Elsevier Editorial System(tm) for Soil Dynamics and Earthquake Engineering
Manuscript Draft

Manuscript Number:

Title: SITE RESPONSE IN TECOMAN, COLIMA, MEXICO. I. COMPARISON OF RESULTS FROM DIFFERENT INSTRUMENTS AND ANALYSIS TECHNIQUES

Article Type: Research Paper

Keywords: site effects; spectral ratios; earthquake data, ambient vibration

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Dear Sir,

Please find enclose the paper SITE RESPONSE IN TECOMAN, COLIMA, MEXICO. I. COMPARISON OF RESULTS FROM DIFFERENT INSTRUMENTS AND ANALYSIS TECHNIQUES by J. Tejeda-Jácome and myself, which we submit for possible publication in Soil Dynamics and Earthquake Engineering. This paper is the first part of a two-part study of site effects in Tecoman. The second part is being submitted simultaneously.

Sincerely,

Francisco J. Chávez-García

Instituto de Ingeniería, UNAM

Mexico

SITE RESPONSE IN TECOMAN, COLIMA, MEXICO. I. COMPARISON OF RESULTS FROM DIFFERENT INSTRUMENTS AND ANALYSIS TECHNIQUES

by

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Submitted to

Soil Dynamics and Earthquake Engineering

May, 2009

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ABSTRACT

This paper presents a study of site effects in the urban area of Tecoman in Colima, Mexico. A variety of instruments (both accelerometers and seismometers) were used to record earthquakes and ambient vibration throughout the city. Earthquake records were analysed using several techniques to estimate site effects: spectral ratios relative to a reference station, spectral ratios of the horizontal components relative to the vertical recorded at the same site, and a parametric inversion of Fourier spectra. Ambient noise records were used to estimate a local transfer function using horizontal to vertical spectral ratios. The results show that local amplification at Tecoman is significant. Dominant frequency varies between 0.5 and 0.7 Hz, suggesting a large thickness of the soft sedimentary deposits. We did not observe systematic variations throughout the city. Our more reliable estimates indicate that maximum amplification is comprised between a factor 6 and 8. Comparisons among different sensors and recorders show that all combinations between velocimeters, accelerometers and recorders provide reliable results provided that the electronic noise is smaller than the noise being recorded. This is notably not the case for accelerometers at quiet sites and for frequencies smaller than 2 Hz. This explains why previous studies disagree as to the usefulness of accelerometers to record ambient noise for site effect studies. This factor is, however, a function of noise amplitude at each site.

Keywords: site effects, spectral ratios, earthquake data, ambient vibration

1. Introduction

It is well known that seismic motions may be increased significantly in surface sedimentary basins. The subsoil impedance contrast can amplify the vibration level and increase the duration of strong ground motion. It is also widely accepted that the most reliable estimates of the amplification due to soft surficial layers is obtained analyzing earthquake records. For example, if a suite of events is recorded simultaneously on soft soil and at a reference site, free of local amplification, spectral ratios provide a reliable estimate of the soft soils transfer function (e.g. [1,2]). However, if the seismicity rate is moderate, or an adequate reference site cannot be found, it becomes a difficult method to apply. For this reason, alternatives based on records of ambient vibration have gained popularity. Noise records, usually analysed using horizontal to vertical spectral ratios [3,4], have proved reliable to determine a dominant frequency of soft soil deposits. Regarding the maximum amplification, results have been mixed. Although it is mostly accepted that a simple geometry and large amplification factors usually mean that amplification is reliable, more sites where noise results are compared with earthquake estimates are required.

An additional problem regarding site effect estimation using noise records concerns the recording instrument. It is generally accepted that seismometers are more reliable than accelerometers to record ambient vibration. However, good results have been found sometimes using ambient vibration recorded with accelerographs. There are still few places where noise results to estimate site effects have been compared using several types of instruments at the same sites.

In this paper we present a site effect study in the city of Tecoman, Mexico, located close to the Pacific coast, at the northern end of the Mexican subduction zone (Figure 1). The seismicity rate there is much smaller than further south, in Guerrero. However, large earthquakes do occur. The two more recent destructive Mexican earthquakes occurred there in 1995 [5] and 2003 [6,7]. The study in Tecoman allowed us to investigate site effects comparing results from earthquake and ambient vibration data recorded using accelerometers and seismometers. Our results provide a reliable determination of local amplification at Tecoman and show significant amplification at relatively low frequencies. Surprisingly, amplification functions determined using noise records prove to be more stable than those determined using earthquake data, a result that is due to the limited number of events recorded by our temporary seismic arrays but which is likely to affect results obtained in similar regions of moderate seismicity. Finally, we are able to shed some light on the reason for the occasional differences between results using accelerometers and seismometers. We show that this difference is related to the amplitude of seismic noise and is therefore site dependent.

2. Data

We recorded both earthquake data for small events and ambient seismic noise, using a variety of recorders and sensors installed temporally at Tecoman. We took advantage of a permanent acceleration station operating close to this city on rock: COJU (Etna recorder by Kinemetrics coupled to an Episensor accelerometer) installed on limolite-sandstone. We used this station as reference. It is located 9.0 km from the center of Tecoman. In addition to that station, we have earthquake records from two arrays: a large scale linear array covering more than 100 km and a small one, installed specifically to determine site effects in Tecoman. From the first array we use the two stations located in Tecoman: BAC5, where a Geosig GSR18 operated, and CTEC, where a Kinemetrics Etna accelerograph was installed. This array operated from March to

August, 2006. BAC5 station recorded 9 events (5 of which were also recorded at COJU, the reference station) and CTEC station recorded 3 events (2 of which were also recorded at COJU). The second array was installed in September, 2006, and operated 9 seismographs for 4 months. Each station consisted of three 4.5 Hz geophones coupled to a SADC-20 digitization card by Sara. The resulting data streams were recorded by a dedicated PC at each site. This weak motion array recorded 15 events at three stations or more. Table 1 gives relevant data of all recorded events, while Figure 2 shows the location of the stations.

In addition to earthquake data, ambient seismic noise was also recorded. Short noise records were obtained from false triggers at the permanent acceleration station COJU, and at stations BAC5 and CTEC. The 9-station seismograph array recorded continuously ground motion. Thus, we had plenty of noise windows for analysis at those sites. In addition, we recorded ambient vibration at some of those sites using three additional combinations of sensor and recorder: a K2 accelerograph by Kinemetrics coupled either to a FBA-23 acceleration sensor or to a Guralp CMG40 velocity sensor and an Etna accelerograph by Kinemetrics coupled to an Episensor acceleration sensor. Not all sites were covered with all instrument arrangements. However, we have enough sites to be able to discuss the results obtained using different instrument types.

