EARTHQUAKE GROUND MOTION AND SITE CHARACTERIZATION DATABASE FOR EARTHQUAKES IN EASTERN CANADA

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ABSTRACT

This report describes an earthquake ground motion and site characterization database for 3358 **M**≥1.5 earthquake recordings in eastern Canada, recorded on 25 stations of the Canadian National Seismic Network. Included records are within 150 km and have a minimum sampling rate of 100 Hz. The database contains instrument-corrected time series for each record, computed Fourier amplitude spectra for the full earthquake time series and multiple windows of the earthquake time series, including the shear wave, the primary wave, a noise window, and the coda window, and response spectra with a 5% damping ratio. We also provide station metadata which includes computed horizontal-to-vertical spectral ratios for each station, geological descriptions, and information on the velocity profile. This database was developed to facilitate ground motion studies that examine earthquake source, regional path, and site characterization, as reported in the thesis of Palmer (2022). The full databases of records and products can be freely accessed via: https://doi.org/10.17603/ds2-3b7s-yw72

INTRODUCTION

Compiled ground motion databases, including event and site metadata, are required for studies that characterize earthquake source, path, and site effects on ground shaking. Eastern Canada is a stable continental region, for which there are relatively abundant ground motion recordings for small to moderate earthquakes (**M**<5) but few records for larger events. Nevertheless, larger potentially-damaging earthquakes such as the 1925 Charlevoix-Kamouraska (**M**6.2), 1929 Laurentian slope Newfoundland and Nova Scotia (**M**7.2), 1935 Timiskaming (**M**6.1), 1982 Miramachi (**M**5.7) and 1988 Saguenay (**M**5.9) earthquakes do occur [Lamontagne et al., 2018]. Thus, understanding ground motions is vital to the assessment of seismic hazard in the region.

Ground motion databases that have been compiled for other regions have been referenced widely in seismological and engineering studies. Examples of such databases include the PEER NGA-West database [Ancheta et al., 2013], and PEER NGA-East database [Goulet et al, 2014; 2021] – both of which have been useful in the development of ground motion models used in hazard assessments. The NGA-East database compiled ground motions in the central and eastern regions of north America (CENA) for magnitudes greater than 2.5; it comprises records from 96 candidate earthquakes, of which ~ 1/3 are from eastern Canada. Thus, the NGA-East database has some overlap with the database compiled in this study.

This report aims to provide a high-quality database of Fourier Spectra and Response Spectra from earthquake records in eastern Canada having moment magnitudes **M**≥1.5 at epicentral distances ≤150 km. The distance range is selected to focus on records for which path effects on high frequency amplitudes are not severe. For this purpose, Ktenidou et al. [2016] suggest restricting studies of high frequency ground motions to records within 100 – 150 km in central and eastern North America. Similarly, Palmer and Atkinson [2020] found that high frequency effects in eastern Canada become most significant at distances beyond 50 – 150 km, dependent on the location.

The Canadian National Seismic Network (CNSN) has 67 active seismic stations in eastern Canada. These stations record earthquakes continuously on a single component (vertical) or on 3 components (vertical and two orthogonal horizontal), at sampling rates of 40 or 100 samples per second. The continuous records are stored and made available through Earthquakes Canada - Canadian National Data Center waveform archive (see Data and Resources). Our compiled database draws from these resources to provide data resources for events of **M** ≥1.5 in eastern Canada recorded at distances <150 km.

The compiled database provides the following products:

1) an event table that summarizes earthquake event metadata including date, time, location, magnitudes, and number of records, stations;
2) station metadata including station names, locations, geological and mounting conditions, and velocity profiles;
3) instrument-corrected time series;

4) Fourier amplitude spectra for the vertical and horizontal components, for several window choices; the horizontal component is represented by the Effective Amplitude Spectra (EAS) [Kottke et al., 2018, 2021]; and
5) 5%-damped response spectra (the psueudo-spectral acceleration (PSA)).

This article describes the database generation criteria, compilation process and record processing approach. Selected data products are available for download from seismotoolbox.ca with all database products being archived at https://doi.org/10.17603/ds2-3b7s-yw72

DATA SELECTION: EARTHQUAKE EVENTS AND STATIONS

We considered earthquakes recorded within the region 43ºN to 60ºN, 95ºW to 50ºW from 1989/01/01 to 2020/09/01. For each event we adopted the epicenter location provided by Earthquakes Canada. Moment magnitude (**M**), if not available from Earthquakes Canada (see Data and Resources), was estimated using the conversion equations of Fereidoni et al. [2012].

