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Abstract:

Natural Resources Canada was asked for assistance by the Ontario Ministry of the Environment in their ongoing investigation of “rumblings” reported in Essex County, Ontario. Reports of the rumblings which appear to be a combination of vibrations and low frequency noise began in March 2011 and are continuing as of this writing (September 2011). In June 2011 four seismometers were installed in the western part of the city of Windsor where the largest number of noise complaints originated. The stations ran until late August 2011. Examination of the data revealed a signal on two of the stations that was consistent in character with the reported rumblings in terms of time, duration and behavior. Further analysis of the signals revealed that they were propagating as acoustic waves in the atmosphere and that they originated from the general vicinity of Zug Island, Michigan. Further investigation is required to determine the exact source of the signal.

Background:

Since March 2011, the Ontario Ministry of the Environment (MOE) has been receiving complaints about “rumblings” in the Windsor area. These rumblings have been described as being analogous to a large diesel truck idling or a loud boom box. The rumblings are usually intermittent but sometimes continue for several hours. MOE investigated several local industries but could not identify the source of the rumblings.

Periodically throughout the spring of 2011 Natural Resources Canada (NRCan) received calls asking whether there had been any earthquake activity in the Windsor area. In each case, the seismograms recorded by the Canadian National Seismograph Network (CNSN) were checked and no evidence of earthquake activity was found. The CNSN has sufficient coverage in that region to record earthquakes too small to be felt. Note that the long durations of the rumblings are not consistent with earthquake activity; earthquakes may produce effects similar to those described but lasting for seconds rather than hours.

In response to a request for assistance from the MOE, NRCan installed four three-component, short-period seismometers in the Windsor area on 14 June 2011. The instruments were concentrated in the western part of the city (Figure 1) as that was where the largest number of complaints originated. MOE aided in the site selection and provided logistical and operational support while the instruments were operating. The instruments were removed on 25 August 2011. The data were sent to NRCan for analysis.

This report covers the technical aspects of the analysis and conclusions resulting from it.

Seismometers:

The seismometers installed in Windsor were L4 short-period instruments. At each site three sensors were installed to record three orthogonal components of ground motion: vertical, north-south and east-west. The instruments record ground velocity with a sampling rate of 100 samples per second. The sampling rate means that 50 Hz is the highest frequency that can be resolved. The lower bound of human hearing is approximately 20 Hz. Thus, the range of human hearing overlaps with the frequency range of the seismometers. The instruments record continuously but the data are stored internally and must be manually retrieved.

It should be emphasized, however, that although the seismometers are extremely sensitive they can record only ground motion. Earthquakes, because they originate beneath the Earth's surface, produce waves that propagate efficiently over long distances (Figure 2). For signals originating at the Earth's surface or in the atmosphere to be recorded by seismometers, sufficient energy must be transferred to the ground.

The four seismometers were installed at the Ontario Ministry of the Environment (station code MEMO), University of Windsor (UNIV), Brighton Beach Power Station (POWR) and a private residence on Lyoness Ave (LYON). Their locations are shown in Figure 1. Station UNIV was closed on 12 July 2011 due to construction at the site. The other three stations operated until 25 August 2011. Data through 22 July 2011 were returned to Ottawa in late July for analysis. Preliminary conclusions were derived from these data. The data through the end of the deployment were returned to Ottawa shortly after the station closures and were analyzed to verify the consistency of the recorded signals and to validate and refine the results.

Analysis:

Dates and times when there were multiple reports of rumblings were provided by MOE (Table 1). The initial analysis based on data recorded prior to 22 July 2011, focused on 17 June and 11 July 2011. Because it was not clear what the signal from the rumblings would look like or whether it would have been recorded, the first step was to compare the data starting an hour or two before the rumblings were reported to the time periods of the reported rumblings and look for differences. All three components of data were examined. If any difference was noted, random checks were made to compare the data to additional times when no rumblings were reported. In particular, the records were compared to those for the same time of day and day of the week when the background noise was likely to be similar. Because the stations are in an urban environment there is considerable background noise (Figure 3). No obvious signal was seen on the seismograms (raw data). However, by converting the seismogram to a spectrogram it was possible to analyze the data in greater depth.

In simple terms a spectrogram represents the distribution of energy as a function of time and frequency; it is a two-dimensional representation of three dimensions just as a topographical map may be used to add a third dimension to a geographical map. In this case, the x-axis is time, the y-axis is frequency and the color indicates the amplitude (intensity) of the signal. By contrast, a seismogram shows amplitude as a function of time and a spectrum shows amplitude as a function of frequency. Figure 4 shows a typical spectrogram for a small earthquake recorded at a relatively close distance.

Note that the color scale on the spectrograms is autoscaled by the plotting program and cannot be controlled by the user. It is based on the content of the data file plotted and is not identical from one plot to another. For example, the value for red may not be the same on two plots, but in each case red indicates that the amplitude of the signal is relatively high for that time period. Blue indicates a lower amplitude signal for the same time period. A scale bar is shown on each plot and should be consulted before comparing the amplitudes on different spectrograms. Square root scaling is used as it enhances weaker signals without over emphasizing them. The amplitude is given in units of "counts" which can be converted to ground velocity with the exact conversion being dependent on the frequency of the signal.

It was observed that on the records from stations POWR and LYON there was a signal that was seen during the times the rumblings were reported (Table 2) and usually not seen or occasionally very weakly seen for short durations at times when there were no reports. The recorded signal was very similar on both stations and was consistent in character with the reported rumblings. That is, the recorded signals matched each other in terms of duration, frequency and relative intensity and they were consistent with the reports in that they were within the range of human hearing, intermittent with varying durations and intensities but continuing for a period of several hours. Examples are shown in Figures 5-13. For lack of a more precise term, the words "packet of energy" are employed to describe individual segments of the recorded signal.

The dominant frequency of the signals is approximately 35 Hz (34-37 Hz). On closer inspection it was found that for each packet of energy that can be clearly seen on both stations the onset at POWR is approximately 16 seconds prior to that at LYON. The stations are roughly 6 km apart implying that the signal is propagating as an acoustic wave in the atmosphere. Had the signals been traveling through the ground the difference in the onset times would have been less than 2 seconds.

Because three components of ground motion are recorded, the relative direction of the source and station can be determined by comparing the signal on the different components at the same station. This method will not distinguish between two directions that are 180º apart (for example, north vs. south) but because the signal is observed at two stations we can combine the information to determine the location of the source.

Particle motion plots (Figure 14) show the relative amplitudes on two components at the same time. Because acoustic waves are compressional waves they are polarized in the direction of propagation. We show the north-south plotted against the east-west component. The first step was to determine the time period within each packet of energy when the total horizontal ground motion (vector sum of north-south and east-west) was a maximum and then make particle motion plots for the time window and frequency of interest. The azimuths of the peaks were then measured. Several measurements were made for each station. A mean and standard deviation were calculated. The mean azimuth was 66.6º (or 246.6º) for POWR with a standard deviation of 6º and 155.7º (or 335.7º) for LYON with a standard deviation of 10º. This information was entered into a grid search algorithm which determined the best location for the source of the signal as well as an uncertainty estimate.

Source Location:

From the azimuthal information discussed in the previous section, a grid search algorithm was employed to determine the location of the source of the recorded signal. It is assumed that the signal is emanating from a point source and traveling in a straight line from the source to the recording station. The 95% confidence intervals for each station plot as two infinite triangles whose apexes are at the station. The most likely location for the source is the region where the triangles from the two stations overlap (Figure 15). The 95% confidence region for each station depends on the assumption that the measurements were independent and that the ground is homogenous with a flat surface. This does not take wind, topography or local geology into account. The source location corresponds to Zug Island, Michigan or its immediate vicinity. We note that much of the location box plots over water. Since the signal is propagating through the atmosphere, many of the points within the box can be excluded as the source for practical purposes.