3. Techniques of analysis

The analysis of the earthquake data to estimate a local transfer functions made recourse to spectral ratios and to a parametric inversion of the Fourier spectra. In both cases, input data were Fourier amplitude spectra of a 20 sec window centered on the S-wave train. We computed spectral ratios relative to a reference station (SSR) following the standard procedure (e.g., [1, 2]). This technique is accepted as providing a reliable estimate of local amplification when results for several (the number varies according to the author) events are averaged. Unfortunately, in regions of moderate seismicity, it is not easy to obtain simultaneous records in the reference and soft soil stations. This was our case in spite of the operation of our arrays during several months. For this reason, we also estimated site effects computing the spectral ratio of the horizontal components relative to the vertical recorded at the same site (HVSR) using the same spectra for the S-wave window [8]. In this case, each single record can contribute to the average estimate at the recording site.

The third technique we used to estimate site effects from earthquake data was to compute a parametric inversion (PI) of the same Fourier amplitude spectra for the 20 sec window of S-waves. This technique, initially proposed in [9], fits a ω^2 model, described by two parameters, seismic moment and corner frequency, to the observed spectra. Propagation is taken into account using a constant Q factor throughout the region. Site effects are estimated as the average residual of all observations at a site to this simple model [10, 11, 12]. One problem with this technique is an inherent ambiguity: a constant amplification factor can be arbitrarily applied to the source term and equivalently removed from all site responses. To remove this ambiguity, an independent determination of seismic moments or the local transfer function at anyone site must be known. We do not have such an independent constraint. Thus, the transfer functions we determined using PI are relative to the average site response for all stations and therefore biased to smaller values.

Local transfer functions were also estimated using ambient vibration records. We have followed current practice and estimated those functions using horizontal to vertical spectral ratios (e.g., [3, 4]). HVSR using microtremors have been shown to give a very reliable estimate of dominant frequency. Its estimates of amplitude of amplification are considered less reliable. A more complete discussion may be found in [13] and in the documents produced by the SESAME project (http://sesame-fp5.obs.ujf-grenoble.fr/index.htm). From the records at each site of the seismograph array, 30-minute windows were selected, where the noise record was stationary, without transients (usually at night time). From those records, a number of 40 s time windows were extracted. The final estimate is the average of many HVSR computed for 40 sec windows. The same technique was applied to shorter time windows of ambient vibration, recuperated from false triggers of the acceleration stations. In all cases we computed an average transfer function from the two horizontal components.

4. Results using earthquake data

Figure 3 shows the transfer functions obtained at sites CTEC and BAC5 from the SSR technique using 2 and 5 events respectively. Although amplification values are large (larger than 10 for CTEC), the transfer functions do not identify particular frequencies for site effects. Moreover, when we look at individual spectral ratios for each event, we observe a large scatter without a good agreement among them. The first possible problem comes from COJU being installed on limolite-sandstone, whereas the geologic basement consists of limestone. Thus, although local site conditions for COJU are firm ground and no local amplification is expected (see below for results for ambient noise at this station), it is extremely likely that ground motion recorded at COJU is not representative of incident ground motion below the sediments filling Tecoman valley. Another possible problem is that the records come from nearby small events, which implies very short durations of the S-wave window. Finally, the distance between soft soil and reference stations (BAC5 is 7.7 km away from COJU, while CTEC is located 5.4 km from

COJU) may not be negligible relative to the epicentral distance, as required by the assumptions behind SSR.

Consider now the results from horizontal-to-vertical spectral ratios using earthquake data. The average curves were superposed to SSR curves in Figure 3. The amplification obtained using HVSR with the acceleration records at BAC5 and CTEC is smaller than that from SSR. The frequency bands where amplification occurs are better defined by HVSR, with one peak at almost 0.7 Hz and a second between 1.3 and 2 Hz. The observation that local amplification is significant in those 2 frequency bands is confirmed when we observe the HVSR for all events recorded by the seismograph network (Figure 4). All empirical transfer functions show clearly a simple shape with a first peak around 0.6-0.7 Hz and a second peak between 1.2 and 2.1 Hz. The frequency relation between them suggests a simple 1D site response, where the HVSR curves are able to identify both the fundamental and the first higher resonant peaks. Neither the value of resonant frequency nor the peak amplification show a systematic variation throughout Tecoman, which suggests that the differences between measurements points are due to small irregularities in the interface between sediments and bedrock or to small laterally varying stiffness of the sediments (something expected for soil deposits close to the sea). The similarity in the results for HVSR between BAC5 and COJU and the stations of the seismograph array suggest that SSR for earthquake records are not able to estimate site effects, even using the 5 records at BAC5.

We may compare the results in Figure 4 with those obtained from the parametric inversion of S-wave Fourier amplitude spectra, shown in Figure 5. The general shapes are very similar (perhaps with the exception of INDE) though the amplitudes are much smaller. However, the results from PI confirm that site response at Tecoman is simple, with the resonant frequency located at about 0.6-0.7 Hz. These results suggest again that HVSR using earthquake records are more trustworthy than SSR in Tecoman’s case.

5. Results using ambient vibration records

We computed local amplification using HVSR for noise records obtained at observed sites in Tecoman. At most sites we obtained results using four instruments: the SADC20 seismographs coupled to 4.5 Hz geophones, a K2 by Kinemetrics coupled to a FBA accelerometer or to a Guralp, CMG40, broad band seismometer, and an Etna accelerograph by Kinemetrics coupled to an Episensor accelerometer. A representative example of the results is shown in Figure 6, for the two stations AYTO and BOMB. In both cases the estimate of local amplification produced with the combination K2-Guralp is very close to the estimate using HVSR of earthquake records. Two amplification peaks are well defined at 0.6 and 1.4 Hz. These two peaks are well identified by the curve obtained from the SACD20 seismograph at BOMB, although the relative amplitudes are reversed. In the case of AYTO, only the second peak appears clearly and the amplitude of the curve decreases at lower frequency values. In the two cases, the transfer functions estimated from noise records obtained using Episensor or FBA accelerometers are able to identify the second amplification peak, with reduced amplitude and shifted to higher frequencies. However, for frequencies smaller than 1.5 Hz those estimates become useless. Similar results were observed for all the other stations.

HVSR was also computed for noise windows recorded during false triggers at the accelerograph stations. The records were carefully windowed to avoid the spikes that triggered the instrument, and only keep windows of stationary ambient vibration. Of particular interest are the results for COJU, shown in Figure 7. They show a flat transfer function, as expected for a station on firm ground. This result indicates that the failure of SSR to estimate local amplification is not due to site effects present in the reference station.

6. Discussion

We showed that HVSR of ambient vibration recorded either with FBA or Episensor accelerometers were not useful for frequencies below 1.5 Hz. This contrasts with the good results obtained using broad band seismometers or even 4.5 Hz geophones, which correctly indentified an amplification peak at 0.6 Hz. Following [14], we investigated whether electronic noise could be the problem. We triggered recording in our K2 accelerograph after shorting the terminals corresponding to the sensor. The recorded signal corresponds thus to the electronic noise of the accelerograph. The power spectral density (PSD) of this record is shown in Figure 8 together with the PSD of noise recorded at PROC using Episensor or FBA accelerometers. Figure 8 also shows the low and high noise models of [15] as reference. Clearly, the amplitudes of the PSD of noise recorded with accelerometers are too close to the electronic noise measured for the K2 accelerograph for frequencies below 2 Hz. The low sensitivity of the sensor gives a signal of low amplitude that has the same amplitude as the electronic noise of the recording instrument. We can compare this with the PSD of ambient vibration recorded with the same K2 accelerograph but coupled to a Guralp seismometer, also shown in Figure 8. The PSD has much larger amplitudes and the corresponding signal is representative of seismic noise of the ground at the recording site.

