.9	1.281E+00	1.877E+01
2014.04.14_02.27.586	3.64	-	-	-	3.57	3.18	1.428	525.9	1.132E+00	4.219E+00
2014.04.18_01.07.285	-	-	3.80	-	3.74	3.35	1.448	538.7	1.163E+00	6.072E+00
2014.04.19_19.27.549	3.89	4.30	4.70	-	4.33	3.95	1.455	487.8	1.128E+00	2.407E+01
2014.05.25_20.03.059	3.70	-	3.80	-	4.01	3.63	1.501	518.9	1.171E+00	1.179E+01
2014.05.27_07.49.146	-	-	3.80	-	3.73	3.34	1.571	572.2	1.114E+00	6.140E+00
2014.05.27_07.52.227	4.04	4.10	4.33	-	4.42	4.03	1.533	544.7	1.148E+00	2.996E+01
2014.06.17_00.33.421	4.20	-	3.90	-	4.01	3.63	1.555	490.2	1.305E+00	1.132E+01
2014.06.25_20.05.509	3.63	-	4.20	-	4.21	3.82	1.471	426.2	1.196E+00	1.873E+01
2014.07.03_12.57.109	3.66	3.90	4.20	-	4.22	3.84	1.378	518.0	1.197E+00	1.871E+01
2014.08.03_08.30.144	5.70	6.24	5.55	6.17	6.29	5.90	0.935	298.8	1.022E+00	2.101E+03
2014.08.17_20.42.065	-	-	3.80	-	3.65	3.27	1.470	504.0	1.204E+00	4.961E+00
2014.08.21_23.54.441	3.82	3.90	4.25	-	4.26	3.87	1.477	431.4	1.201E+00	2.015E+01
2014.09.03_01.08.323	-	-	3.50	-	3.78	3.39	1.508	484.7	1.139E+00	6.777E+00
2014.09.03_08.45.418	3.67	-	3.70	-	3.37	2.98	1.508	523.6	1.059E+00	2.591E+00
2014.09.06_10.37.421	4.01	3.90	4.45	-	4.66	4.27	1.341	440.1	1.130E+00	4.980E+01
2014.09.09_09.28.226	5.15	5.20	4.30	5.43	6.14	5.75	1.177	204.2	5.320E-01	1.417E+03
2014.09.16_06.42.588	4.30	-	4.15	-	4.35	3.96	1.474	480.1	1.147E+00	2.471E+01
2014.09.16_06.43.345	-	-	4.20	-	4.35	3.96	1.437	455.0	1.175E+00	2.492E+01
2014.09.21_14.39.405	3.55	-	-	-	3.36	2.97	1.527	585.2	1.155E+00	2.590E+00
2014.09.23_06.27.558	3.66	-	3.80	3.70	4.13	3.74	1.522	487.8	1.054E+00	1.914E+01
2014.09.24_17.26.453	3.57	-	4.10	4.00	4.26	3.87	1.299	546.7	1.055E+00	1.981E+01
2014.09.27_22.49.041	5.05	4.53	4.95	5.05	5.32	4.93	1.265	424.3	1.104E+00	2.296E+02
2014.10.14_09.27.276	-	-	3.85	-	4.29	3.90	1.451	437.2	1.047E+00	2.142E+01
2014.11.14_01.24.160	5.44	5.08	5.30	5.27	5.55	5.17	1.250	338.7	1.099E+00	3.885E+02
2014.11.22_08.55.265	5.60	6.13	5.60	6.02	6.34	5.95	0.985	177.4	7.185E-01	2.411E+03
2015.02.08_17.32.186	4.19	4.30	4.60	-	4.66	4.28	1.380	432.3	1.199E+00	5.151E+01
2015.02.10_07.21.554	3.73	-	3.60	-	4.07	3.69	1.528	480.2	1.205E+00	1.277E+01
2015.02.16_22.28.471	3.94	-	4.20	-	4.19	3.80	1.500	474.4	1.155E+00	1.687E+01
2015.04.01_03.12.237	3.62	3.50	-	-	3.85	3.46	1.426	460.5	1.168E+00	7.756E+00
2015.04.03_17.39.181	3.58	4.20	-	-	3.13	2.75	1.574	580.0	1.234E+00	1.469E+00
2015.04.15_07.39.272	5.00	5.13	5.20	5.45	5.91	5.52	1.127	383.0	1.114E+00	8.930E+02
2015.04.25_06.11.266	6.56	7.77	6.43	7.80	8.14	7.75	1.100	188.4	8.431E-01	3.182E+05
2015.04.25_08.55.550	5.20	5.45	5.30	-	4.80	4.41	1.234	389.5	9.402E-01	7.348E+01
2015.04.25_12.44.039	5.02	4.40	5.10	-	4.35	3.97	1.273	523.8	9.906E-01	2.510E+01
2015.04.25_17.42.495	5.08	4.82	5.13	5.20	5.94	5.55	1.183	204.0	8.004E-01	5.972E+02
2015.04.25_23.16.140	5.28	4.64	5.30	5.10	5.46	5.08	1.257	301.4	8.781E-01	3.567E+02
2015.04.26_07.09.069	6.23	6.85	6.17	6.67	7.90	7.51	1.113	189.1	9.138E-01	1.173E+05
2015.04.26_16.26.023	5.36	4.82	5.30	5.10	5.99	5.60	1.227	236.5	8.460E-01	9.508E+02
2015.05.12_07.05.188	6.45	7.53	6.05	7.28	7.14	6.75	1.154	211.1	7.288E-01	1.469E+04
2015.05.16_11.34.101	5.51	5.15	5.40	5.40	5.90	5.52	1.260	277.2	8.502E-01	9.289E+02
2015.05.21_16.05.315	4.46	3.98	4.80	-	4.89	4.50	1.370	358.2	1.199E+00	8.643E+01
2015.06.09_14.29.084	-	-	3.70	-	3.99	3.60	1.425	428.5	1.159E+00	1.053E+01
2015.06.12_06.40.348	3.58	-	4.00	-	3.77	3.38	1.544	423.6	1.292E+00	6.433E+00
2015.06.15_18.26.000	3.50	-	-	-	3.16	2.77	1.516	527.8	1.289E+00	1.572E+00
2015.06.28_23.03.230	3.79	3.80	4.07	-	4.42	4.03	1.462	393.1	1.235E+00	2.818E+01
2015.06.29_11.37.554	3.72	3.80	4.40	-	4.21	3.82	1.462	488.7	1.222E+00	1.802E+01
2015.07.03_01.07.462	5.80	6.54	5.95	6.36	6.63	6.24	1.164	394.8	1.011E+00	4.665E+03