The onset time difference between the stations POWR and LYON is consistent with this general location. We cannot use this information to refine the solution further as there are many unquantifiable, albeit generally small, uncertainties associated with this data. For example, the speed of sound in air can vary according to atmospheric conditions. Additionally, although the signal is predominantly propagating through the atmosphere, in order for it to be recorded a small portion of the path must be in the ground. The exact percentage is unknown and because the speed of sound in air and rock can differ by more than an order of magnitude the relative proportions will affect any uncertainty estimate.

The station UNIV was at comparable distances from the source to the stations POWR and LYON. The data were re-examined and the signal was not observed.

However, this station had very high background noise which likely masked the signal. Alternatively, the signal may be propagated preferentially in some directions. The signal was also not recorded by the station MEMO, which was the furthest from the source.

Summary:

Two of four seismograph stations deployed in Windsor from 14 June 2011 to 25 August 2011 recorded an approximately 35 Hz signal originating from the vicinity of Zug Island, Michigan during the time periods when the rumblings were reported. The recorded signal is consistent in terms of time, duration and character with the rumblings reported in the Windsor area during this time period. The seismic data cannot identify the source of the signal but only its location. Further investigation will be required to determine the exact source of the signal.

Acknowledgments:
Janet Drysdale and Sylvain Brazeau of NRCan installed the seismometers. MOE staff, in particular Archie Parastatidis, Allan MacKinnon and Robert Hunt, provided us with the list of times the rumblings were reported and assisted with the station operations. We also thank Honn Kao for his constructive review of the manuscript.

Table 1
Times of Multiple Reports of Rumblings*

Date	**Time(s): EDT**	**Comments**
17 June 2011	2-4 PM	Some additional reports earlier and later
11 July 2011	0:00-1:30	
28 July 2011	8-10 AM, 10-12 PM	Larger number of complaints for 10-12PM
30 July 2011	5-8:10 PM	
3 August 2011	2-4:30 AM	
7 August 2011	4AM, 9:30AM, 9:50AM, 6:30 PM, 8PM	
11 August 2011	9-10 AM	
17 August 2011	10AM-3AM	
24 August 2011	6:30-10AM, 12-2:30PM, 8-11:30PM	Largest number of complaints for 8-11:30PM

* times obtained from MOE

Table 2
Summary of Recorded Signals*

Date (2011)	Time (EDT)	POWR	LYON	Azimuth-POWR[1]	Azimuth-LYON[1]	Δt (sec) LYON-POWR
17 June	2-4 PM	Yes	Yes	69	149.5	16
11 July	0-1:30 AM	Yes	Yes	69	149.5	16
28 July	8-10:30 AM	Yes-weak	Yes	66	157	16
	10-12PM	Yes	Yes	72	149	16
30 July	5-8 PM	No	Uncertain[2]		164	
3 August	2-4:30 AM	Yes	Yes	54	155	15.5
7 August	4 AM	Yes	Yes	68	153	16
	9:30-10 AM	Yes	Yes	67	152	15.5
	6:30 PM	No	Yes-weak		167	
	8 PM	Yes-EW only	Yes		145	15
11 August	9-10 AM	Yes	Yes	71	170	Can't measure POWR accurately
17 August	10AM-3AM	Yes	Yes	54	180	16
24 August	6:30-10 AM	Yes	Yes	68	147	Can't correlate accurately
	12-2:30 PM	Yes- weak	Yes-very weak	66	148	Too weak to measure accurately
	8-11:30 PM	Yes	Yes	75	150	17

* see description in text; yes-no refers to whether a signal matching that description was recorded; unless indicated otherwise, a "yes" indicates that the signal was seen on all 3 components

[1] we measure azimuths from 0º to 180º, but value in table plus 180º is an equally valid azimuth

[2] see signal at expected frequency but it is continuous; other recordings show intermittent signal

Figures

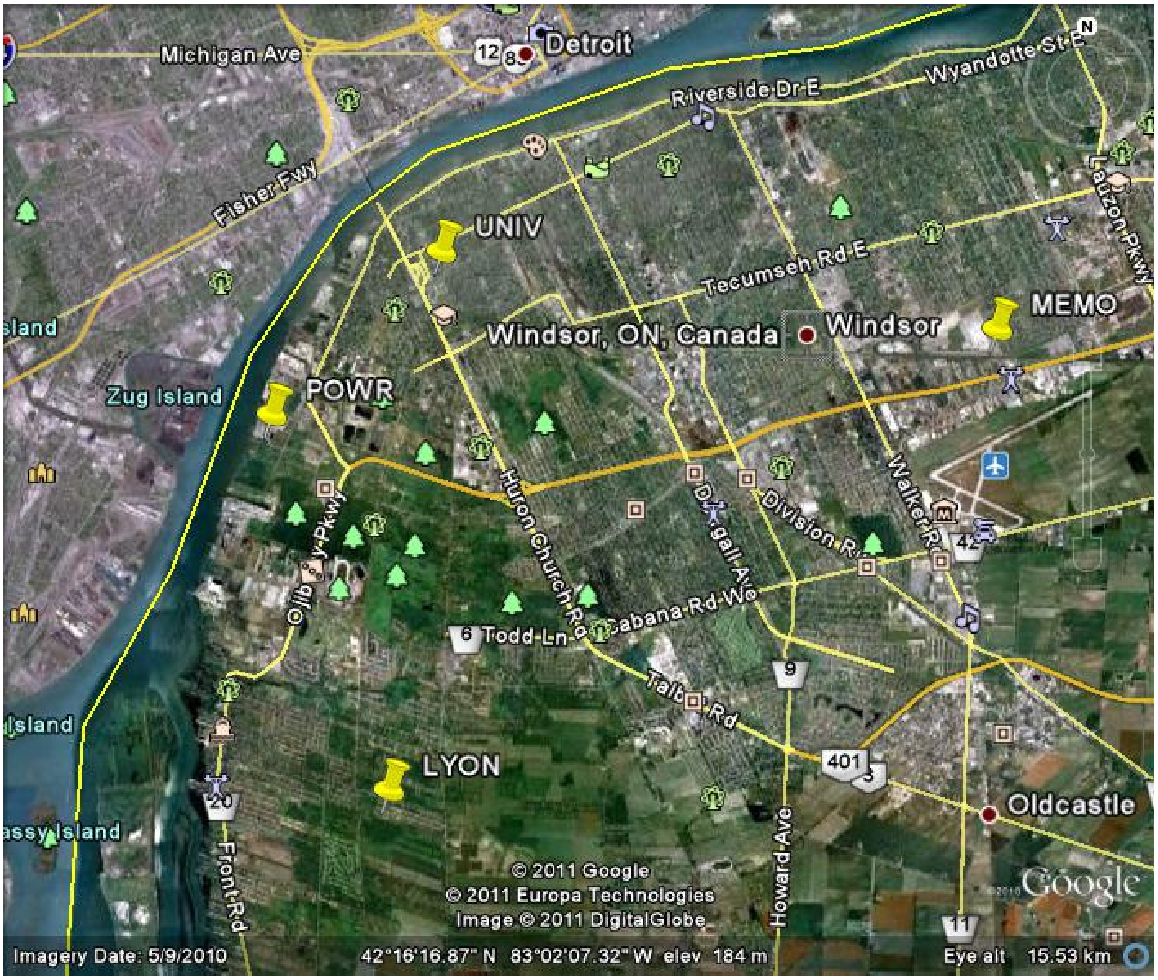

Figure 1: Map showing locations of four stations deployed in Windsor.

