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Title: Seismic and hydroacoustic analysis relevant to MH370

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Seismic and hydroacoustic analysis relevant to MH370

Abstract

The vicinity of the Indian Ocean is searched for open and readily available seismic and/or hydroacoustic stations that might have recorded a possible impact of MH370 with the ocean surface. Only three stations are identified: the IMS hydrophone arrays H01 and H08, and the Geoscope seismic station AIS. Analysis of the data from these stations shows an interesting arrival on H01 that has some interference from an Antarctic ice event, large amplitude repeating signals at H08 that obscure any possible arrivals, and large amplitude chaotic noise at AIS that obscures any arrivals at lower frequencies while the low sample rate at AIS precludes any analysis at higher frequencies of interest. The results are therefore rather inconclusive but may point to a more southerly impact location within the overall Indian Ocean search region. The results would be more useful if they can be combined with any other data that are not readily available.

Introduction

MH370 is a Malaysian Airlines flight that was lost over the Indian Ocean, and assumed to have crashed sometime shortly after 00:00 UTC on 2014/03/08. The impact of a large passenger jet with the ocean surface should create a signal that could be observed on hydrophones or nearby seismic stations. The study discussed here is an analysis of the hydroacoustic and seismic data readily available, in an effort to determine is such signals are present and if they can provide any information regarding the hypothesized impact event.

Data

The Indian Ocean is a relatively poorly monitored region of the globe. For sources near the ocean surface, the best records would be hydrophone stations, followed by near-shore seismic stations (to look for signals that result from the conversion of hydroacoustic energy to seismic energy, known collectively as T phases). In the southern Indian Ocean, there are only 2 hydrophone stations readily available, both from the CTBT IMS network: Cape Leeuwin, Australia, having the code H01, and Diego Garcia, an island in the British Indian Ocean Territory (BIOT), Chagos Archipelago, having the code H08. Both hydrophone stations have 3-element triangular arrays of hydrophones installed well offshore and positioned in the SOFAR channel. Other hydrophone stations in the Atlantic and Pacific are generally blocked from this source region. There is only one nearby seismic station for the expected region of impact, and that is Amsterdam Island, code AIS, a Geoscope station (Geoscope is a French international seismic network). This station has a three-component broadband seismometer. The IMS data are available from the CTBTO located in Vienna, Austria. The data from AIS are available at the IRIS DMC located in Seattle, Washington, USA.

Analysis

H01

H01 is the closest hydrophone station, and as such has the highest likelihood of recording any signal that may have been generated by the expected impact event. H01 consists of a single 3-element array.

We started with a scan of the raw, broadband hydrophone data, for approximately 2 hours around the expected time of impact, adjusted for some travel time from the point of impact to the station. This scan revealed only one set of signals that was significantly above the background noise, including various small signals. These signals were observed at approximately 00:52 UTC, and shown in Figure 1. We focus all further analysis on these signals.