2015.07.22_00.51.528	3.97	3.80	4.50	-	4.58	4.19	1.465	356.7	1.178E+00	3.883E+01
2015.07.24_06.25.146	3.82	3.80	-	-	4.26	3.88	1.369	438.9	1.095E+00	1.983E+01
2015.08.04_04.25.279	4.46	3.92	4.20	-	4.69	4.30	1.434	414.0	1.169E+00	5.418E+01
2015.08.06_01.58.590	3.62	-	4.00	-	4.26	3.87	1.528	414.2	1.149E+00	2.002E+01
2015.09.25_23.24.112	4.44	4.30	5.60	4.75	4.92	4.53	1.235	500.9	1.134E+00	9.026E+01
2015.10.09_09.20.245	3.85	-	3.83	-	4.10	3.71	1.452	404.7	1.380E+00	1.388E+01
2015.10.21_05.58.223	4.13	4.08	5.10	-	4.99	4.60	1.383	430.1	1.162E+00	1.086E+02
2015.11.04_19.38.528	3.50	-	-	-	3.65	3.26	1.513	479.6	1.210E+00	4.852E+00
2015.11.12_00.18.420	3.65	-	3.50	-	3.74	3.35	1.520	572.1	1.079E+00	6.596E+00
2015.11.22_19.57.439	3.95	4.00	4.60	-	4.70	4.32	1.461	399.6	1.190E+00	5.618E+01
2015.11.24_02.27.525	3.50	-	-	-	3.60	3.21	1.495	704.0	1.107E+00	4.363E+00
2015.11.27_18.10.394	3.90	-	4.00	-	4.28	3.89	1.453	372.7	1.204E+00	2.162E+01
2015.12.07_07.50.045	6.25	7.40	4.70	7.15	6.87	6.49	1.071	312.7	1.021E+00	8.396E+03
2015.12.07_08.30.549	5.31	5.83	4.77	-	5.79	5.41	1.348	301.6	9.037E-01	6.886E+02
2015.12.18_22.16.570	5.15	4.75	5.05	5.20	4.30	3.92	1.326	582.8	9.299E-01	2.188E+01
2015.12.21_19.31.246	4.13	3.90	4.20	3.90	4.48	4.09	1.417	423.7	1.191E+00	3.246E+01
2015.12.24_23.56.147	3.83	-	-	-	3.87	3.49	1.329	297.2	1.225E+00	8.096E+00
2016.01.20_01.04.596	4.00	-	4.00	-	4.15	3.76	1.488	332.4	1.110E+00	1.580E+01
2016.01.20_17.13.133	5.96	5.79	5.50	5.90	6.27	5.88	1.012	341.6	1.054E+00	2.027E+03
2016.02.19_16.56.587	3.88	-	-	-	4.19	3.81	1.435	470.4	1.166E+00	1.719E+01
2016.03.17_16.53.471	4.00	4.00	4.40	-	4.42	4.04	1.448	503.4	1.147E+00	2.883E+01
2016.03.30_13.56.219	3.98	4.20	4.00	-	4.30	3.91	1.385	424.9	1.132E+00	2.215E+01
2016.05.11_01.15.474	5.29	5.22	4.85	5.35	5.43	5.04	1.079	180.2	7.641E-01	2.851E+02
2016.05.22_02.05.553	5.03	4.67	5.00	5.20	5.42	5.03	1.264	213.6	4.051E-01	3.844E+02
2016.05.22_09.08.053	4.52	4.17	4.77	-	5.14	4.75	1.423	362.8	1.156E+00	1.492E+02
2016.06.11_16.30.559	4.16	3.70	3.95	-	4.18	3.79	1.399	483.0	1.146E+00	1.646E+01
2016.06.23_00.37.352	4.02	3.80	3.90	-	4.56	4.17	1.486	429.9	1.098E+00	3.957E+01
2016.06.26_11.17.112	6.11	6.57	5.60	6.38	6.83	6.45	1.049	335.1	9.618E-01	7.160E+03
2016.06.28_21.38.037	5.49	5.25	4.90	5.47	5.85	5.47	1.157	310.1	1.056E+00	8.003E+02
2016.07.05_11.33.037	4.45	4.27	4.60	4.80	5.18	4.80	1.182	409.9	1.157E+00	1.705E+02
2016.09.10_10.09.378	4.20	4.60	4.10	-	4.59	4.21	1.360	410.8	1.142E+00	4.411E+01
2016.09.11_08.07.430	4.18	3.97	4.70	-	4.81	4.42	1.299	473.8	1.130E+00	7.022E+01
2016.09.12_10.44.328	4.72	4.70	5.60	5.07	5.44	5.06	1.140	391.8	1.146E+00	3.069E+02
2016.09.12_11.32.550	5.22	5.32	5.95	5.47	6.07	5.68	1.080	361.4	1.134E+00	1.292E+03
2016.09.19_11.33.585	4.02	3.83	4.80	4.45	4.93	4.55	1.254	433.8	1.148E+00	9.591E+01
2016.10.17_07.14.491	5.90	5.96	5.55	5.95	5.99	5.61	0.996	189.2	8.858E-01	1.096E+03
2016.10.28_18.58.111	4.05	-	4.30	-	4.26	3.87	1.483	418.8	1.222E+00	1.972E+01
2016.11.25_14.24.304	6.20	6.67	5.65	6.57	6.61	6.22	1.056	315.3	1.013E+00	4.459E+03
2016.11.27_23.35.208	5.29	4.92	5.53	5.20	5.60	5.22	1.285	271.5	6.141E-01	4.284E+02
2017.01.02_02.10.106	3.50	-	4.10	-	4.14	3.75	1.497	415.8	1.081E+00	1.472E+01
2017.01.03_09.09.023	5.33	5.20	5.20	5.60	6.24	5.85	1.227	224.3	6.512E-01	1.482E+03
2017.01.17_08.53.470	3.78	-	-	-	4.16	3.77	1.409	461.8	1.125E+00	1.585E+01
2017.01.21_03.22.248	4.03	-	-	-	3.59	3.21	1.510	596.1	1.262E+00	4.244E+00
2017.01.21_16.43.343	3.72	4.00	4.05	-	4.29	3.90	1.355	486.6	1.245E+00	2.115E+01
2017.02.06_17.03.058	5.49	4.92	5.25	5.20	4.68	4.29	1.256	560.6	1.103E+00	5.208E+01
2017.02.25_20.34.015	-	-	4.00	-	3.91	3.53	1.518	407.9	1.226E+00	9.199E+00
2017.04.07_18.08.351	3.60	-	4.00	-	4.28	3.89	1.432	374.8	1.175E+00	2.080E+01
2017.05.03_04.47.134	5.82	6.17	5.55	5.93	6.46	6.08	1.081	326.3	9.791E-01	3.226E+03
2017.05.05_05.09.360	5.95	5.77	5.50	5.78	6.02	5.63	1.135	338.2	9.735E-01	1.194E+03