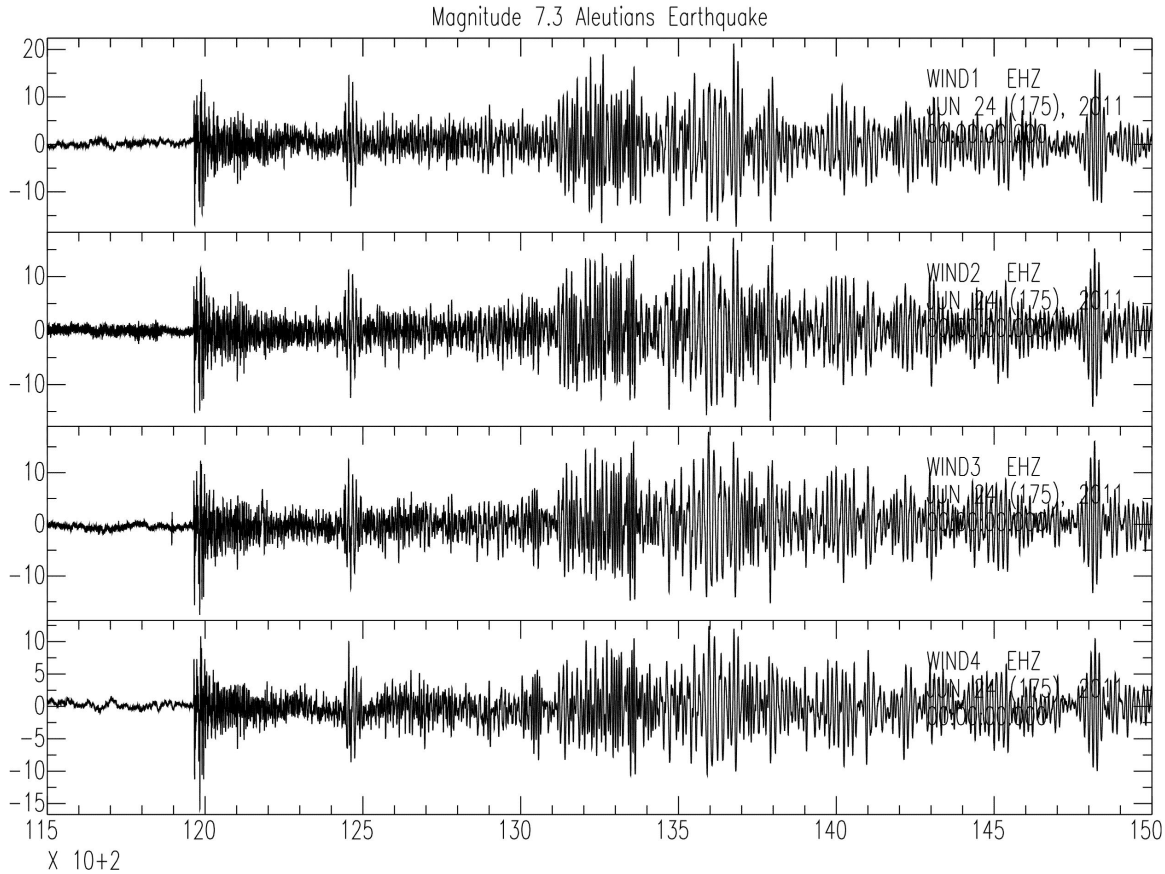

Figure 2. Seismograms of a large earthquake in the Aleutian Islands on 24 June 2011 recorded by the Windsor stations. The vertical component of ground motion is shown. One hour of data is plotted. A lowpass filter with a 0.1 Hz corner frequency was applied to the data.

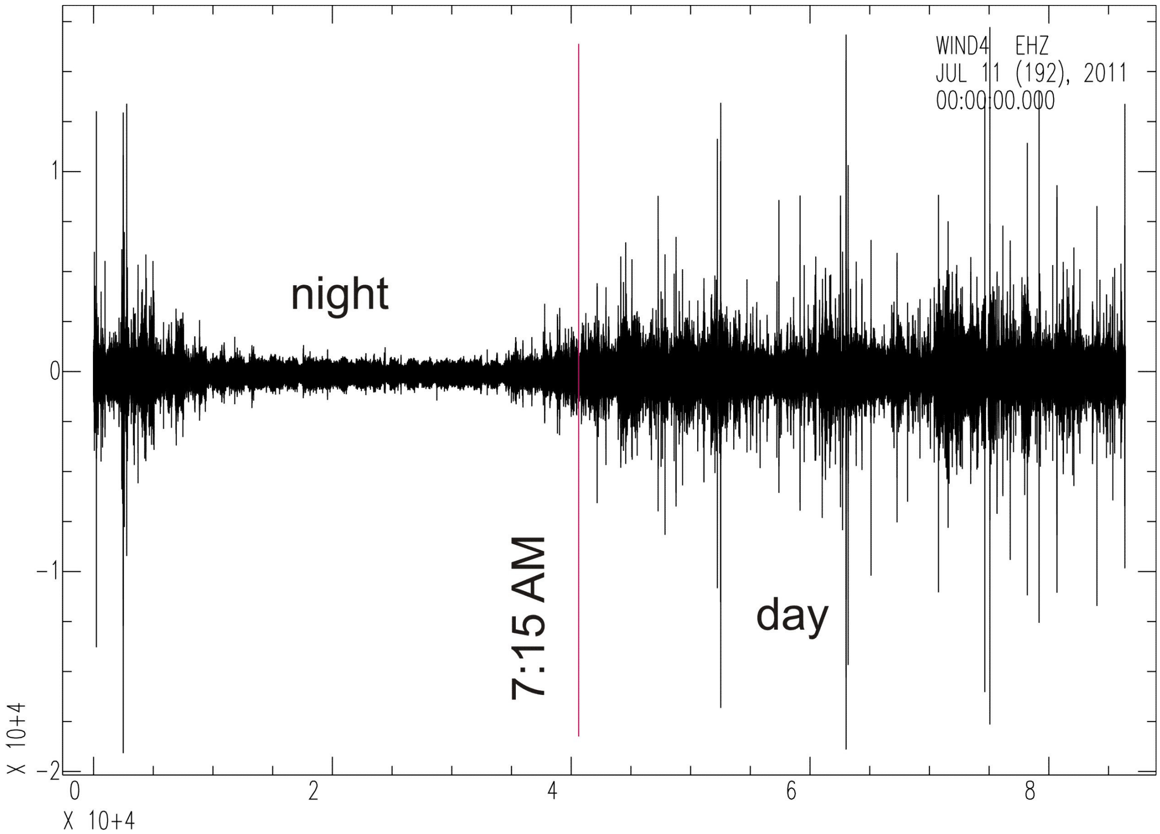

Figure 3. 24 hours of data (8PM 10 July to 8PM 11 July 2011) recorded at station LYON- vertical component. Note that the overall noise level is much higher during the day, typical of seismometers located in urban environments. The vertical red line is at 7:15 AM local time.