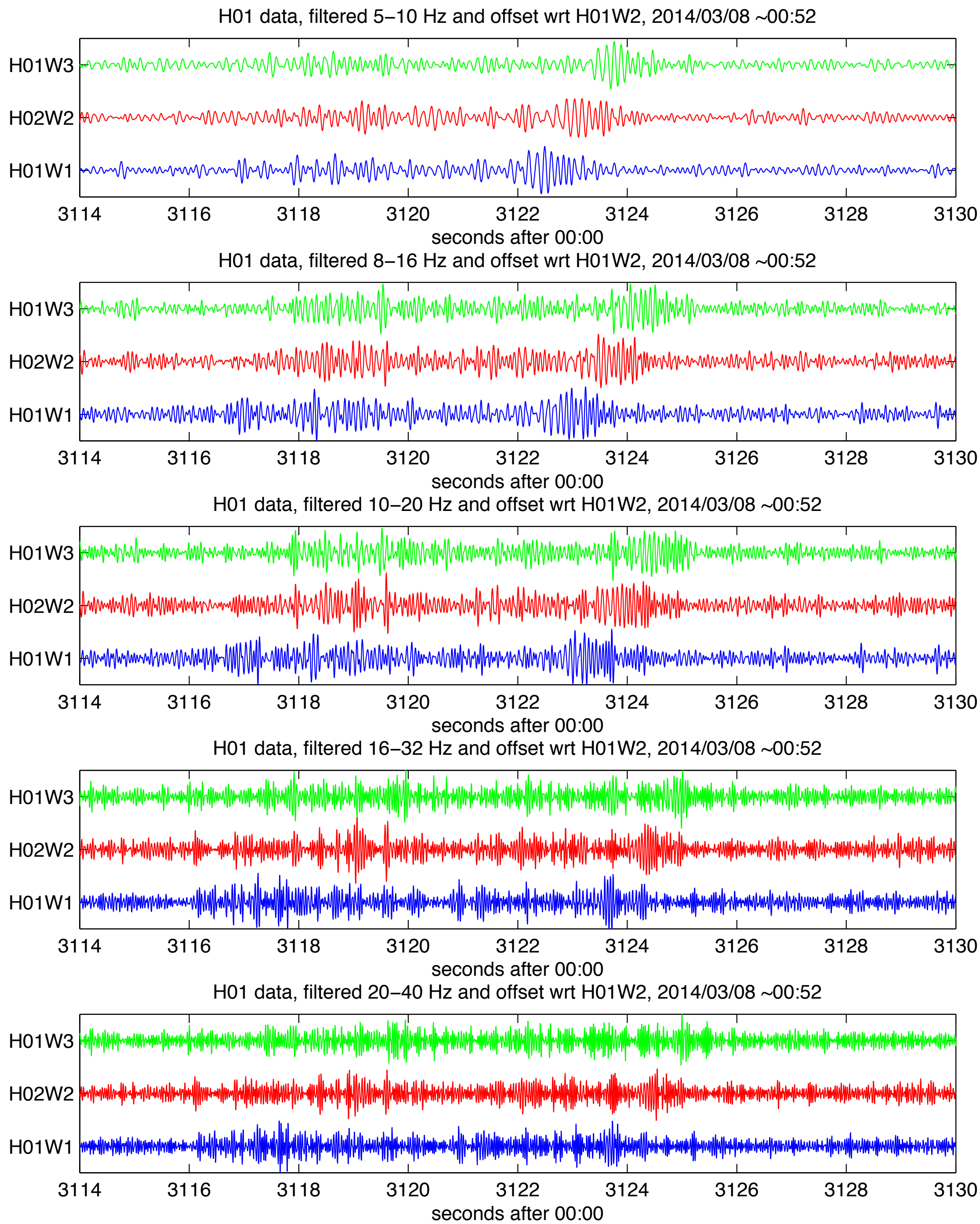

Figure 1: Filtered waveforms from all three elements of H01 around the time 00:52 UTC on 2014/03/08. The filters are 1-octave bands as indicated above each subimage. The features and alignment of the traces will be discussed later in the text.

The signals visible in figure 1 comprise two groups. The largest is the latter group showing large amplitudes and significant dispersion. We begin our analysis with that group. Using a time window relatively tight to just the late signals, we perform a cross-correlation analysis to find the correct alignment of this group. The results are shown in figure 2. All further analysis of these signals is performed in the 10-20 Hz band. Figure 1 shows that the latter signal dominates the waveform at lower frequencies, and the signal-to-noise ratio is poor at higher frequencies. Thus 10-20 Hz is the best band in which to analyze all of the signals present.