Table 4: Earthquakes m_b (Lg) Estimated using RMS Method

Event ID	mb(P)	Ms	ML	Mw	mb(Lg) C=90	mb(Lg) C=199	f_{rms}	Q	SR	A(10km)
2009.01.26_21.30.342	5.07	5.04	4.85	5.40	5.48	5.14	0.986	495.8	1.075E+00	2.718E+02
2009.02.20_03.48.539	5.38	5.01	5.48	5.45	5.24	4.89	1.224	472.9	9.092E-01	1.546E+02
2009.06.13_17.17.382	5.62	5.11	5.57	5.37	5.66	5.31	1.139	422.9	4.569E+00	4.373E+02
2009.06.29_18.03.515	5.15	4.96	4.75	5.25	5.98	5.64	1.024	335.7	1.083E+00	8.618E+02
2009.07.09_11.19.142	5.26	5.63	5.42	5.68	6.08	5.74	0.965	241.6	8.244E-01	1.083E+03
2009.07.13_18.04.580	5.85	6.44	6.06	6.26	5.89	5.54	0.938	386.4	8.762E-01	6.782E+02
2009.07.16_10.48.124	5.23	5.07	5.00	5.43	4.85	4.50	1.078	494.0	9.174E-01	6.380E+01
2009.08.28_01.52.062	6.04	6.24	5.93	6.23	6.32	5.98	1.061	332.4	1.021E+00	1.860E+03
2009.08.28_02.14.571	5.45	5.45	4.85	4.20	5.31	4.97	1.178	344.5	9.827E-01	1.773E+02
2009.08.30_17.15.497	5.01	4.87	5.13	5.40	5.40	5.06	1.137	348.9	9.808E-01	2.369E+02
2009.08.31_10.15.288	5.76	5.59	5.35	5.83	5.85	5.51	0.996	325.7	1.030E+00	6.457E+02
2009.09.18_07.02.130	4.79	4.60	4.75	-	5.15	4.81	1.178	314.8	8.042E-01	1.278E+02
2009.09.21_08.53.029	5.66	6.11	6.55	6.13	6.63	6.29	1.138	163.4	7.478E-01	4.032E+03
2009.10.03_17.36.032	5.72	5.83	5.92	5.96	5.78	5.43	0.935	387.1	8.411E-01	5.387E+02
2009.11.04_21.56.106	5.36	4.70	5.27	5.20	5.35	5.00	1.127	350.0	1.020E+00	2.071E+02
2009.11.05_09.32.535	5.34	5.33	5.58	5.60	5.72	5.38	1.034	409.3	8.414E-01	4.699E+02
2009.11.05_11.34.181	4.97	4.71	5.40	5.15	5.45	5.11	1.077	429.1	8.598E-01	2.501E+02
2009.11.27_16.04.049	4.98	4.37	4.55	4.77	5.15	4.80	1.112	336.6	1.069E+00	1.224E+02
2009.12.13_16.03.585	5.15	4.11	5.10	5.10	5.25	4.90	1.250	476.0	1.096E+00	1.560E+02
2009.12.20_21.31.123	4.61	3.88	5.00	-	4.88	4.53	1.351	416.8	1.218E+00	6.679E+01
2009.12.21_05.15.070	5.09	4.54	4.95	4.75	5.08	4.73	1.112	341.4	1.014E+00	1.083E+02
2010.01.01_02.22.240	4.60	4.60	4.80	5.20	4.82	4.48	0.962	199.9	4.680E-01	4.579E+01
2010.01.02_02.15.100	5.26	5.04	5.15	5.40	5.35	5.00	1.077	342.5	1.087E+00	2.011E+02
2010.01.19_06.09.237	4.64	4.06	4.80	4.90	4.82	4.47	1.195	501.6	9.460E-01	5.958E+01
2010.01.24_02.36.116	4.81	4.27	4.40	-	5.24	4.90	1.236	343.3	1.104E+00	1.566E+02
2010.02.12_02.42.368	4.74	4.45	5.06	4.67	4.88	4.54	1.079	473.5	9.689E-01	7.120E+01
2010.02.22_05.21.018	5.16	4.88	5.67	5.17	4.65	4.31	1.079	536.0	9.376E-01	3.711E+01
2010.02.25_04.56.516	4.84	4.53	5.33	5.05	5.37	5.02	1.063	275.3	6.679E-01	2.101E+02
2010.02.26_01.07.554	5.41	4.94	5.72	5.43	4.66	4.32	1.087	495.2	1.045E+00	4.046E+01
2010.03.08_09.26.195	4.11	3.83	4.95	4.60	4.67	4.33	1.208	528.5	9.504E-01	4.228E+01
2010.03.10_14.32.199	4.56	4.56	-	5.10	4.35	4.01	1.082	350.4	9.907E-01	2.096E+01
2010.03.24_02.06.096	5.38	5.47	4.50	5.60	5.86	5.52	0.988	144.8	8.166E-01	6.189E+02
2010.03.24_02.44.477	5.30	5.08	5.10	5.50	5.94	5.60	1.009	136.3	6.832E-01	7.867E+02
2010.04.09_22.23.001	3.74	-	-	-	2.58	2.24	1.296	383.5	2.249E+02	3.451E-01
2010.04.11_04.57.276	5.04	4.67	5.26	5.23	4.85	4.51	1.050	516.0	8.377E-01	6.670E+01
2010.04.13_20.49.065	4.52	4.35	4.88	4.63	4.51	4.17	1.118	531.2	9.408E-01	2.952E+01
2010.04.13_23.49.407	6.10	6.90	5.85	6.78	6.50	6.16	0.851	232.3	1.017E+00	2.845E+03
2010.04.14_01.25.178	5.47	6.01	5.00	6.10	5.66	5.32	0.877	182.2	8.714E-01	3.731E+02
2010.04.17_00.58.571	4.78	4.72	4.40	5.30	5.38	5.04	1.106	142.7	7.014E-01	2.311E+02
2010.04.18_20.28.479	5.50	5.28	5.00	5.50	4.95	4.60	1.004	424.8	1.208E+01	1.181E+02
2010.05.25_06.11.531	5.08	4.53	4.75	5.00	5.36	5.01	1.169	350.8	1.140E+00	1.997E+02
2010.05.29_02.29.495	5.37	5.63	5.10	5.73	5.60	5.26	0.968	205.9	9.168E-01	3.600E+02
2010.06.03_05.35.420	5.04	5.14	4.65	5.50	5.23	4.89	1.024	198.0	8.274E-01	1.590E+02
2010.06.10_06.38.022	5.37	4.74	4.95	5.15	5.26	4.91	1.221	317.6	1.136E+00	1.625E+02
2010.06.15_00.31.162	4.95	4.93	5.07	5.14	5.13	4.78	1.058	472.7	8.655E-01	1.199E+02
2010.06.18_01.08.432	4.55	3.97	4.80	4.70	4.42	4.07	1.214	537.3	9.900E-01	2.320E+01
2010.06.22_08.46.010	4.30	3.78	4.30	-	5.09	4.75	1.308	403.6	1.123E+00	1.136E+02
2010.06.27_20.33.250	4.68	4.13	5.13	4.63	4.75	4.41	1.176	491.4	9.322E-01	4.749E+01