However, ambient noise recorded using accelerometers have been shown to give reliable results. For this reason, we made similar analyses for ambient vibration recorded at Roma, a site close to downtown in Mexico City, where traffic and people generate large amplitude noise even at frequencies smaller than 1 Hz. The observed PSD's are shown in Figure 9. The amplitude of cultural noise is able to overcome the low sensitivity of the accelerometer and the site effects determined using those records provided a transfer function that has been validated using many earthquake recordings. Thus, the low sensitivity of the accelerometers is a problem only at quiet sites, where ambient vibration has small amplitudes, and is therefore site dependant.

7. Conclusions

We have presented an experimental study of site effects at Tecoman city using different analysis techniques applied to earthquake and ambient noise records obtained using seismographs and accelerographs. Our results suggest that SSR using earthquake data may fail to determine a reliable local amplification transfer function, even if it is generally considered a very dependable technique. Possible causes are the small number of simultaneously recorded events, small magnitudes, and large (relative to epicentral) distances between soft soil sites and reference station (site effects at the reference station were ruled out by the results of HVSR of microtremors). However, we believe that the more likely cause in Tecoman's case is that ground motion recorded at the reference station (COJU) is not representative of incident motion below the sediments. COJU site is located on limolite-sandstone, while the basin's basement consists of limestone. The use of HVSR with earthquake records proved to be more trustworthy, as shown by the similarity in shape between those and the results from PI. These results show clearly the fundamental mode of soil amplification at 0.6 Hz, even when earthquakes were recorded using 4.5 Hz geophones. This is in agreement with the results reported in [14].

We observe that the results obtained using HVSR of noise records obtained using seismometers are very good. Dominant frequency and amplification are well estimated and fundamental and first higher modes are identified in the transfer functions. The transfer functions have a similar shape to those obtained using PI and HVSR for earthquake records. This is very likely the result of a simple subsoil structure where a single interface controls local amplification. It is remarkable that HVSR of noise records obtained using 4.5 Hz geophones identify correctly the amplification peak between 1 and 2 Hz, and at some sites even the peak at 0.6 Hz appears clearly. Unfortunately, this is not the case for all sites and sometimes the peak below 1 Hz is missed.

It has been reported that HVSR for noise records measured using accelerometers are not reliable, whereas other authors have obtained useful results. In Tecoman’s case, results for noise records are not good using acceleration sensors; they miss the amplification peak corresponding to the fundamental mode at low frequencies. We have shown this to be due to a combination of low sensitivity of the sensor and quiet sites, where ambient vibration has low amplitude.

Our results show that the city of Tecoman is settled over a uniform alluvial valley. The amplification at each station is due to the same soft soil layers, but their thickness changes slightly from site to site which provokes light changes at the natural frequencies of vibration. The fundamental mode is between 0.56 and 0.71 Hz, whereas that of the first higher mode is between 1.4 and 2.1 Hz. Maximum amplification factors attain 8.1. The relation between observed site effects and subsoil structure is explored in a companion paper.

Acknowledgment

We thank the authorities from the different schools and public buildings where the temporal seismic stations were installed. Their support made our measurements possible. We thank J. A. Vázquez Montes for his help. H. Mijares took care of our instruments and made the electronic noise measurements. We thank M. Rodríguez for his suggestions. The data for COJU station was provided by Coordinación de Instrumentación Sísmica, Instituto de Ingeniería, UNAM. This study was supported by CONACYT, Mexico, through contract SEP-2003-C02-43880/A.

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Figure Captions

Figure 1. Location map of Colima and Tecoman in Mexico. Subduction zone is shown as the solid line, parallel to the coast, with the solid triangles. The solid square shows the location of Tecoman city. The open circles show the epicenters of the recorded events while the open triangle shows the location of Colima volcanoe.

Figure 2. Geologic map around the city of Tecoman. Dashes indicate limestone outcrops (cz). Dots indicate outcrops of limolite-sandstone (ar-li). The rest of the map corresponds to alluvial deposits (al). Solid triangles indicate the location of the accelerographic stations both permanent (COJU) and temporal (CTEC and BAC5). The solid circles show the location of the stations of the temporal seismograph array.

Figure 3. Transfer functions determined for stations CTEC and BAC5 using earthquake data. The lines marked as "ssr" correspond to spectral ratios relative to the reference station (COJU). The lines marked "hvsr" were obtained computing horizontal to vertical spectral ratios on the S-wave windows of all earthquake records at each station.

Figure 4. Estimation of site effects for all nine stations of the seismograph network. Each curve shows the average for all events and the two horizontal components of the horizontal to vertical spectral ratios of the S-wave window.

Figure 5. Estimation of site effects obtained from the parametric inversion of Fourier amplitude spectra of events recorded by the 9-station seismograph array.

Figure 6. Comparison of horizontal to vertical spectral ratios of noise records at two sites, using different combinations recorder-sensor. (a) Station Ayto. (b) Station Bomb. ETN-EPI refers to an episensor accelerometer coupled to an Etna accelerograph. K2-FBA means a K2 accelerograph coupled to an FBA accelerometer. K2-GUR refers to a K2 accelerograph coupled to an external broad band Guralp seismometer. SADC indicates the result from ambient vibration measurements obtained with the SADC20 digitizers coupled to 4.5 Hz geophones.

Figure 7. Horizontal to vertical spectral ratios for ambient vibration recorded at the permanent accelerographic station COJU during false triggers. Solid line: average for the NS component. Dashed line: average for the EW component.