We considered only those stations having a minimum sampling rate of 100 Hz (to maximize the useable bandwidth), and recording at least 10 events of **M**>2 within 100 km. We further limited our study to stations having some site characterization information and several recordings of events of **M**≥3.5 earthquakes. These criteria resulted in the selection of 25 seismic stations, as listed in Table 1. Station GBN in Nova Scotia was included due to its unique location and geology, even though it did not strictly meet the criteria for number of events. Earthquakes within 150 km of each selected seismic station were considered. Figure 1 shows the epicentral distribution of 3358 earthquakes and the location of 25 seismic stations included in the database.

Table 1: Location, data channels (band code, instrument code, and orientation code), and operational status of seismic station in Eastern Canada included in the database. The data channels consist of 3 letters: the first letter represents a short-period (E) or broadband (H) seismometer, the second represents a high gain (H) broadband seismometer, and the last letter is the orientation of the instrument in either east-west (E), north-south (N) or the vertical (Z) direction. The recording time provides two date ranges and if the seismometer is still active, we represent the second date with the word active.

Station Name	Location	Data Channels	Recording Time Frame YYYY/MM/DD
A11	47.2431° N, 70.1969° W	EHE/N/Z and HHE/N/Z	1994/10/16 – active
A16	47.4680° N, 70.0096° W	EHE/N/Z and HHE/N/Z	1994/10/15 – active

A21	47.7045° N, 69.6892°W	EHE/N/Z and HHE/N/Z	1994/10/17 – active
A54	47.4568° N, 70.4134° W	EHE/N/Z and HHE/N/Z	1994/10/02 – active
A61	47.6936° N, 70.0914° W	EHE/N/Z and HHE/N/Z	1987/10/30 – active
A64	47.8264° N, 69.8914° W	EHE/N/Z and HHE/N/Z	1987/10/30 – active
BATG	47.2767° N, 66.0599° W	HHE/N/Z	2005/10/22 – 2017/09/26
BCLQ	46.9264° N, 71.1727° W	HHE/N/Z	2007/11/02 – active
CNQ	49.3020° N, 68.0746° W	EHZ	1996/02/01 – active
DAQ	47.9627° N, 71.2437° W	EHZ	1995/11/08 – 2017/08/30
DPQ	46.6803° N, 72.7771° W	EHZ AND HHE/N/Z	1996/09/20 – active
GAC	45.7032° N, 75.4776° W	EHZ AND HHE/N/Z	1993/04/27 – active
GBN	45.4079° N, 61.5128° W	HHE/N/Z	2005/10/17 – active
GSQ	48.9142° N, 67.1106° W	EHZ	1996/01/09 – 2019/01/31
ICQ	49.5223° N, 67.2715° W	EHZ and HHE/N/Z	1996/02/15 – active
KGNO	44.2272° N, 76.4934° W	HHE/N/Z	2015/05/13 – active
LMQ	47.5485° N, 70.3258° W	EHZ and HHE/N/Z	2012/05/01 – active
MCNB	45.5958° N, 67.3198° W	HHE/N/Z	2016/05/21 – active
MOQ	45.3115° N, 72.2409° W	EHZ	1996/02/01 – active
NATG	50.2872° N, 62.8102° W	HHE/N/Z	2005/11/26 – 2017/09/22
ORIO	45.4515° N, 75.5110° W	HHE/N/Z	2016/12/02 – active
OTT	45.3942° N, 75.7167° W	EHZ and HHE/N/Z	1992/06/01 – active
QCQ	46.7792° N, 71.2756° W	EHZ and HHE/N/Z	1997/11/01 – active
SMQ	50.2225° N, 66.7025° W	EHZ	1996/02/02 – active
VABQ	45.9047° N, 75.6079° W	HHE/N/Z	2010/11/29 – 2018/05/18

SITE METADATA DATABASE

In situ non-invasive site characterization field work was completed in summer and fall 2017 to obtain a multi-method site characterization at the 25 seismic station sites. Field techniques involved active surveys such as a refraction survey, and a multi-channel analysis of surface waves and passive surveys which included ambient vibration survey and single station horizontal-to-vertical spectral ratio (HVSR). In addition, rock samples were collected at as many stations as possible. The survey techniques and computation of site characteristics are described in Ladak et al [2021] and Ladak [2020].