2010.09.07_15.41.393	5.51	5.09	4.90	5.30	5.80	5.46	1.136	317.5	1.126E+00	5.808E+02
2010.09.27_15.49.219	4.97	4.68	5.60	5.10	4.74	4.40	1.069	451.3	9.320E-01	5.124E+01
2011.01.01_01.56.047	5.00	4.49	4.55	4.90	5.05	4.70	1.209	329.5	1.122E+00	1.066E+02
2011.02.01_07.11.207	4.66	4.33	5.35	4.40	5.37	5.02	1.037	192.6	8.730E-01	2.175E+02
2011.02.01_08.16.283	4.81	4.98	5.28	5.17	5.03	4.69	1.120	460.8	8.841E-01	9.012E+01
2011.02.04_02.39.148	4.64	4.15	4.40	-	5.00	4.66	1.231	442.6	1.071E+00	9.144E+01
2011.02.10_05.35.128	5.22	5.18	5.37	5.40	5.83	5.49	1.013	444.6	1.100E+00	6.173E+02
2011.02.23_17.10.375	4.57	4.43	4.80	5.00	5.41	5.06	1.147	420.8	1.092E+00	2.330E+02
2011.03.10_04.58.124	5.30	5.27	5.60	5.30	5.77	5.43	1.022	197.1	7.657E-01	5.692E+02
2011.03.17_15.34.304	4.78	4.19	4.40	4.90	4.61	4.27	1.210	365.2	4.868E+00	3.803E+01
2011.03.24_13.55.123	5.93	7.11	6.58	6.80	7.09	6.75	0.882	236.2	7.547E-01	1.243E+04
2011.03.24_15.54.334	5.21	5.30	5.70	5.43	6.27	5.93	0.988	221.2	8.026E-01	1.709E+03
2011.03.25_00.22.387	4.76	4.47	5.30	5.10	5.75	5.40	1.075	228.3	7.221E-01	5.096E+02
2011.04.10_09.02.424	4.88	5.03	4.90	5.40	5.44	5.10	1.130	292.5	1.060E+00	2.440E+02
2011.05.22_01.34.133	4.57	4.70	4.86	4.90	4.61	4.27	1.112	506.5	8.877E-01	3.988E+01
2011.06.08_01.53.234	5.09	4.70	5.20	5.10	5.03	4.69	1.345	431.4	5.927E+00	1.146E+02
2011.06.20_10.16.496	5.14	4.55	5.17	5.10	5.73	5.39	1.067	194.0	7.061E-01	4.843E+02
2011.06.26_07.48.154	5.10	4.70	4.80	5.30	5.33	4.99	0.997	185.9	9.027E-01	1.877E+02
2011.07.12_11.17.067	4.80	4.20	5.10	4.77	4.78	4.43	1.205	519.3	1.015E+00	6.050E+01
2011.07.16_18.38.486	5.15	5.00	4.75	5.27	5.70	5.36	1.032	430.3	1.097E+00	4.565E+02
2011.07.19_19.35.408	5.98	6.16	5.80	6.12	6.20	5.86	1.133	332.7	1.156E+00	1.465E+03
2011.07.22_14.52.557	4.52	3.92	4.53	4.50	4.94	4.59	1.222	421.9	1.188E+00	7.887E+01
2011.07.24_19.05.281	4.71	4.97	4.83	-	4.80	4.46	1.332	446.4	6.401E+00	6.240E+01
2011.08.09_11.50.173	4.68	4.55	5.15	4.85	5.76	5.42	1.040	204.8	6.696E-01	5.207E+02
2011.08.11_10.06.290	5.08	5.34	5.00	5.53	5.85	5.51	1.172	347.4	1.065E+00	6.628E+02
2011.08.27_10.29.440	5.26	5.26	5.47	5.40	5.86	5.51	1.110	397.7	1.151E+00	6.693E+02
2011.09.10_15.20.312	4.17	4.05	5.00	-	5.04	4.69	1.306	349.9	1.130E+00	9.995E+01
2011.09.15_15.26.589	5.20	4.95	5.15	5.30	5.60	5.26	1.368	412.5	1.021E+00	3.588E+02
2011.09.18_12.40.457	6.16	6.59	6.23	6.85	7.42	7.07	0.891	174.5	1.132E+00	2.267E+04
2011.10.14_06.10.102	5.56	5.86	5.80	6.04	6.57	6.22	0.955	451.3	1.075E+00	3.308E+03
2011.10.16_13.44.461	5.03	4.29	4.60	4.80	4.95	4.61	1.298	400.8	7.050E+00	1.054E+02
2011.10.20_20.52.372	4.48	4.28	4.55	5.00	5.18	4.83	1.240	408.5	1.096E+00	1.403E+02
2011.10.31_21.58.150	5.49	4.66	4.90	5.00	5.71	5.36	1.146	349.4	1.109E+00	4.682E+02
2011.11.01_00.21.271	5.88	5.36	5.55	5.53	6.13	5.79	1.154	390.6	1.033E+00	1.276E+03
2011.11.28_15.06.480	4.87	4.57	5.27	4.90	5.77	5.43	1.009	193.9	7.605E-01	5.492E+02
2011.12.01_03.50.563	4.85	4.43	4.77	5.10	4.88	4.54	0.793	215.9	1.493E+00	6.760E+01
2011.12.01_12.48.198	5.02	4.50	5.33	4.90	5.38	5.04	1.234	358.8	4.812E+00	2.444E+02
2011.12.25_16.46.517	4.63	4.00	4.40	-	4.94	4.60	1.213	363.6	1.217E+00	7.547E+01
2011.12.27_15.21.548	5.75	6.68	5.55	6.63	6.54	6.20	0.873	399.8	1.070E+00	3.114E+03
2013.01.18_12.42.501	5.15	5.24	5.10	5.47	5.45	5.10	1.032	265.8	1.176E+00	2.254E+02
2013.01.23_04.18.151	4.69	4.63	5.30	4.90	5.11	4.76	1.282	393.3	1.195E+00	1.152E+02
2013.01.28_16.38.520	5.96	6.04	5.75	6.17	6.52	6.18	0.916	383.6	1.074E+00	2.929E+03
2013.02.11_19.13.001	5.23	4.37	4.60	5.00	5.50	5.15	1.018	363.9	1.076E+00	2.806E+02
2013.02.19_14.17.434	4.45	4.53	4.80	5.10	5.08	4.74	1.063	352.6	1.091E+00	1.130E+02
2013.02.22_03.34.118	4.35	3.93	5.10	-	5.16	4.82	1.145	356.4	1.358E+00	1.257E+02
2013.04.01_09.47.310	4.04	-	4.35	-	4.59	4.25	1.435	415.2	1.242E+00	3.501E+01
2013.04.20_00.02.475	6.05	6.77	5.85	6.64	6.82	6.47	0.892	309.3	1.115E+00	5.925E+03
2013.04.20_03.34.168	4.81	4.75	4.95	5.40	5.41	5.07	1.118	340.1	1.286E+00	2.349E+02
2013.04.20_20.53.444	4.92	4.27	4.70	4.80	5.01	4.67	1.174	349.9	1.256E+00	9.488E+01
2013.04.21_09.05.237	4.99	4.57	4.75	5.20	5.79	5.44	1.085	334.5	1.205E+00	5.485E+02
2013.04.22_09.11.520	4.96	4.68	4.80	5.00	5.32	4.97	1.385	405.4	1.251E+00	1.871E+02
2013.04.24_22.10.300	4.99	4.18	4.85	4.70	5.08	4.73	1.181	366.8	1.240E+00	1.073E+02