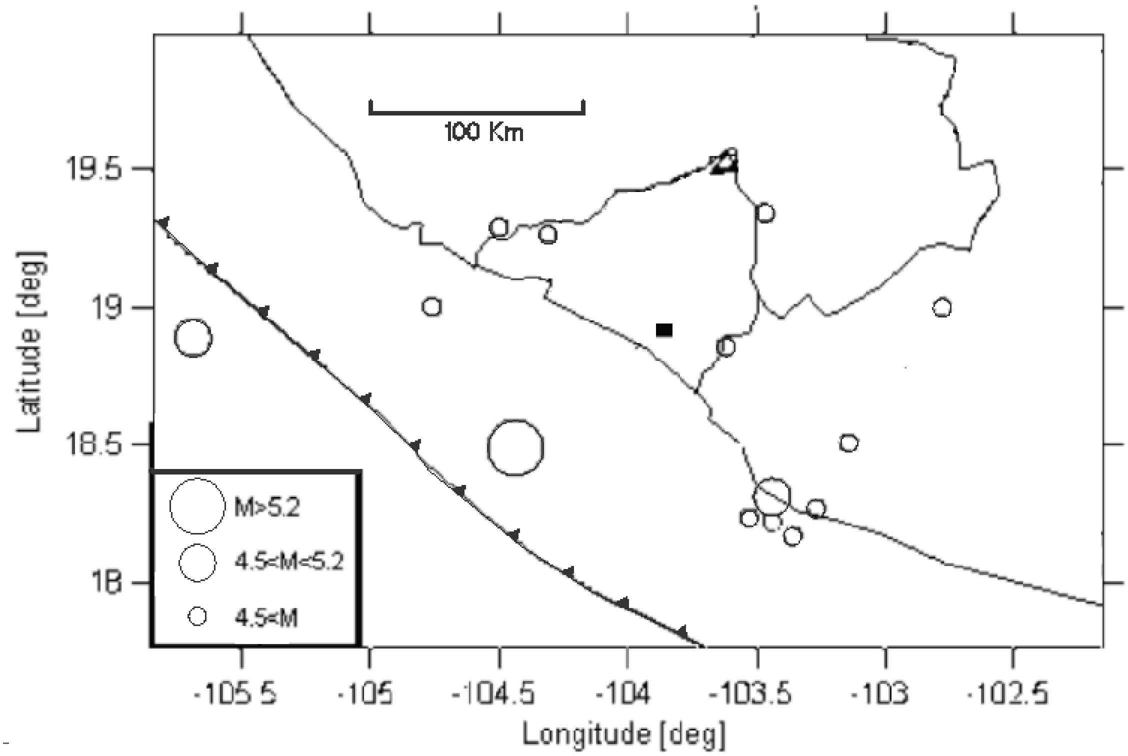
Figure 8. Power spectral density of ambient vibration recorded using different combinations recorder-sensor at station Proc. The key to the lines is the same as in Figure 6. In addition, NHNM and NLNM indicate the new high and low noise models of Peterson (1993), as reference. K2-ELEC refers to electronic noise recorded at a K2 accelerograph after shorting the terminals corresponding to the sensor.

Figure 9. Power spectral density of ambient vibration recorded using different combinations recorder-sensor at a site on the lake-bed zone, close to downtown in Mexico City. The key to the lines is the same as in Figure 6. In addition, NHNM and NLNM indicate the new high and low noise models of Peterson (1993), as reference. K2-ELEC refers to electronic noise recorded at a K2 accelerograph after shorting the terminals corresponding to the sensor.

Table 1. Relevant data of recorded earthquakes

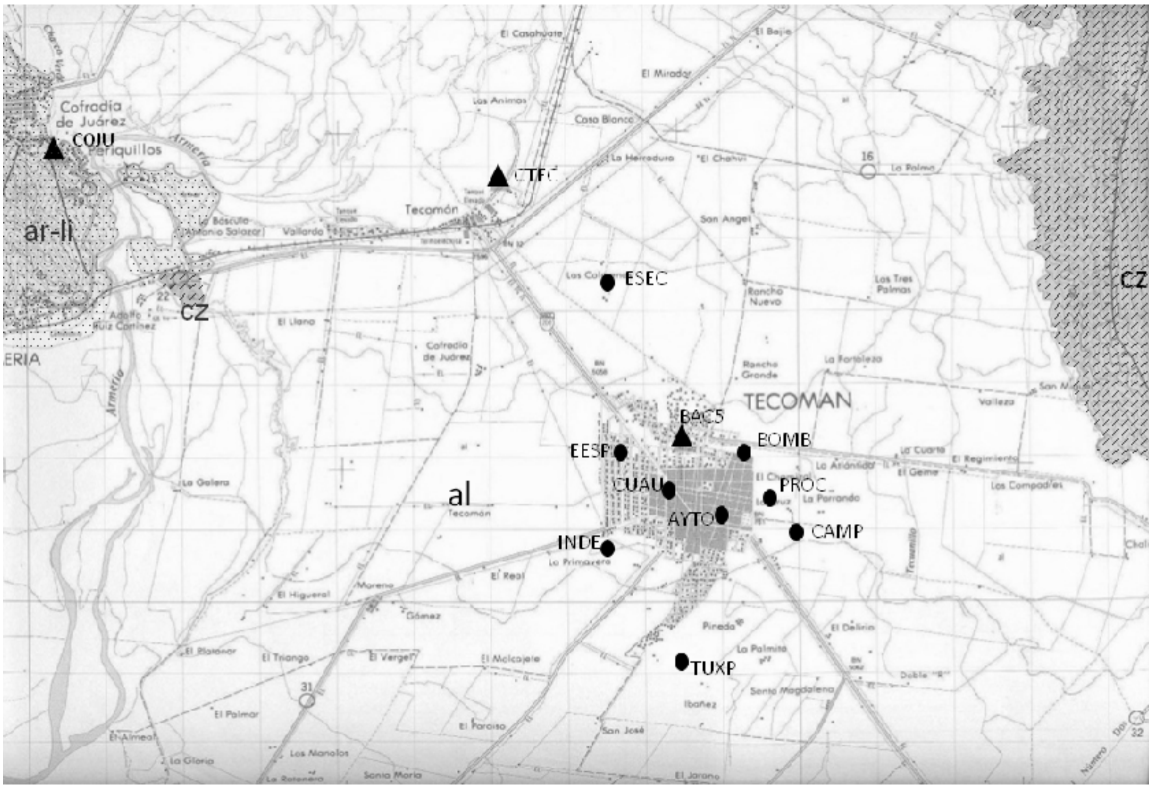
	Date	Latitude	Longitude	Depth [km]	Magnitude
1	16-09-2006	18.89	-105.69	39	4.6
2	20-09-2006	19.00	-104.76	21	3.7
3	13-10-2006	19.29	-104.50	20	4.2
4	14-10-2006	19.34	-103.47	40	4.1
5	19-10-2006	19.00	-102.78	74	4.0
6	21-10-2006	18.24	-103.53	05	4.2
7	06-11-2006	18.86	-103.62	15	3.8
8	12-11-2006	19.26	-104.31	28	4.2
9	19-11-2006	18.49	-104.44	18	5.2
10	21-11-2006	18.60	-101.89	59	4.3
11	25-11-2006	18.22	-103.44	06	4.0
12	10-12-2006	18.31	-103.44	07	4.6
13	27-12-2006	18.51	-103.15	15	4.0
14	29-12-2006	18.17	-103.36	05	3.7
15	05-01-2007	18.27	-103.27	10	4.3