The field data were processed to determine the microtremor HVSR, Vs Profile, P-wave velocity (Vp) of lithological units, and the Poisson ratio of the subsurface beneath the station [Ladak, 2020; Ladak et al., 2021]. Earthquake HVSR were computed for all 3-component seismic stations. Earthquake HVSR were computed using the Konno Ohmachi [1998] (b-value 20) smoothed Fourier amplitude spectrum (FAS) where the horizontal, effective amplitude spectrum [Kotkke et al., 2018; 2021], was divided by the vertical spectrum. This database contains flatfiles for each station which show the resultant station site characterizations from Ladak et al. [2021; Ladak, 2020]; this includes Vs profiles inferred for each station, which vary from shallow (<100 m) profiles to deeper profiles (>1 km).

The metadata for each site includes: i) Station Name; ii) Station Location; iii) Recording type; iv) Surficial Geology [Geological Survey of Canada, 2014]; v) Bedrock Geology [Energie et Ressources Naturelle Quebec, 2012; Keppie, 2000; Ontario Geological Survey, 2011; Department of Natural Resources Minerals, Policy and Planning Division., 2008]; vi) rock sample identification; vii) seismic instrument mounting and housing types; viii) average Poisson Ratio [Ladak, 2020; Ladak et al. 2021]; ix) microtremor HVSR [Ladak, 2020; Ladak et al. 2021]; x) earthquake HVSR; x) Vs Profiles (DINVER and PWSP from Ladak [2020; Ladak et al., 2021]); xi) Vp of lithological units [Ladak, 2020; Ladak et al., 2021]; and xii) curated velocity profiles from literature [Stokoe, 2021; Kao et al., 2014; Bent et al., 2019; Bent personal communication, 2021; Kuponiyi et al., 2016; Cassidy, 1995].

RECORD DATABASE: SIGNAL PROCESSING

Velocity time series for all selected records were obtained from the AutoDRM system from Natural Resources Canada in SEED format (Data and Resources). The requested time series begin 70 seconds prior to the reported event time and contained a signal duration of 360 seconds. Many of the archived SEED files carry incorrect station response information in their header files. Dataless SEED files with the correct information for each station were obtained from Earthquakes Canada and the station response attributes were corrected accordingly.

Data processing was performed using a combination of the Seismic Analysis Code (SAC) program [Goldstein et al., 2003; Goldstien and Snoke, 2005] and Matlab. Using standard SAC procedures, the full time series was processed to obtain the instrument-corrected signal between 0.8 Hz and 0.8*Nyquist frequency (i.e. 40 Hz for 100 samples per second instruments); these procedures include removal of the mean and trends, tapering, and removal of the instrument response in the Fourier domain.

A Matlab script was used to update SAC earthquake event files to contain all reported event data, such as location of event, magnitude, etc., and the predicted P and S wave arrivals. The predicted P- and S-wave arrivals are computed by adding the expected travel times (as computed from a regional P- (6.0 km/s) and S-wave (3.7 km/s) velocity value and the hypocentral distance for the earthquake) to the reported origin time for the earthquake. A single analyst utilized SAC to manually select the P- and S-wave arrivals. As a primary check on the arrival picks, a Matlab script was used to flag the manually selected arrivals which differed from the predicted arrivals by >2%. The flagged arrivals were reexamined to confirm or correct the P- and S-wave arrival times.

From the processed full time-series seismograms, windowed signals were generated. The time series were windowed using the Goulet et al. [2014; 2021] windowing technique to produce a full signal, noise, P-wave, S-wave, and Coda wave signal. In this study, the "S-window" includes the S and Lg phases. Figure 2 shows a sample time series with the marked windows. Time series were cut, a 5% Hanning taper applied, and the time series were zero-padded to 400 seconds. Having a consistent time window ensures consistent frequency steps for all Fourier spectra. The Fast Fourier Transform was computed from the processed signals using SAC and then differentiated in the frequency domain to obtain the FAS of acceleration. From here on the FAS will refer to the FAS of acceleration.