2013.05.14_04.39.276	4.21	4.00	4.35	-	4.86	4.52	1.235	447.9	1.076E+00	6.568E+01
2013.06.05_00.43.364	5.13	4.58	5.30	5.10	4.76	4.42	1.082	370.7	1.233E+00	5.286E+01
2013.06.20_09.05.117	4.34	4.04	5.15	-	5.32	4.97	1.279	447.2	1.175E+00	1.871E+02
2013.07.21_23.45.565	5.84	6.07	5.80	5.93	6.50	6.16	0.900	318.9	1.112E+00	2.837E+03
2013.07.22_01.12.360	5.40	5.01	5.25	5.40	5.91	5.57	1.029	330.5	1.162E+00	7.306E+02
2013.07.26_16.25.046	4.56	4.00	4.20	-	5.17	4.83	1.196	348.5	1.227E+00	1.366E+02
2013.08.01_08.46.508	3.84	-	4.25	-	4.40	4.06	1.497	520.8	1.128E+00	2.299E+01
2013.08.07_18.51.426	4.30	3.73	4.00	-	4.75	4.40	1.251	363.6	1.234E+00	4.826E+01
2013.08.16_03.38.132	3.82	4.30	4.05	-	4.75	4.41	1.415	374.5	1.304E+00	5.094E+01
2013.08.22_21.02.007	3.87	4.00	4.57	-	4.38	4.04	1.255	404.0	1.335E+00	2.113E+01
2013.09.03_22.23.260	4.09	4.80	4.77	-	4.88	4.53	1.220	379.0	1.395E+00	6.997E+01
2013.09.16_22.43.385	4.69	4.06	4.60	-	5.25	4.91	1.235	382.9	1.216E+00	1.645E+02
2013.09.19_21.37.014	5.04	4.63	4.90	5.05	5.52	5.18	1.171	375.6	1.164E+00	3.031E+02
2014.03.31_19.48.357	4.71	4.22	5.07	4.80	5.31	4.96	1.274	468.8	1.132E+00	1.807E+02
2014.04.03_16.12.182	4.13	3.70	4.60	-	4.72	4.38	1.297	402.9	1.224E+00	4.631E+01
2014.04.04_17.37.037	-	-	3.60	-	3.50	3.15	1.487	504.3	1.279E+00	2.884E+00
2014.04.08_11.07.425	-	-	3.50	-	2.86	2.52	1.554	742.5	1.485E+00	6.742E-01
2014.04.12_21.22.446	4.17	5.03	4.10	-	4.15	3.81	1.356	608.4	1.216E+00	1.264E+01
2014.04.14_02.27.586	3.64	-	-	-	3.49	3.15	1.423	526.3	1.128E+00	2.777E+00
2014.04.18_01.07.285	-	-	3.80	-	3.70	3.36	1.392	509.7	1.226E+00	4.623E+00
2014.04.19_19.27.549	3.89	4.30	4.70	-	4.27	3.93	1.418	487.8	1.113E+00	1.694E+01
2014.04.27_23.59.476	-	-	3.60	-	3.28	2.94	1.461	613.9	1.502E+00	1.686E+00
2014.05.25_20.03.059	3.70	-	3.80	-	3.91	3.56	1.488	519.9	1.218E+00	7.180E+00
2014.05.27_07.49.146	-	-	3.80	-	3.63	3.29	1.549	553.1	1.158E+00	3.776E+00
2014.05.27_07.52.227	4.04	4.10	4.33	-	4.38	4.03	1.514	531.3	1.087E+00	2.106E+01
2014.06.17_00.33.421	4.20	-	3.90	-	3.99	3.64	1.530	474.7	1.262E+00	8.864E+00
2014.06.25_20.05.509	3.63	-	4.20	-	4.16	3.82	1.433	420.6	1.207E+00	1.335E+01
2014.07.03_12.57.109	3.66	3.90	4.20	-	4.16	3.82	1.355	491.1	1.183E+00	1.326E+01
2014.08.03_08.30.144	5.70	6.24	5.55	6.17	6.26	5.92	0.899	294.0	1.013E+00	1.623E+03
2014.08.17_20.42.065	-	-	3.80	-	3.61	3.26	1.432	500.3	1.182E+00	3.669E+00
2014.08.21_23.54.441	3.82	3.90	4.25	-	4.21	3.87	1.439	429.0	1.216E+00	1.493E+01
2014.09.03_01.08.323	-	-	3.50	-	3.68	3.34	1.444	478.2	1.285E+00	4.319E+00
2014.09.03_08.45.418	3.67	-	3.70	-	3.34	3.00	1.486	515.8	1.021E+00	1.909E+00
2014.09.06_10.37.421	4.01	3.90	4.45	-	4.59	4.24	1.304	439.1	1.139E+00	3.536E+01
2014.09.16_06.42.588	4.30	-	4.15	-	4.31	3.97	1.465	471.4	1.132E+00	1.821E+01
2014.09.21_14.39.405	3.55	-	-	-	3.33	2.99	1.482	561.8	1.206E+00	1.990E+00
2014.09.23_06.27.558	3.66	-	3.80	3.70	3.98	3.63	1.512	520.9	1.118E+00	7.958E+00
2014.09.24_17.26.453	3.57	-	4.10	4.00	4.23	3.88	1.259	525.6	1.063E+00	1.551E+01
2014.10.14_09.27.276	-	-	3.85	-	4.19	3.85	1.416	446.5	1.211E+00	1.436E+01
2014.11.14_01.24.160	5.44	5.08	5.30	5.27	5.45	5.11	1.206	322.2	1.184E+00	2.492E+02
2014.11.22_08.55.265	5.60	6.13	5.60	6.02	6.25	5.91	0.954	172.2	7.743E-01	1.590E+03
2015.02.08_17.32.186	4.19	4.30	4.60	-	4.60	4.26	1.357	419.6	1.198E+00	3.575E+01
2015.02.10_07.21.554	3.73	-	3.60	-	4.02	3.67	1.493	474.7	1.205E+00	9.496E+00
2015.02.16_22.28.471	3.94	-	4.20	-	4.17	3.83	1.453	464.4	1.204E+00	1.338E+01
2015.04.01_03.12.237	3.62	3.50	-	-	3.79	3.45	1.403	452.6	1.148E+00	5.504E+00
2015.04.03_17.39.181	3.58	4.20	-	-	3.04	2.70	1.552	537.8	1.229E+00	9.519E-01
2015.04.15_07.39.272	5.00	5.13	5.20	5.45	5.86	5.52	1.099	382.0	1.100E+00	6.577E+02
2015.04.26_07.09.069	6.23	6.85	6.17	6.67	7.85	7.50	1.035	150.7	2.699E-01	5.958E+04
2015.05.21_16.05.315	4.46	3.98	4.80	-	4.82	4.47	1.305	366.6	1.139E+00	6.030E+01
2015.06.09_14.29.084	-	-	3.70	-	3.92	3.57	1.371	425.1	1.105E+00	7.560E+00
2015.06.12_06.40.348	3.58	-	4.00	-	3.61	3.27	1.560	461.5	1.142E+00	3.603E+00
2015.06.15_18.26.000	3.50	-	-	-	3.10	2.76	1.520	524.7	1.190E+00	1.169E+00