Figure1



100 Km
19.5
19
18.5
18
Latitude [deg]
-105.5
-105
-104.5
-104
-103.5
-103
-102.5
Longitude [deg]
M>5.2
4.5<M<5.2
4.5<M

Figure2



COJU
CTEC
ESEC
BAC5
EESP
BOMB
CUAU
PROC
AYTO
CAMP
INDE
TUXP
ar-li
cz
CZ
al
TECOMAN

Figure3

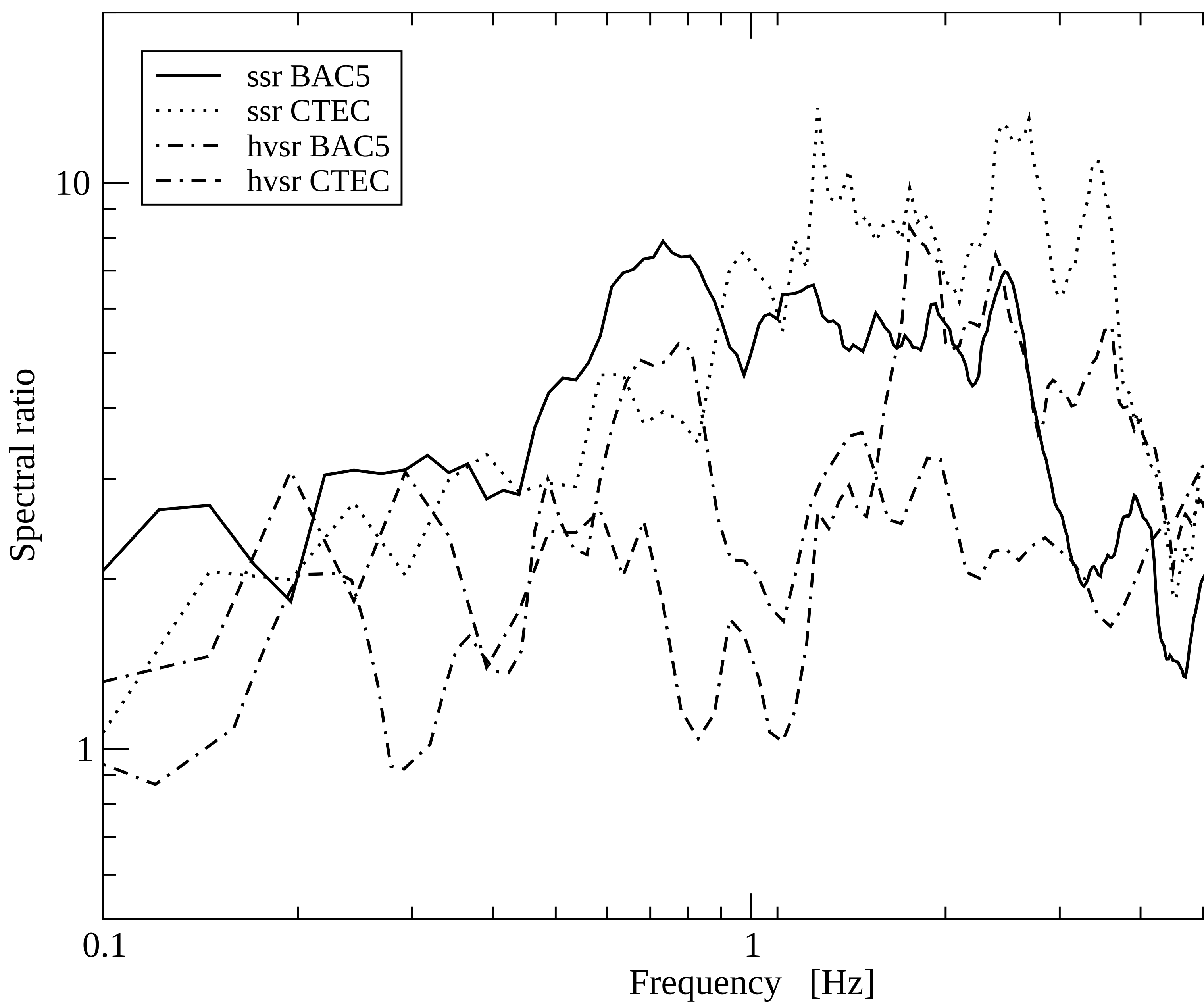

ssr BAC5
ssr CTEC
hvsr BAC5
hvsr CTEC
10
1
Spectral ratio
0.1
1
Frequency [Hz]

Figure4

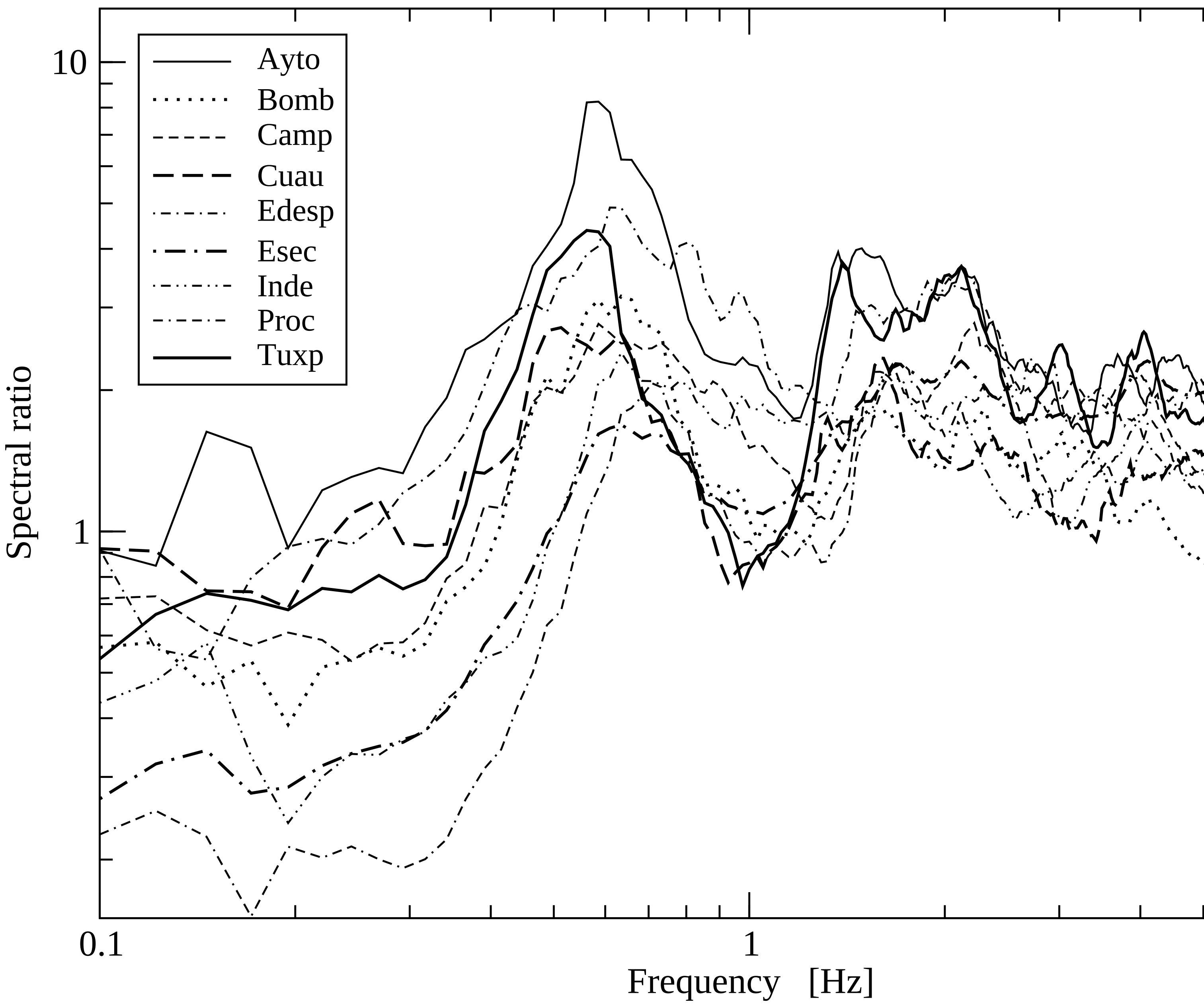

10
1
0.1
1
Ayto
Bomb
Camp
Cuau
Edesp
Esec
Inde
Proc
Tuxp
Spectral ratio
Frequency [Hz]