FAS are generated for all records from a station – this can include the vertical, east-west, and north-south components. If a record has an east-west and north-south component then the effective amplitude spectra (EAS) [Kottke et al., 2018, 2021] was computed. We provide the Vertical and EAS Fourier spectra in our database. The resultant FAS were smoothed using a Konno and Ohmachi [1998] smoothing filter with a bandwidth coefficient b-value of 20; the smoothed FAS contains 400 log10-spaced frequency steps from 0.8 Hz to 40 Hz. Figure 3 shows a sample FAS before and after smoothing for the vertical and horizontal (EAS) components for the SLg and Noise windows. The smoothed FAS database contains a unique record name (data, time, and station); earthquake latitude, longitude, and depth; catalog magnitude and type [NRCan, 2020]; moment magnitude; the recorded station name, latitude, longitude, and elevation; component; the epicentral and hypocentral distances; the azimuth and back azimuth, origin time of the earthquake, the P and S-wave arrival times, the upper and lower frequencies for a signal-to-noise ratio (SNR)>3, and the smoothed FAS. The SNR is computed for all wave types using the Fourier amplitude spectral density (FASD) as outlined in Perron et al. [2018]. The FASD is the length-independent Fourier spectrum computed by dividing the FAS by the square root of the duration of the time window.

5%-damped response spectra are computed for all records from a station using the full signal window of the processed time series [Goulet et al., 2014; 2021]. We utilized Boore's [2010] RotDnn method to compute response spectra for period-dependent rotation angles (D) for 3 fractiles (nn): 0 (minimum), 50 (median), and 100 (maximum). When a record has two orthogonal horizontal velocity time series, we converted the time series to acceleration and then computed the rotated acceleration time series from 0 to 180 degrees in steps of 1 degree. We compute response spectrum at 30 frequencies log10-spaced from 0.8 to 40 Hz. The response spectrum were computed at each angle and the resultant pseudo-spectral acceleration (PSA) is the fractile spectral amplitude at all angles for a given frequency. The response spectrum database contains a unique record name (data, time, and station); earthquake latitude, longitude, depth; catalog magnitude and type [NRCan, 2020]; moment magnitude; recorded station name; station latitude and longitude; epicentral distance; hypocentral distance; the 5%-PSA at 30 frequencies; the peak ground velocity (PGV); and the peak ground acceleration (PGA).

The record database comprises: i) processed time series; ii) unsmoothed Fourier amplitude spectrum for the vertical and horizontal (EAS) components for each Goulet et al. [2014; 2021] window; iii) smoothed Fourier amplitude spectrum for the vertical and horizontal (EAS) components for each Goulet et al. [2014; 2021] window; and iv) the 5% damped response spectrum for the orientation-independent horizontal component using the Goulet et al. [2014; 2021] full signal time series.

SUMMARY/CONCLUSIONS

This report describes a compiled earthquake record database for eastern Canada that includes processed time series, Fourier amplitude spectra (unsmoothed and smoothed) for horizontal and vertical components for Goulet et al.'s [2014, 2021] windows, and station metadata describing conditions of each station. The database includes 39,424 records from 3318 events of **M**≥1.5 recorded at hypocentral distances from 5 to 150 km. The database has been used by Palmer and Atkinson (2020) to better understand high-frequency ground motions on rock sites, but may have many other potential uses.

We caution that the data from the smaller earthquakes may have a limited bandwidth for which SNR>3. Moreover, arrival pick error has not been estimated.

DATA AND RESOURCES

The earthquake database was provided from Natural Resources Canada's Earthquakes Canada - Geological Survey of Canada (GSC) on-line bulletin earthquake search at http://www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bulletin-en.php (last accessed September 2020). The seismograms for the earthquakes used in this study were provided by Earthquakes Canada – GSC email data service at AutoDRM@seismo.NRCan.gc.ca (last accessed September 2020). rdSEED is available from https://ds.iris.edu/ds/nodes/dmc/software/downloads/rdseed/. Seismic Analysis Code (SAC) program used for processing is available at https://ds.iris.edu/ds/nodes/dmc/software/downloads/sac/ [Goldstein et al. 2003; Goldstein and Snoke, 2005].