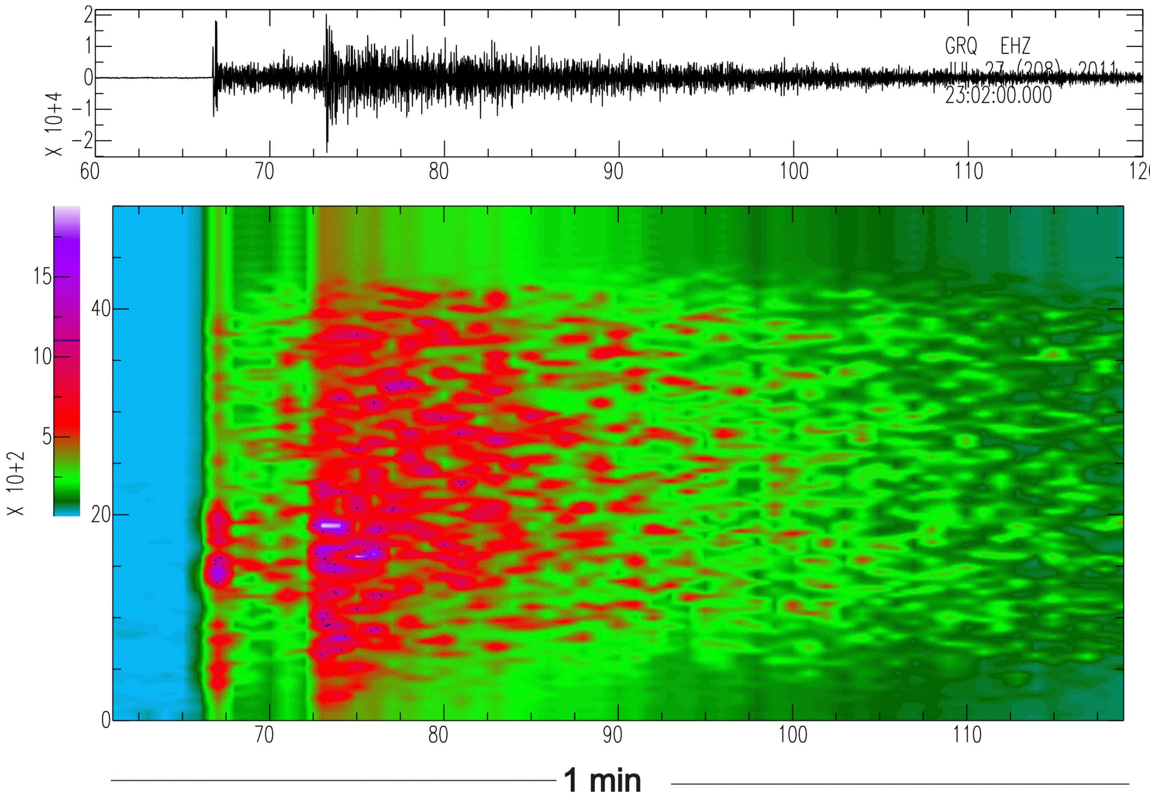

Figure 4: A small earthquake recorded at a distance of 50 km from the epicenter. Note that there are two distinct phases (or packets of energy), that the overall duration of the signal is less than one minute and that there is significant energy recorded over a wide range of frequencies. For a larger earthquake, the duration would increase as would be longer period energy but the overall characteristics of the spectrogram would be similar. The seismogram is shown above the spectrogram. In this example, both the earthquake and the recording station are located in western Quebec.

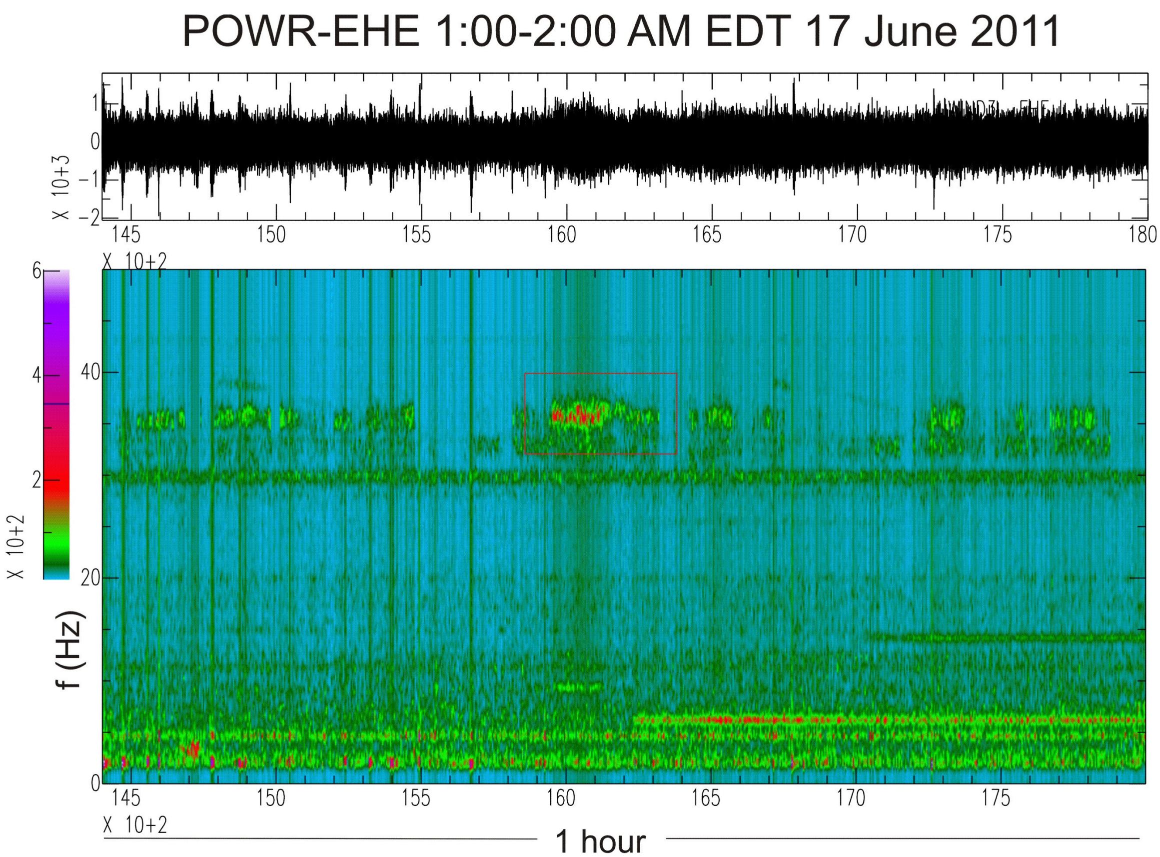

Figure 5a. Spectrogram showing 1 hour of data recorded by the east-west component at station POWR. The recorded seismogram is shown above the spectrogram. The signal in the red box is shown in more detail in Figure 5b. The intermittent signal at approximately 35 Hz is the signal of interest in this and subsequent figures.