Figure5

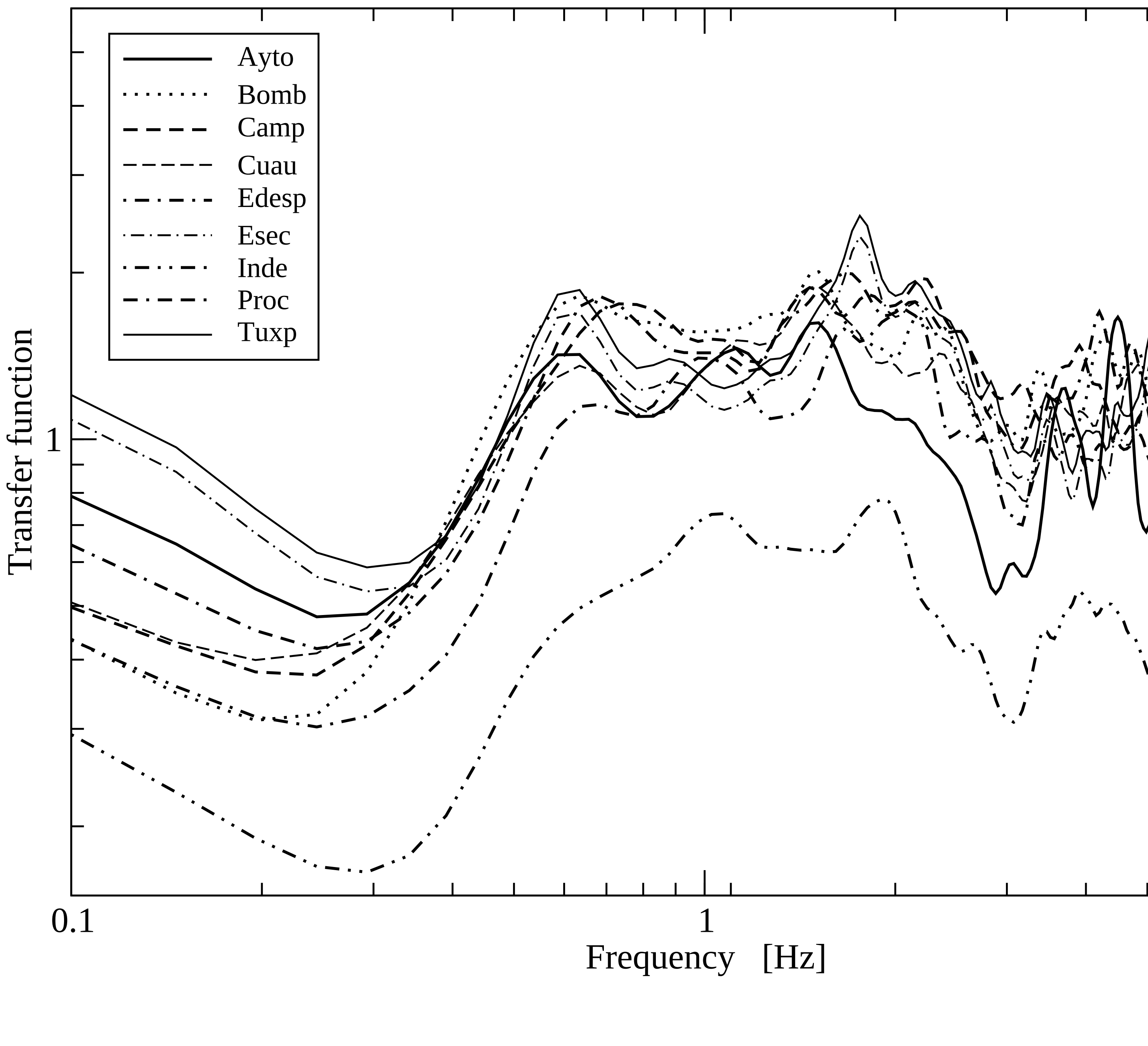

Ayto
Bomb
Camp
Cuau
Edesp
Esec
Inde
Proc
Tuxp
Transfer function
1
0.1
1
Frequency [Hz]