2015.06.28_23.03.230	3.79	3.80	4.07	-	4.38	4.03	1.402	414.2	1.242E+00	2.165E+01
2015.06.29_11.37.554	3.72	3.80	4.40	-	4.15	3.81	1.440	487.0	1.193E+00	1.247E+01
2015.07.03_01.07.462	5.80	6.54	5.95	6.36	6.78	6.44	1.100	405.9	9.786E-01	5.360E+03
2015.07.22_00.51.528	3.97	3.80	4.50	-	4.59	4.24	1.425	361.4	1.191E+00	3.353E+01
2015.07.24_06.25.146	3.82	3.80	-	-	4.23	3.89	1.381	437.3	1.132E+00	1.451E+01
2015.08.04_04.25.279	4.46	3.92	4.20	-	4.68	4.33	1.400	410.7	1.191E+00	4.201E+01
2015.08.06_01.58.590	3.62	-	4.00	-	4.14	3.80	1.528	426.0	1.191E+00	1.254E+01
2015.09.25_23.24.112	4.44	4.30	5.60	4.75	4.87	4.53	1.207	497.0	1.133E+00	6.757E+01
2015.10.09_09.20.245	3.85	-	3.83	-	4.06	3.72	1.482	426.5	1.193E+00	1.016E+01
2015.10.21_05.58.223	4.13	4.08	5.10	-	4.96	4.61	1.364	426.1	1.205E+00	8.173E+01
2015.11.04_19.38.528	3.50	-	-	-	3.60	3.25	1.478	469.0	1.217E+00	3.565E+00
2015.11.12_00.18.420	3.65	-	3.50	-	3.65	3.31	1.482	558.5	1.129E+00	4.295E+00
2015.11.22_19.57.439	3.95	4.00	4.60	-	4.65	4.30	1.441	399.4	1.214E+00	3.962E+01
2015.11.24_02.27.525	3.50	-	-	-	3.63	3.28	1.439	604.6	1.142E+00	3.688E+00
2015.11.27_18.10.394	3.90	-	4.00	-	4.20	3.86	1.412	385.0	1.182E+00	1.413E+01
2015.12.07_07.50.045	6.25	7.40	4.70	7.15	6.81	6.47	0.985	297.4	1.060E+00	5.926E+03
2015.12.07_08.30.549	5.31	5.83	4.77	-	5.68	5.33	1.335	301.3	9.583E-01	4.441E+02
2015.12.21_19.31.246	4.13	3.90	4.20	3.90	4.41	4.07	1.398	422.2	1.174E+00	2.285E+01
2015.12.24_23.56.147	3.83	-	-	-	3.79	3.45	1.303	291.4	1.204E+00	5.416E+00
2016.01.20_01.04.596	4.00	-	4.00	-	4.09	3.75	1.423	329.4	1.114E+00	1.115E+01
2016.01.20_17.13.133	5.96	5.79	5.50	5.90	6.23	5.89	0.965	335.8	1.060E+00	1.568E+03
2016.02.19_16.56.587	3.88	-	-	-	4.15	3.81	1.402	460.8	1.134E+00	1.280E+01
2016.03.17_16.53.471	4.00	4.00	4.40	-	4.29	3.95	1.420	503.5	1.139E+00	1.812E+01
2016.03.30_13.56.219	3.98	4.20	4.00	-	4.23	3.89	1.341	417.1	1.163E+00	1.534E+01
2016.05.11_01.15.474	5.29	5.22	4.85	5.35	5.68	5.34	1.073	163.4	8.587E-01	4.031E+02
2016.05.22_09.08.053	4.52	4.17	4.77	-	5.07	4.73	1.404	366.0	1.151E+00	1.071E+02
2016.06.11_16.30.559	4.16	3.70	3.95	-	4.10	3.76	1.354	472.8	1.154E+00	1.162E+01
2016.06.23_00.37.352	4.02	3.80	3.90	-	4.47	4.13	1.467	424.7	1.102E+00	2.632E+01
2016.06.26_11.17.112	6.11	6.57	5.60	6.38	6.85	6.51	1.017	351.9	1.056E+00	6.370E+03
2016.06.28_21.38.037	5.49	5.25	4.90	5.47	5.71	5.37	1.130	313.2	1.072E+00	4.609E+02
2016.07.05_11.33.037	4.45	4.27	4.60	4.80	5.15	4.80	1.158	408.5	1.152E+00	1.247E+02
2016.09.10_10.09.378	4.20	4.60	4.10	-	4.54	4.19	1.346	399.5	1.154E+00	3.045E+01
2016.09.11_08.07.430	4.18	3.97	4.70	-	4.71	4.37	1.292	472.6	1.137E+00	4.691E+01
2016.09.12_10.44.328	4.72	4.70	5.60	5.07	5.39	5.04	1.119	398.4	1.118E+00	2.189E+02
2016.09.12_11.32.550	5.22	5.32	5.95	5.47	6.04	5.69	1.052	357.3	1.095E+00	9.754E+02
2016.09.19_11.33.585	4.02	3.83	4.80	4.45	4.86	4.52	1.225	424.3	1.159E+00	6.674E+01
2016.10.17_07.14.491	5.90	5.96	5.55	5.95	5.84	5.50	0.911	176.7	9.311E-01	5.718E+02
2016.10.28_18.58.111	4.05	-	4.30	-	4.19	3.85	1.461	419.3	1.191E+00	1.403E+01
2016.11.25_14.24.304	6.20	6.67	5.65	6.57	6.65	6.30	0.990	345.0	1.011E+00	3.841E+03
2017.01.02_02.10.106	3.50	-	4.10	-	4.02	3.67	1.481	416.9	1.104E+00	9.564E+00
2017.01.17_08.53.470	3.78	-	-	-	4.09	3.74	1.391	458.6	1.137E+00	1.089E+01
2017.01.21_03.22.248	4.03	-	-	-	3.51	3.17	1.499	602.9	1.159E+00	3.110E+00
2017.01.21_16.43.343	3.72	4.00	4.05	-	4.22	3.87	1.318	480.2	1.191E+00	1.491E+01
2017.02.25_20.34.015	-	-	4.00	-	3.83	3.49	1.465	410.0	1.155E+00	6.148E+00
2017.04.07_18.08.351	3.60	-	4.00	-	4.21	3.87	1.392	378.2	1.215E+00	1.503E+01
2017.05.03_04.47.134	5.82	6.17	5.55	5.93	6.38	6.03	1.041	313.1	1.129E+00	2.157E+03
2017.05.05_05.09.360	5.95	5.77	5.50	5.78	5.91	5.57	1.098	314.9	1.098E+00	7.400E+02