POWR-EHE 17 June 2011: Close-up of signal of interest

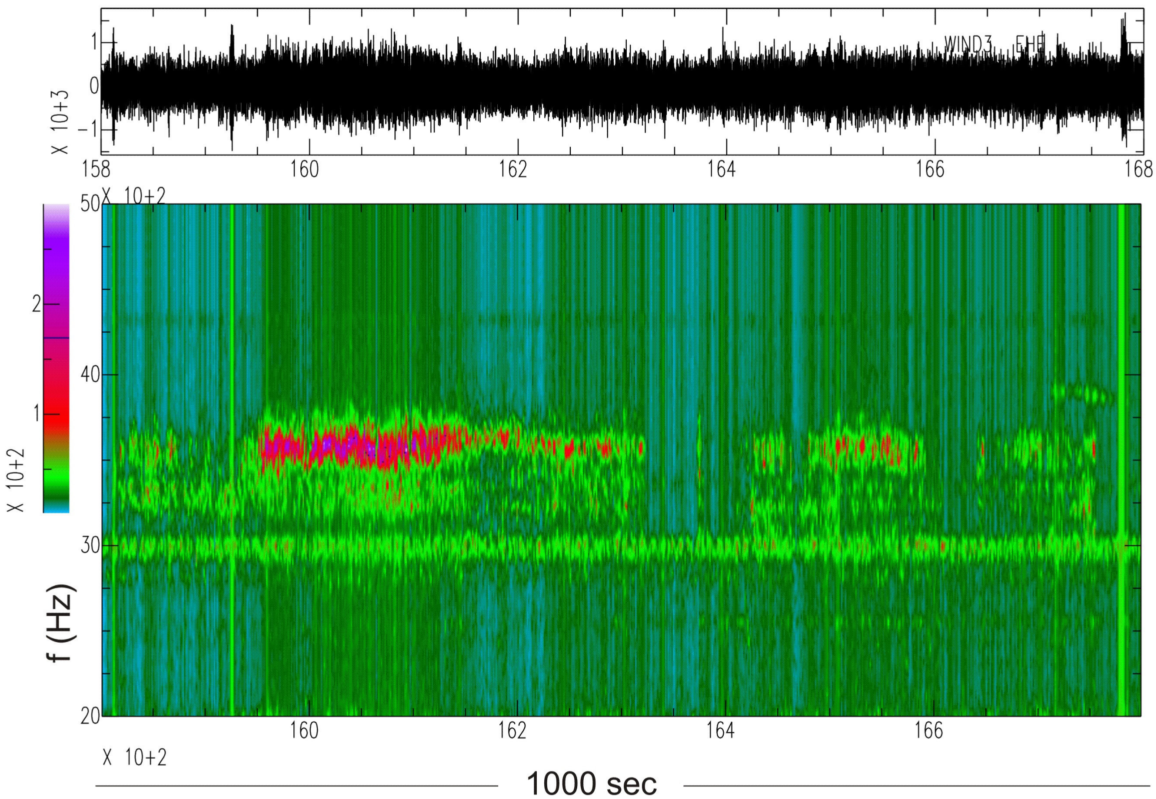

Figure 5b. Blow-up of area shown in box in Figure 5a.

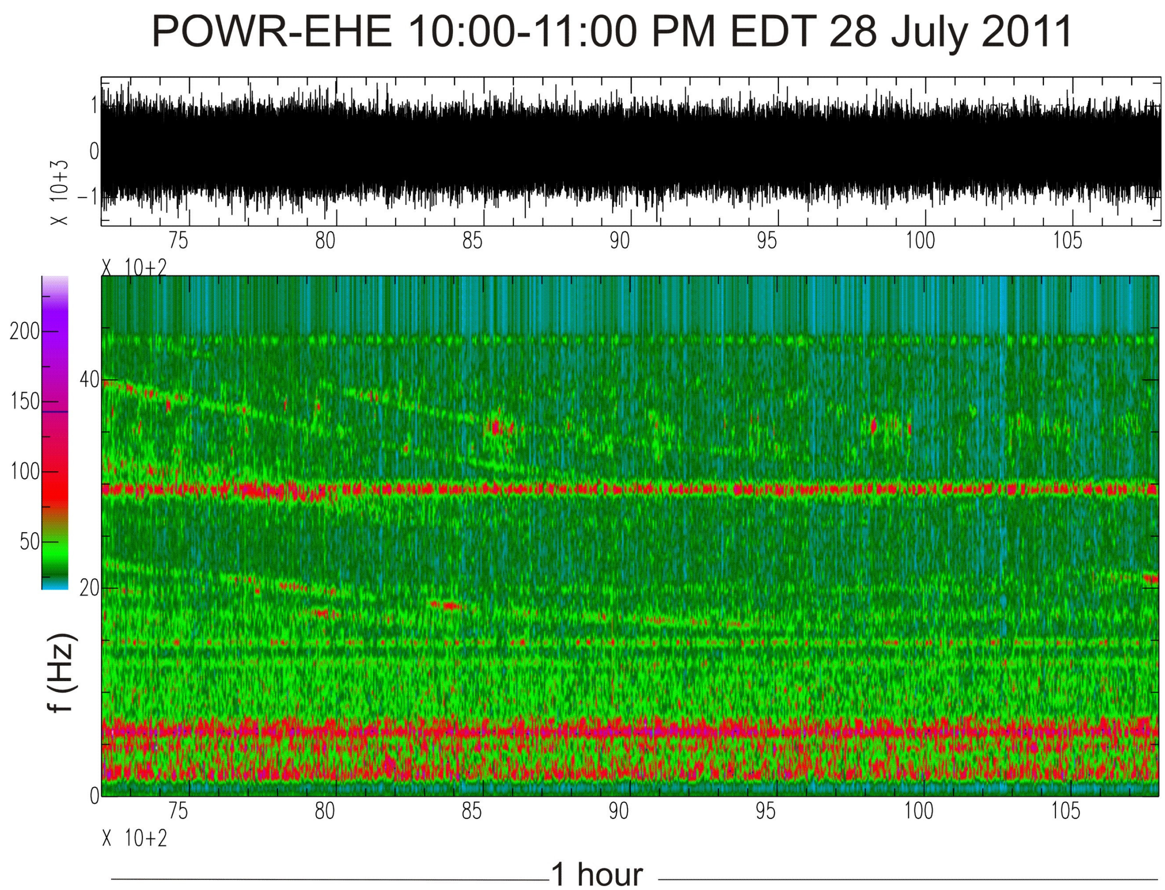

Figure 6. Spectrogram for the east-west component at POWR for 28 July.

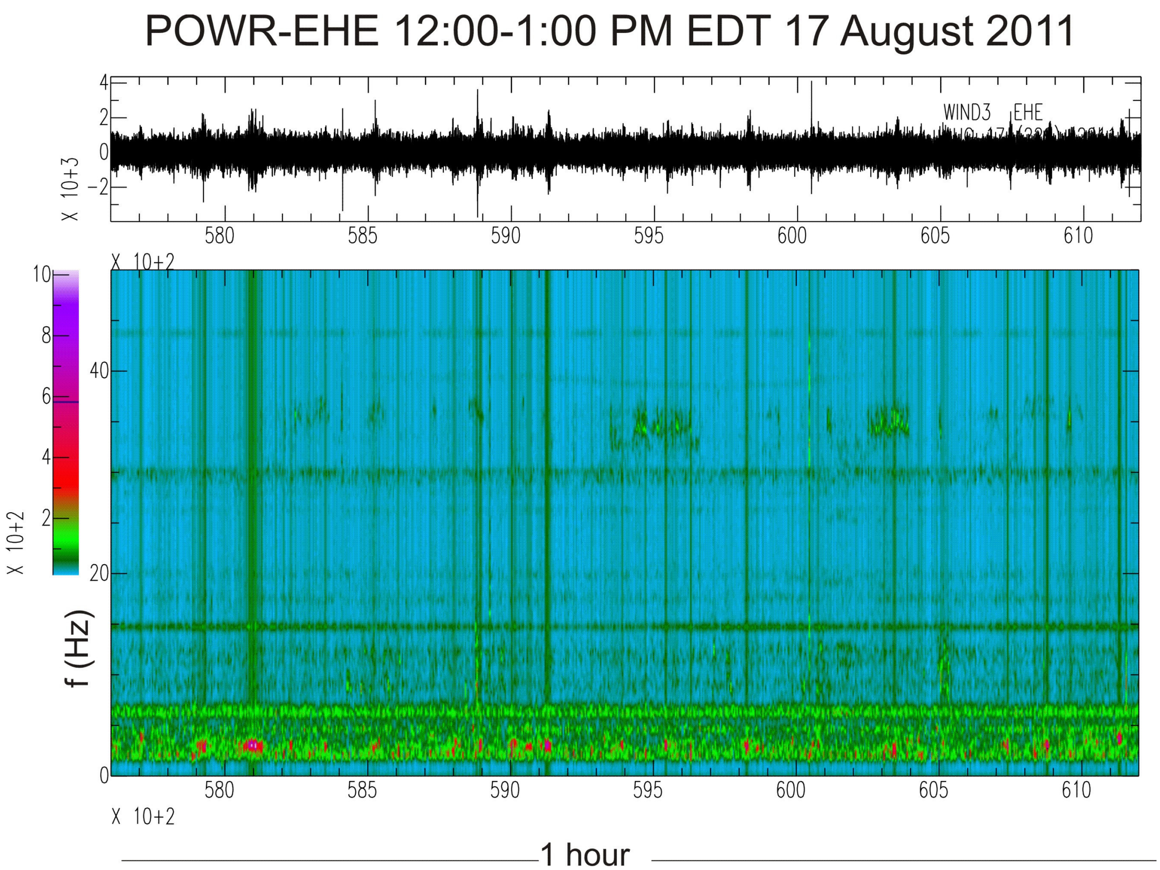

Figure 7. Spectrogram for the east-west component at POWR for 17 August 2011.