Figure6

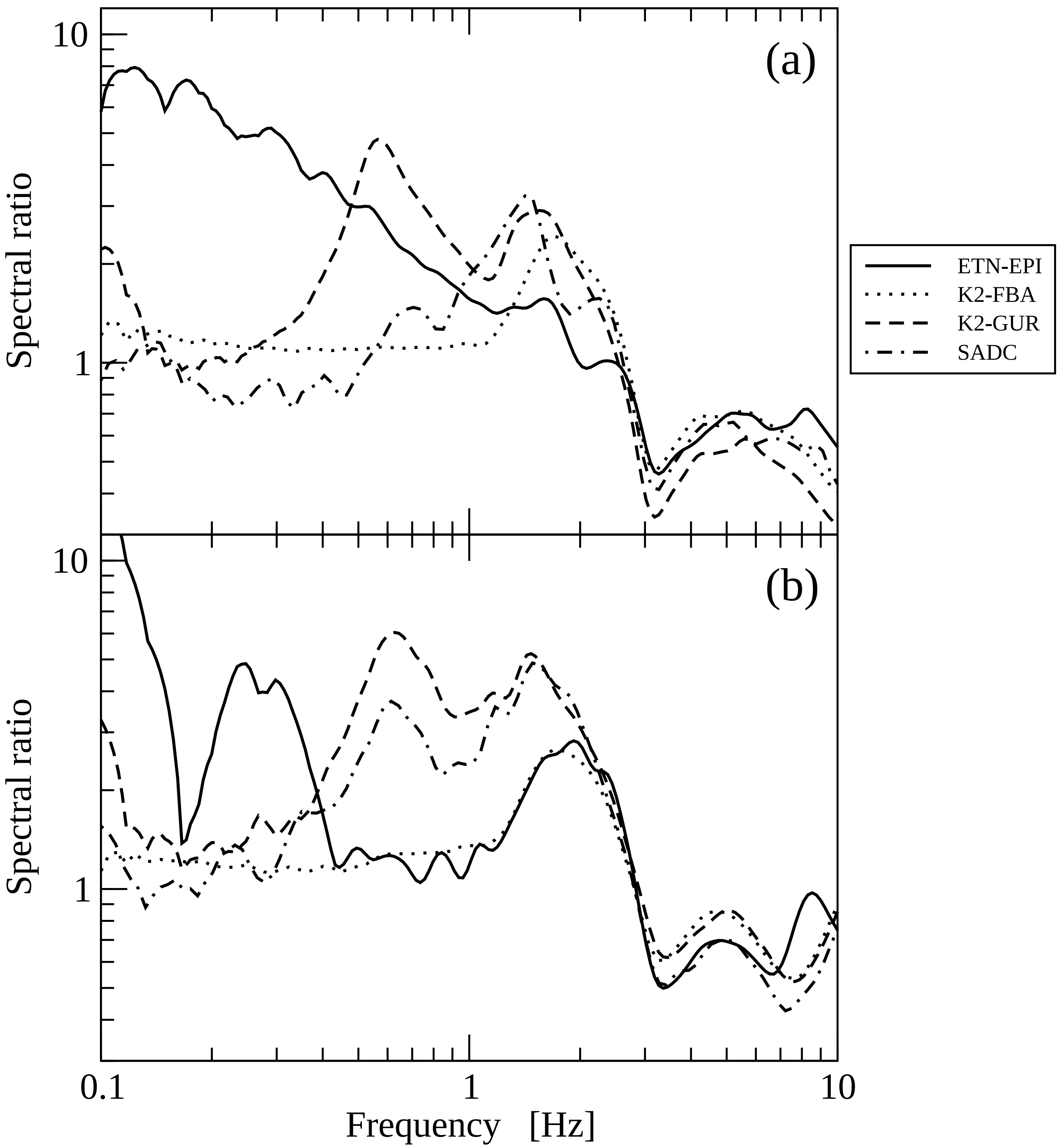

10
1
(a)
10
1
(b)
Spectral ratio
Spectral ratio
0.1
1
10
Frequency [Hz]
ETN-EPI
K2-FBA
K2-GUR
SADC