For the earthquakes in Table 3, we use $C = 110\mu\text{m}$ and $C = 268\mu\text{m}$ to calculate $m_b(\text{Lg})$ respectively. The scaling relationship between the two $m_b(\text{Lg})$ is fitted by $m_b(\text{Lg})_{\text{new}} = 1.0000m_b(\text{Lg})_{\text{Nuttli}} - 0.3866$, where $m_b(\text{Lg})_{\text{Nuttli}}$ is calculated using $C = 110\mu\text{m}$ and

$m_b(\text{Lg})_{\text{new}}$ is calculated using $C = 268\mu\text{m}$ (Figure 19a). The $m_b(\text{Lg})_{\text{new}}$ is smaller than $m_b(\text{Lg})_{\text{Nuttli}}$ by 0.39 units. For the earthquakes in Table 4, we use $C = 90\mu\text{m}$ and $C = 199\mu\text{m}$ to calculate $m_b(\text{Lg})$ respectively. The scaling relationship between the two $m_b(\text{Lg})$ is fitted by $m_b(\text{Lg})_{\text{new}} = 0.9997m_b(\text{Lg})_{\text{Nuttli}} - 0.3420$, which means that $m_b(\text{Lg})_{\text{new}}$ is smaller than $m_b(\text{Lg})_{\text{Nuttli}}$ ($C = 90\mu\text{m}$) by 0.34 unit (Figure 19b). The scaling relationship between the $m_b(\text{Lg})$ estimated by the 3rd peak method and the $m_b(\text{Lg})$ estimated by the RMS method is fitted by $m_b(\text{Lg})_{\text{rms}} = 0.9960m_b(\text{Lg})_{3\text{rd}} - 0.0033$ (Figure 20). All earthquakes concentrate on the diagonal line, meaning the $m_b(\text{Lg})$ estimated by the 3rd peak method and the RMS method are consistent without systematical bias.

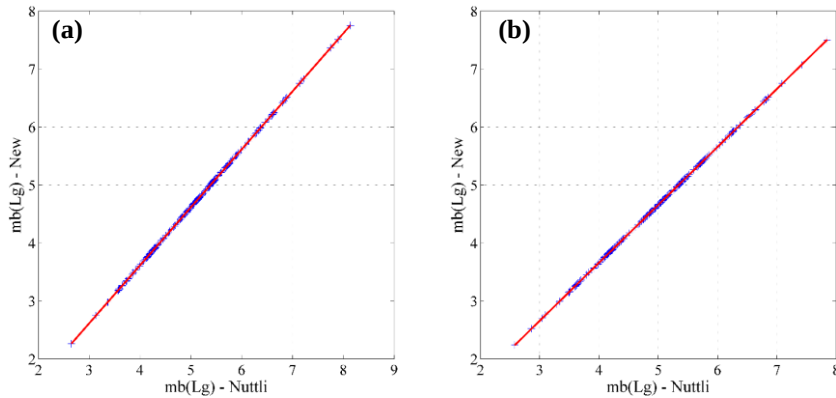


Figure 19. (a) Comparison between the $m_b(\text{Lg})$ of earthquake data calculated using $C = 110\mu\text{m}$ and $C = 168\mu\text{m}$. The Lg amplitudes are measured using the 3rd peak method. (b) Comparison between the $m_b(\text{Lg})$ of earthquake data calculated using $C = 90\mu\text{m}$ and $C = 119\mu\text{m}$. The Lg amplitudes are measured using RMS method.

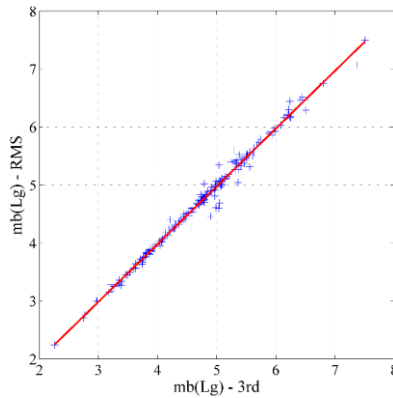


Figure 20. (a) Comparison between the $m_b(\text{Lg})$ of earthquake data calculated using the 3rd peak method with $C = 168\mu\text{m}$ and using RMS method with $C = 119\mu\text{m}$.

Table 5 lists the magnitudes of the six DPNK explosions. For each explosion, the six $m_b(\text{Lg})$ values are estimated using the 3rd and RMS methods with different constant C values, respectively. The network-averaged path Q and SRs used for $m_b(\text{Lg})$ estimation are also listed in Table 5.

Table 5: DPNK Explosions $m_b(\text{Lg})$ Estimated Using Different Methods and Constant C

Event ID	mb(P)	Ms	ML	mb(Lg) 3 rd C=110	mb(Lg) 3 rd C=268	mb(Lg) 3 rd C=45	mb(Lg) RMS C=90	mb(Lg) RMS C=199	mb(Lg) RMS C=33	Q	SR
2006.10.09_01.35.276	4.17	-	3.90	3.28	2.89	3.67	3.28	2.94	3.72	660.7	1.0227E+00
2009.05.25_00.54.428	4.64	3.82	4.55	4.46	4.07	4.85	4.37	4.03	4.82	520.4	1.1978E+00
2013.02.12_02.57.509	5.03	4.02	4.50	4.86	4.48	5.25	4.80	4.46	5.24	468.9	1.1440E+00

2016.01.06_01.30.007	4.94	3.97	4.60	4.66	4.27	5.05	4.60	4.26	5.04	495.6	1.1933E+00
2016.09.09_00.30.008	5.20	4.53	4.30	4.88	4.49	5.27	4.78	4.43	5.22	484.0	1.1746E+00
2017.09.03_03.30.017	6.23	5.10	5.85	5.60	5.22	5.99	5.56	5.22	6.00	428.3	1.1354E+00

6 DISCUSSION, CONCLUSIONS AND FUTURE WORK

In the first-year technical progress period, we process more than 51,000 broad-band regional waveforms of 232 seismic events (including the six DPRK nuclear explosions) recorded at ~890 stations in Asia. We develop an iterative method to jointly invert for Lg source spectra, Q and SRs. This method is applied to the large volume of waveform data collected in Asia and performed at 45 narrow frequency bands from 0.1 to 5.5Hz. These improved event-station path Q are combined with all inter-station and inter-event Q measurements as input data for the refined Lg Q tomographic models. The resulting SRs on individual stations are more accurately reflect the amplification and de-amplification effects of receiver sites than the relative SRs. The new SRs are also independent of the zero-mean assumption made on log-SRs for the inversion of relative SRs. The large volume of seismic events and stations facilitates the implementation of our methodology, and in turn, the Lg source spectra of these seismic events, SRs of these stations, and all event-station path Q are obtained for further process.