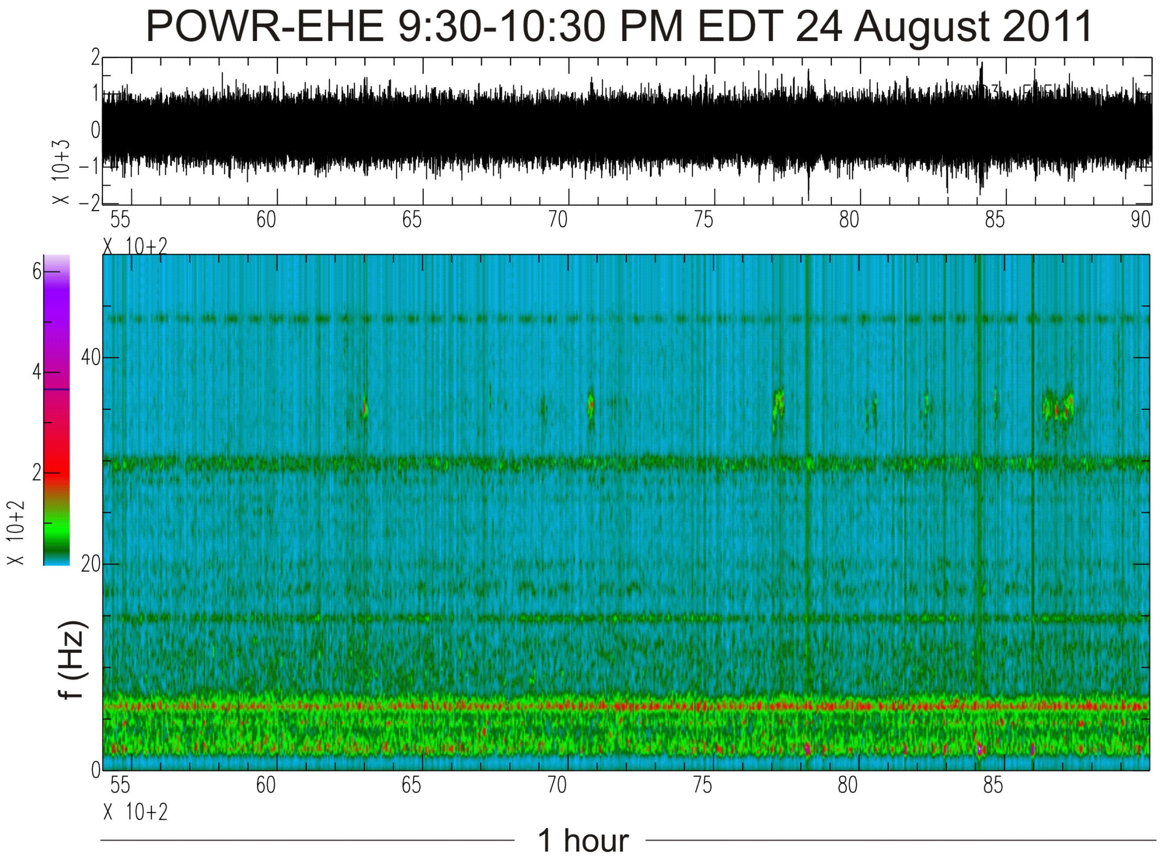

Figure 8. Spectrogram for the east-west component at POWR for 24 August 2011.

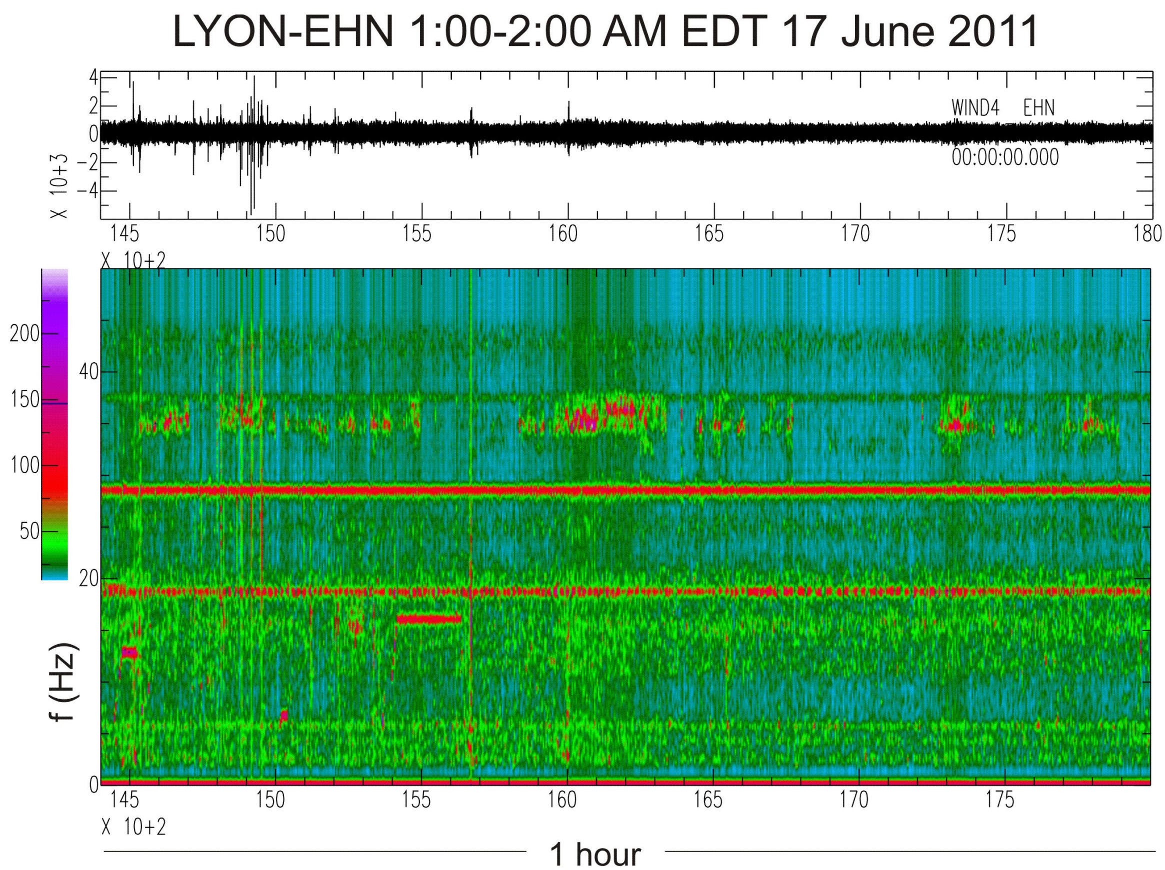

Figure 9. Spectrogram for the north-south component at LYON for 17 June.2011.