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FIGURES

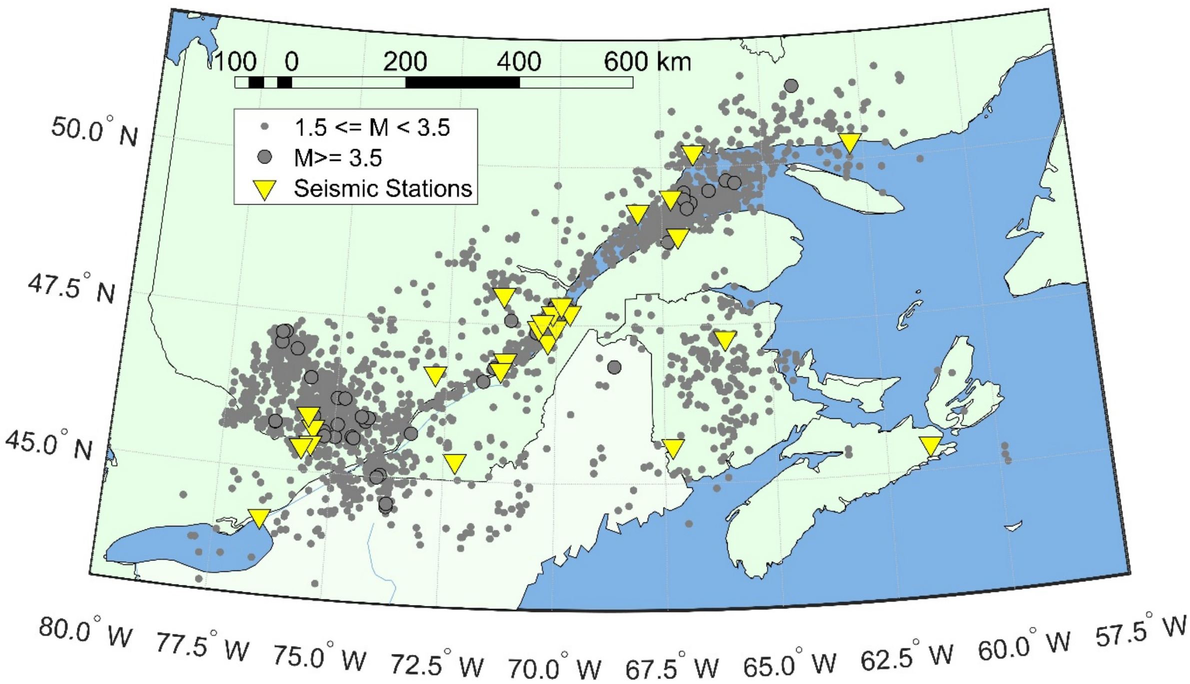

Figure 1: Earthquake locations (grey circles) for **M**≥3.5 (large with black ring) and **M**<3.5 (small) and the seismic stations (yellow triangles) in this database.