The results after four iterations are applied to calibrate $m_b(\text{Lg})$ estimator. Currently, we have used the 3rd peak and RMS method to measure Lg amplitudes on simulated WWSSN-SP seismograms. The other proposed methods that will use Lg spectral amplitudes to calibrate $m_b(\text{Lg})$ will be implemented in further progress periods. The hypothetical Lg amplitudes at 10km from the source, $A(10\text{km})$, are obtained after corrections for the path and receiver site effects. For each seismic event, we predict the path Q to all recording stations using the refined 2D Q tomographic maps. The site effects of all recording stations are explicitly considered and corrected using our new SRs. Because many stations have amplifying or de-amplifying effects on waveforms, the corrections for SRs at individual stations reduce the spreading of Lg amplitudes (Figure 14 and 15), particularly for those near-field records. For most events, the station average SRs are not close to unity (Table 3 and 4). This means that if the SRs of individual stations are not corrected, their effects cannot be canceled from the network average. The fact that resulting $A(10\text{km})$ become independent on epicentral distances confirms the correctness of our derived Q and SR models.

We perform a linear regression between $\log_{10}[A(10\text{km})]$ and $m_b(\text{P})$ to calibrate the constant C . When Lg amplitudes are measured by the 3rd peak method, we calibrate $C = 283\mu\text{m}$ when only using earthquake data, $C = 45\mu\text{m}$ when only using DPRK explosion data, and $C = 268\mu\text{m}$ when using combined earthquake and explosion data, respectively. When Lg amplitudes are measured by the RMS method, constant C is calibrated to $212\mu\text{m}$, $33\mu\text{m}$, and $199\mu\text{m}$ for the three cases, respectively. The accuracy of C calibration is not only dependent on the estimation of $A(10\text{km})$ but is also dependent on $m_b(\text{P})$. Currently, we use the results after four iterations to perform path and site effects corrections. With more iterations until to the end, some path Q and SRs will continue to be improved, which will modify $A(10\text{km})$ estimates and C value consequently. Such modification shall only be a slight adjustment for C value. The $m_b(\text{P})$ values employed for this study are those given in the bulletin of ISC. If more than one seismic agency reported $m_b(\text{P})$ to ISC, we use their average in the regression. As the $m_b(\text{P})$ is an average of a large number of stations, the error introduced by $m_b(\text{P})$ could be ignorable. Our calibrated C values ($283\mu\text{m}$ or

268 μ m) using the 3rd peak Lg amplitudes for Asia are of considerable difference from the value for eastern North America (110 μ m), but are very close to the value for Iran (268 μ m vs. 270 μ m) [Nuttli, 1980].

The constant C values are used to estimate m_b (Lg) for earthquakes and explosions. For earthquakes, the m_b (Lg) estimated using $C = 283\mu$ m and $C = 268\mu$ m are of only 0.025 magnitude unit difference. For explosions, the m_b (Lg) estimated using $C = 45\mu$ m are quite different from using $C = 268\mu$ m (Table 5). The magnitudes estimated using the 3rd peak method and RMS method are in good agreement. In further technical progress periods, we will study the scaling relationship between m_b (Lg) and other types of magnitudes, such as Ms, ML and Mw. If the m_b (Lg) of DPRK explosions are calculated using a C value much different from the C for earthquakes, we will examine if Ms:mb a successful discriminant able to separate DPRK explosions from earthquake population.

For simplicity, we still use Ms, ML and Mw values that are given by ISC for further study. Because we make use of many small earthquakes in this study, there are no Mw values reported to ISC for these events (Table 1, 3 and 4). The Lg source spectra for earthquakes will be used to estimate moment M_0 and Mw when they are fitted using Brune's model. Moreover, we will fit the Lg source spectra of DPRK explosions using various explosion source models. The scaling of the seismic moment (and yield) of the DPRK explosions with the depth of burial or depth-dependent media parameters will be established for various explosion source models.

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Appendix A: Conversion between RMS Amplitudes and Spectral Amplitudes

Parseval's theorem states that if $X(\omega)$ is the Fourier transform of $x(t)$, then:

$$\int_{-\infty}^{\infty} x^2(t)dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} X^2(\omega)d\omega \quad (A1)$$

If we window a given phase using a window of time with length T , and bandpass filter between a low-cut and high-cut frequency, $\omega_l = 2\pi f_l$ and $\omega_h = 2\pi f_h$, respectively. In this case Equation (A1) becomes:

$$\int_0^T x^2(t)dt = \frac{1}{\pi} \int_{\omega_l}^{\omega_h} X^2(\omega)d\omega \quad (A2)$$

where the factor of 2 is eliminated due to the symmetry of the Fourier transform of a real seismic trace. The mean-square of $x(t)$ over time window T is given by:

$$\langle x^2(t) \rangle = \frac{1}{T} \int_0^T x^2(t)dt \quad (A3)$$

Combining Equation (A2) and (A3), we have

$$A_{rms}^2 = \langle x^2(t) \rangle = \frac{2}{T} \int_{f_l}^{f_h} X^2(f)df \quad (A4)$$

If A_{rms} is the RMS amplitude of Lg wave, Equation (A4) shows how it can be calculated from the corresponding Lg spectrum. Equation (A4) can also be applied to pre-event noise and pre-phase noise. Taylor *et al.* [2002] used Parseval's theorem to convert the RMS measurements in the time domain into pseudo-spectra. Here, we simply invert Taylor *et al.* [2002] procedure for our work.

Appendix B: Calculation of Wave Frequencies Using Complex Trace Analysis

Complex trace analysis is a transform technique to treat a time trace as the real part of an analytical signal or complex trace. Transformations of data from one form to another, such as Fourier transform, are common in signal analysis. Interpreting data from different points of view results in new insight and the discovery of relationships not otherwise evident. In practice, the complex trace can be obtained by Fourier transforms [Taner *et al.*, 1979]: (1) Fourier transforming the seismic trace, (2) zeroing the spectral amplitudes for negative frequencies and doubling the spectral amplitudes for positive frequencies to maintain the power, and then (3) inverse Fourier transforming the spectrum.

Comparing to the Fourier transform of a seismic trace, which allows us to look at the average properties of a reasonably large portion of the trace, the complex trace retains the significance of local variations. So that the “instantaneous frequency” of the time trace can be investigated from the phase of the complex trace. Taner *et al.* [1979] defined the instantaneous frequency, $\omega(t)$, of the time trace as the rate of change of the time-dependent phase of the complex trace:

$$\omega(t) = \frac{d\theta(t)}{dt} = \frac{f(t)\frac{df^*(t)}{dt} - f^*(t)\frac{df(t)}{dt}}{[f(t)]^2 + [f^*(t)]^2} = \frac{f(t)\frac{df^*(t)}{dt} - f^*(t)\frac{df(t)}{dt}}{[A(t)]^2} \quad (B1)$$

where $\theta(t)$, $A(t)$, $f(t)$ and $f^*(t)$ is the phase, amplitude, real part and imaginary part of the complex trace, respectively. Taner *et al.* [1979] also defined a “weighted average frequency” $\bar{\omega}(t)$ as:

$$\bar{\omega}(t) = \frac{\int_{-\infty}^{\infty} A(t-\tau)\omega(t-\tau)L(\tau)d\tau}{\int_{-\infty}^{\infty} A(t-\tau)L(\tau)d\tau} \quad (B2)$$

where $L(\tau)$ is a low-pass filter.