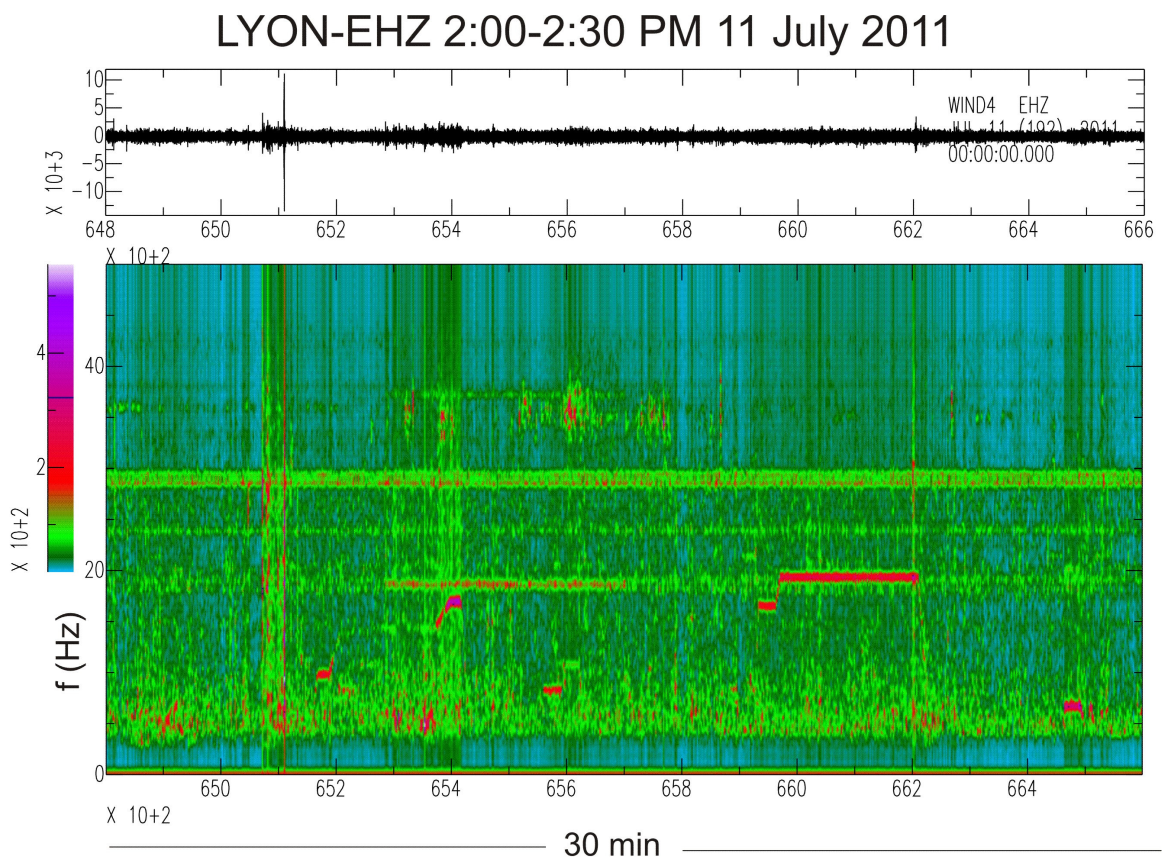

Figure 10. Spectrogram for the vertical component at LYON for 11 July 2011.

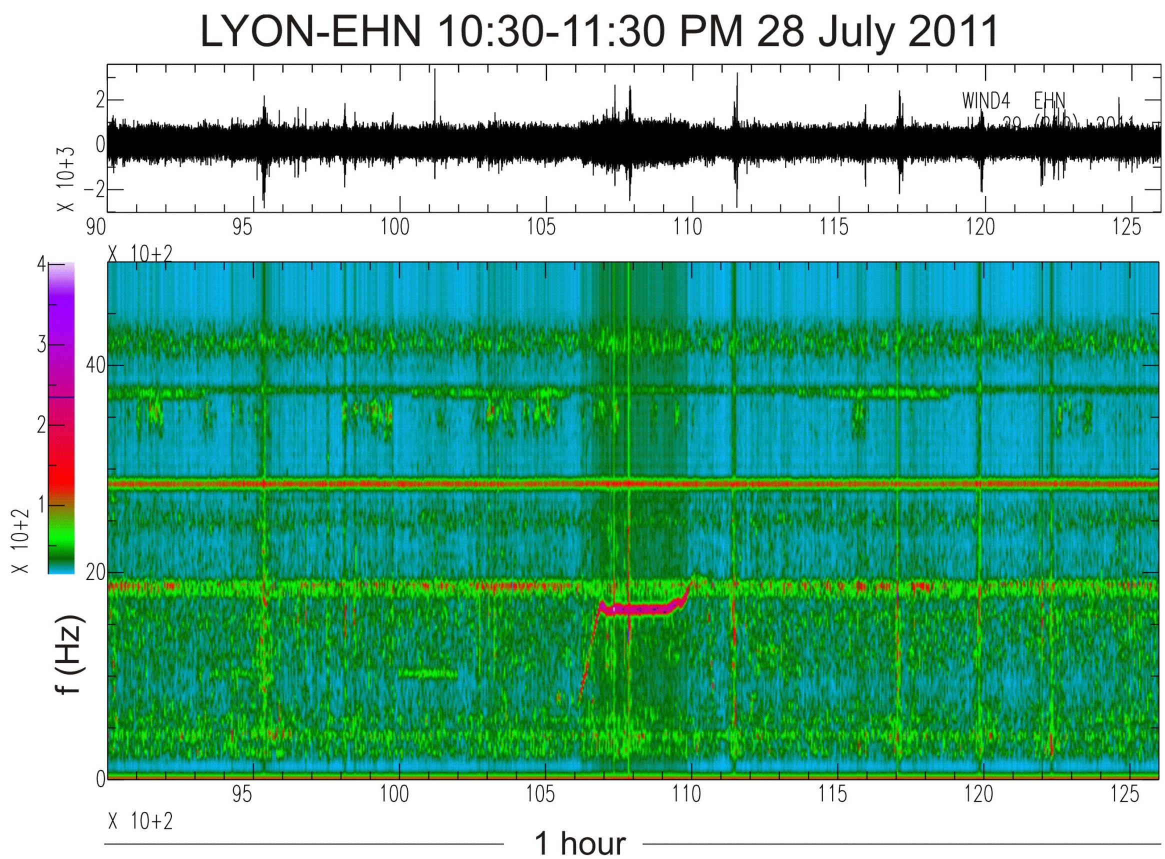

Figure 11. Spectrogram for the north-south component at LYON for 28 July 2011.