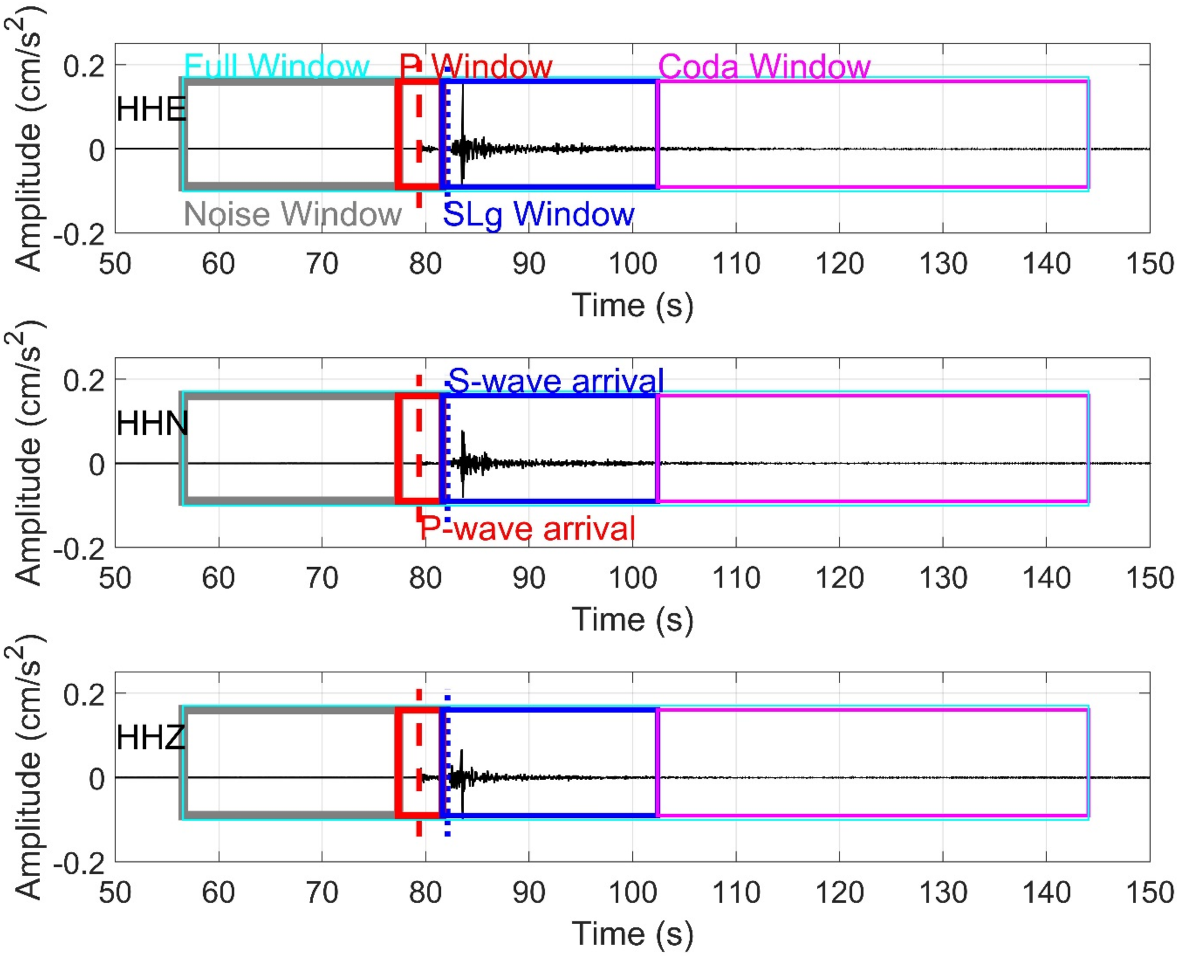

Figure 2: Sample time series of earthquake 2013/07/11 20:16:07 for station A21 showing the Goulet et al. [2013;2021] windowing method. The full window (cyan box), noise window (grey box), P-wave window (red box), S-wave window (blue box), and Coda window (magenta box) are shown in each of the three components time series. The P wave arrival manual pick is shown by a vertical dashed red line and the S-wave arrival manual pick in dotted blue line.

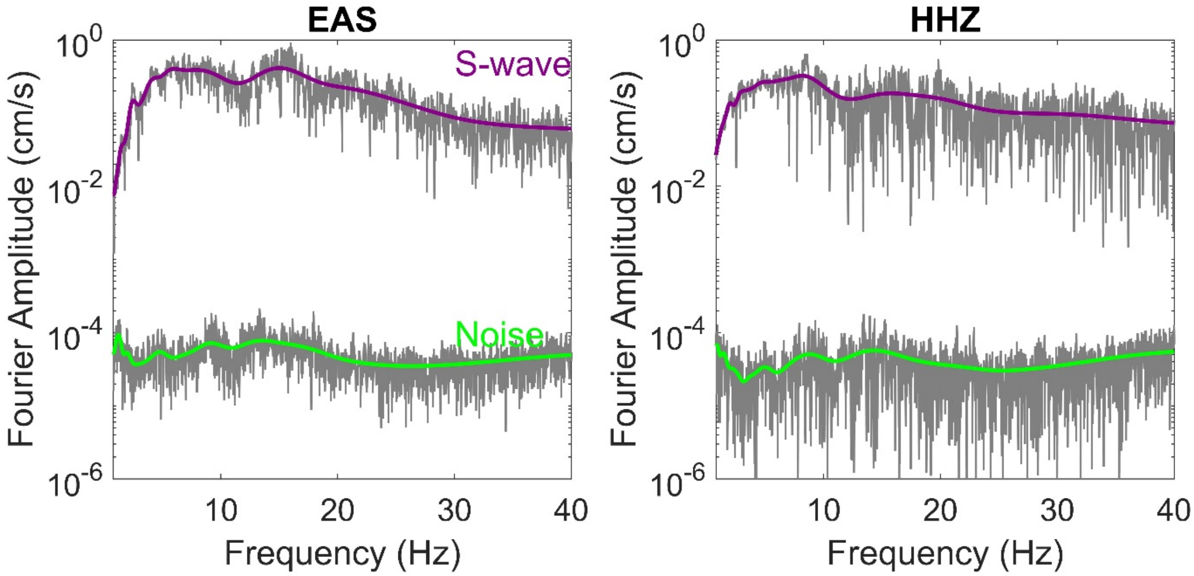

Figure 3: Sample Fourier amplitude spectrum of acceleration for earthquake 2013/07/11 20:16:07 recorded at station A21. The S-wave and noise window uncorrected (grey) are shown beneath the respective smoothed S-wave (purple) and noise window (green) Fourier amplitude spectrum of acceleration for the EAS (left) and the vertical spectrum (right).