Figure7

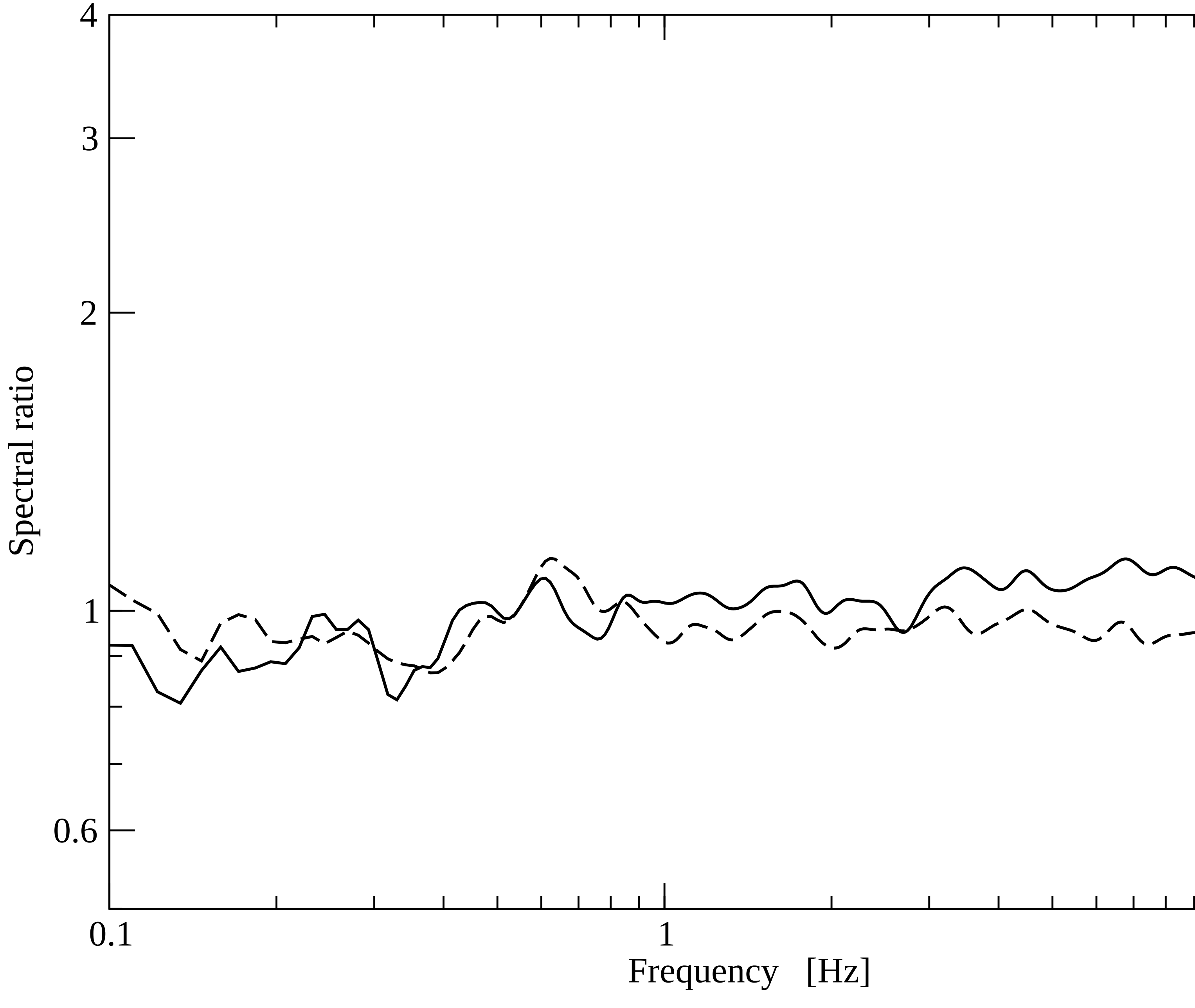
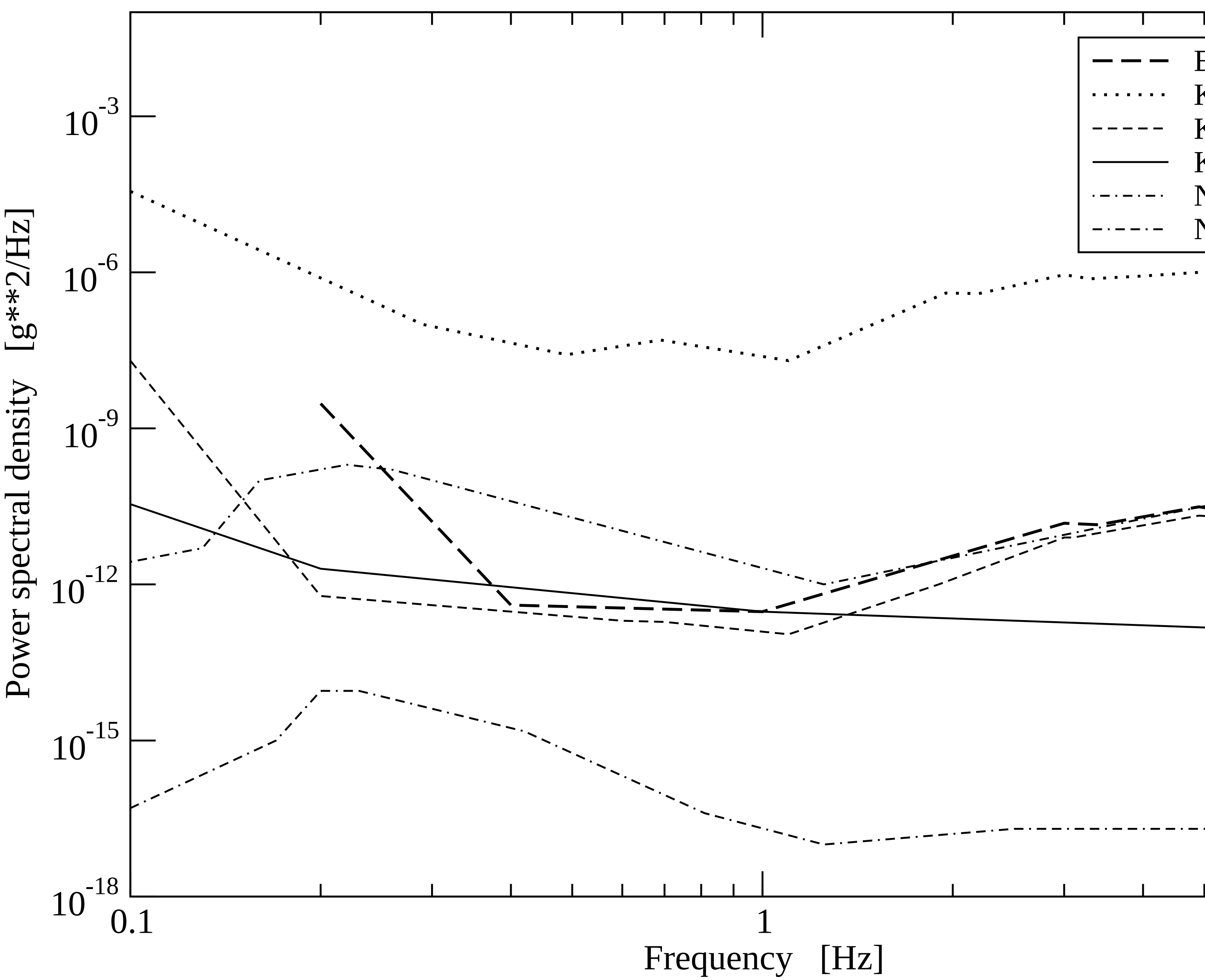
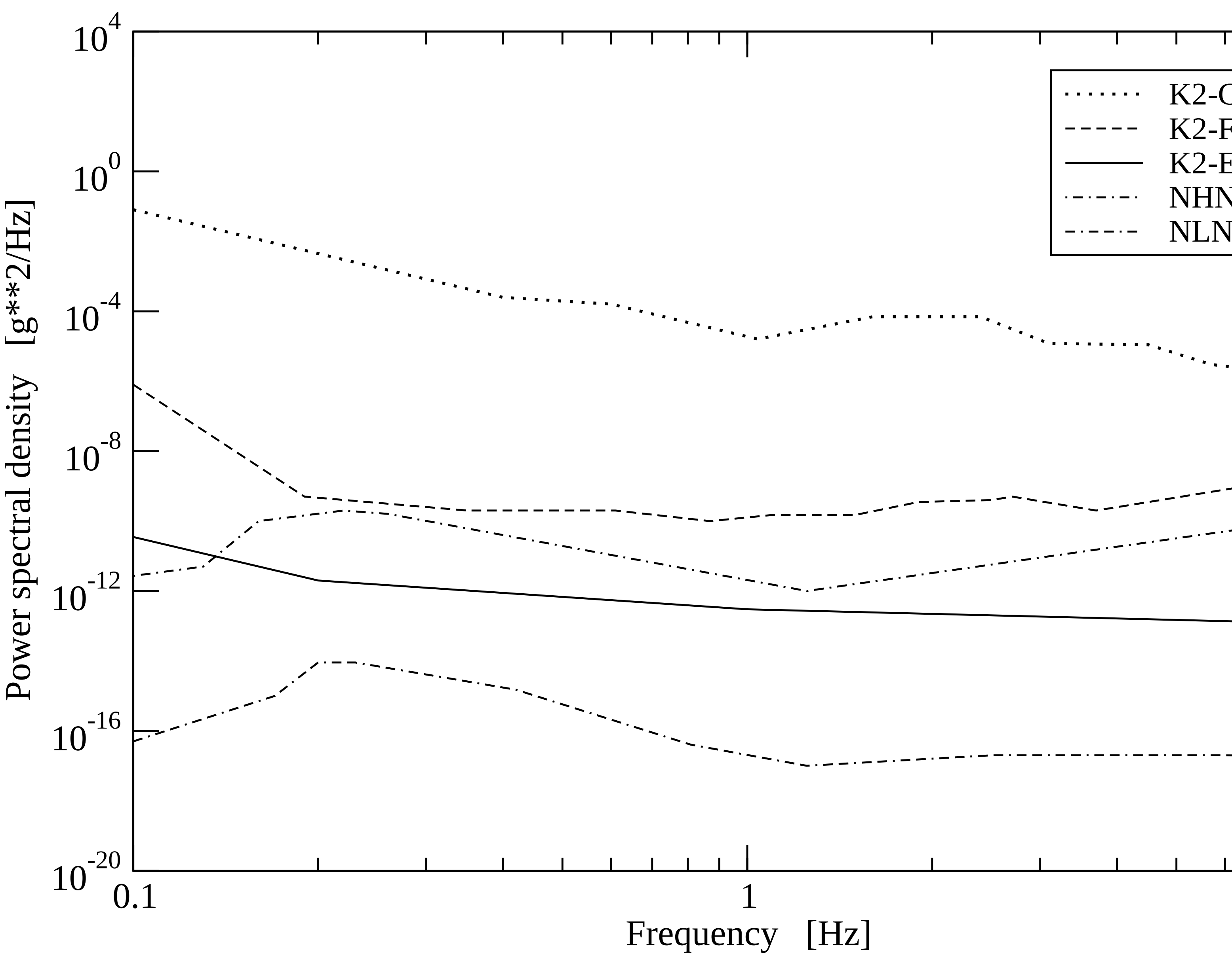


Figure8



Power spectral density [g**2/Hz]
Frequency [Hz]
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
0.1
1

Figure9



K2-C
K2-F
K2-E
NHN
NLN
Power spectral density [g**2/Hz]
Frequency [Hz]
10^4
10^0
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
0.1
1