LYON-EHN 9:00-10:00 AM EDT 11 August 2011

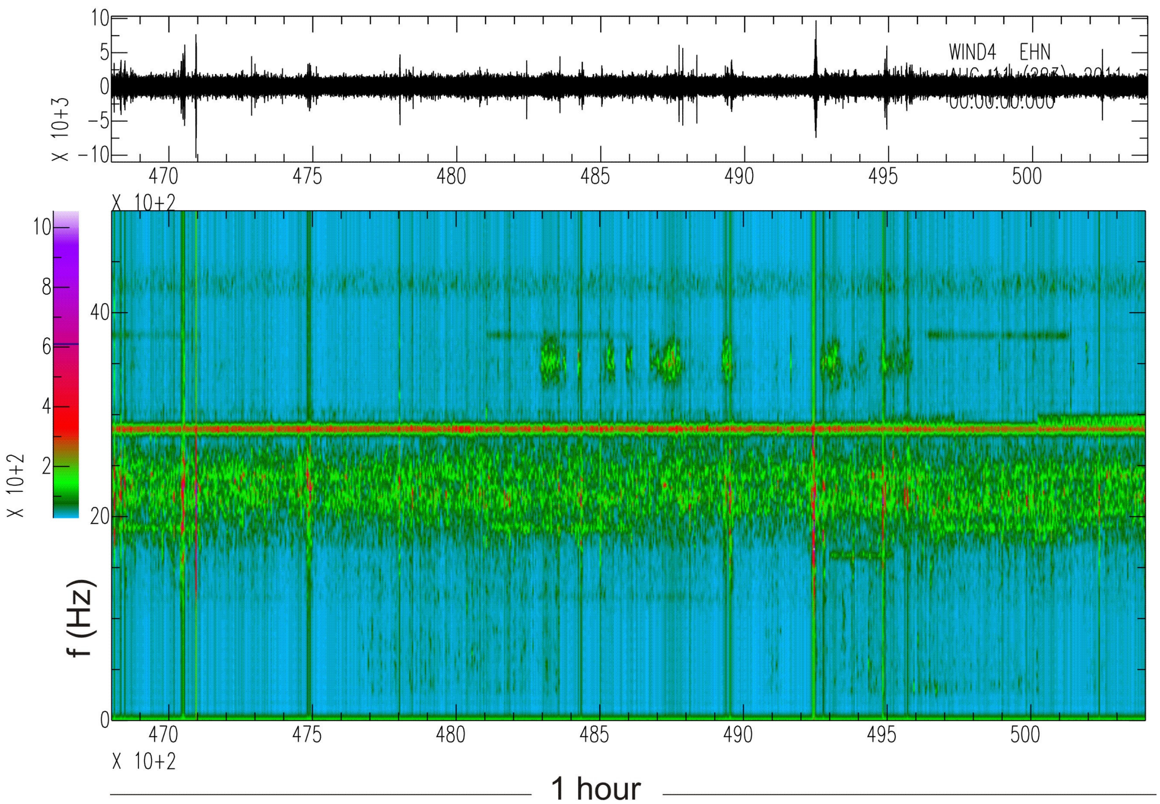

Figure 12. Spectrogram for the north-south component at LYON for 11 August 2011.

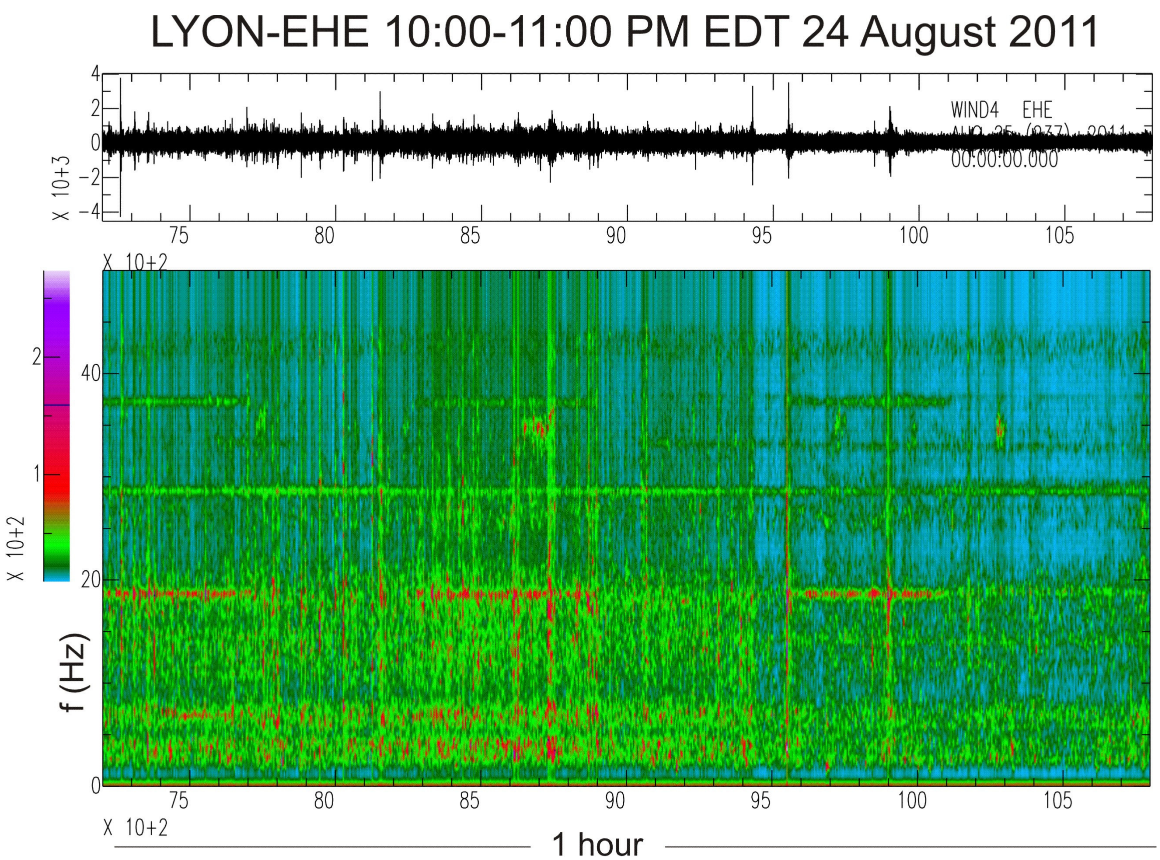

Figure 13. Spectrogram for the east-west component at LYON for 24 August 2011.

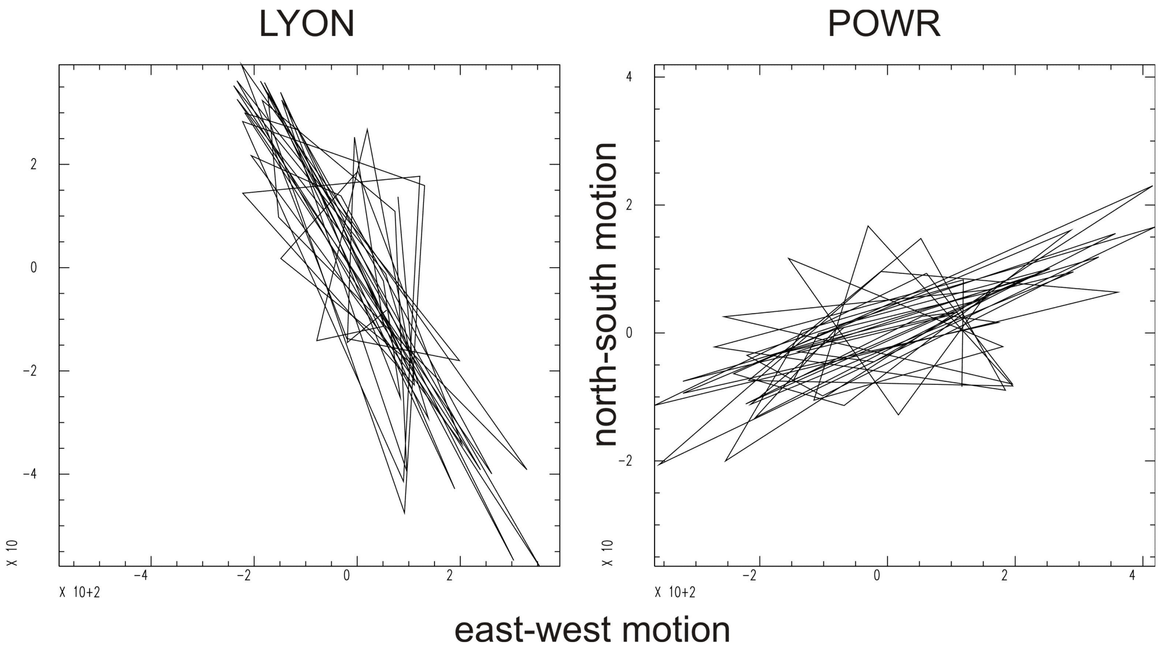

Figure 14: Particle motion plots for the north-south and east-west components at LYON and POWR.

Figure 15. Map showing locations of seismograph stations and best estimate (red region) for the location of the recorded signal discussed in the text. The red box indicates the region where the 95% confidence intervals of the data from stations LYON (yellow lines) and POWR (blue lines) overlap.