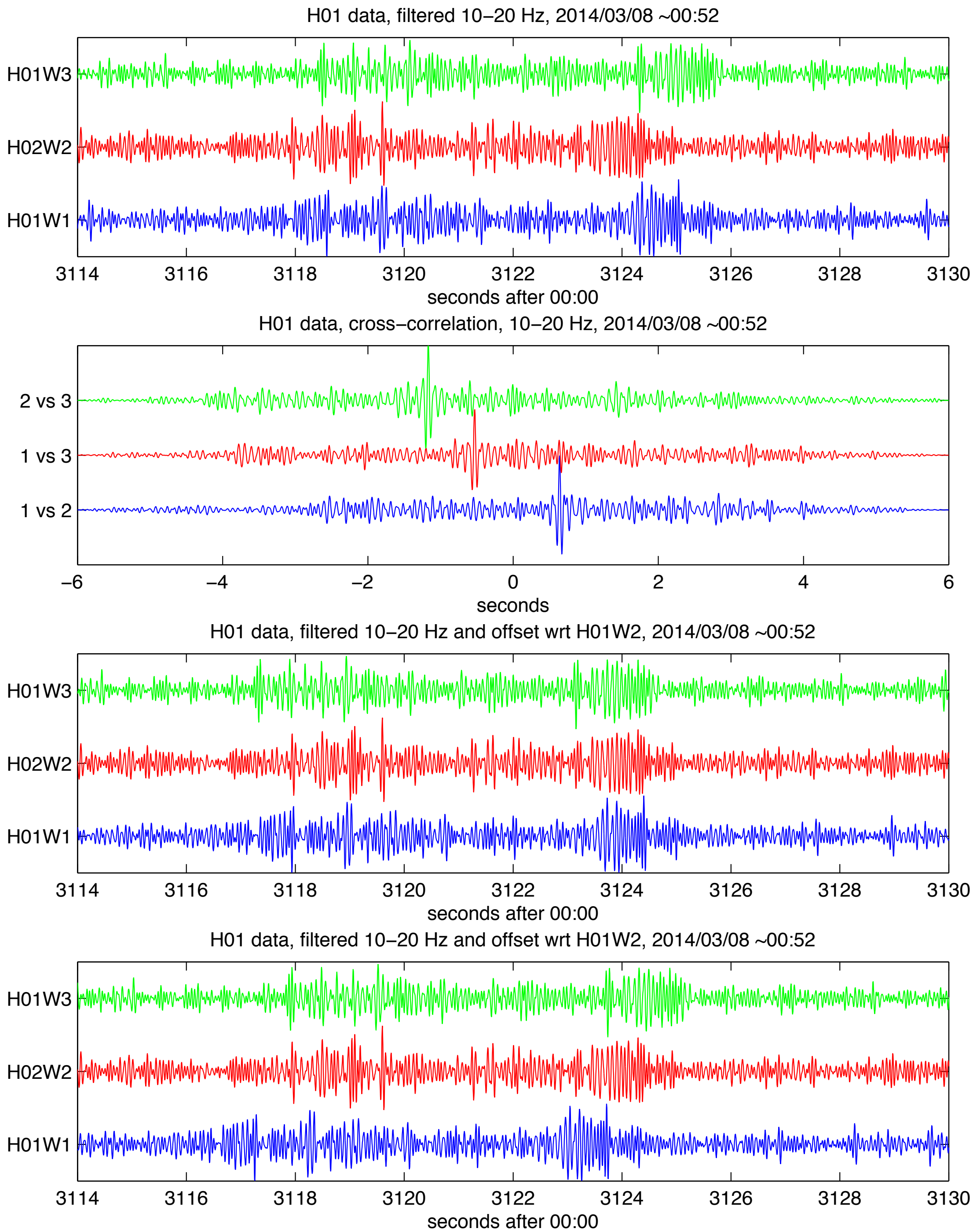

Figure 2: Cross-correlation analysis of the signals at H01. The first subimage shows all 3 elements, filtered 10-20 Hz and aligned on true time. The second shows the

cross-correlation analysis of just the 6 seconds surrounding the latter, large, dispersive signal, also performed in the 10-20 Hz band. The third subimage is aligned using the results of the cross-correlation analysis. Note the excellent alignment of the latter signal, particularly frequency dispersion, but the lack of alignment of earlier features. The alignment of the fourth subimage is discussed later in the text.

The cross-correlation analysis works very well on the latter, large-amplitude, dispersive signal. But it does not work well on the earlier signals. This leads us to conclude that the two sets of signals may originate from different sources. Other characteristics seem to support this conclusion, since the earlier signals seem to lack significant dispersion and also lack significant energy in the lower frequencies, such as 5-10 Hz, as can be seen in Figure 1. Using the offsets for the latter phase, we compute the direction of arrival (DOA, always given here as a 2D horizontal DOA measured in degrees clockwise from north) and observed phase velocity for that phase. DOA is 190.5°, and the phase velocity (inverse of apparent slowness) is 1.46 km/s, quite consistent with expected SOFAR channel phase velocities. For that direction, it is most likely that this signal originated in an ice-related event in the vicinity of Antarctica.

Cross-correlation was attempted on the earlier signals, without success – there were no significant peaks found, unlike the clear peaks shown in figure 2 for the latter signal. This is not surprising, since the separation of the array elements, which is on the order of 2 km, represents multiple wavelengths at this phase velocity and frequency. Most signals would not be expected to have strong coherence between the elements, especially those that are more impulsive and not dispersed. Instead of cross-correlation, we rely on a manual alignment of key features. Beginning with elements W2 and W3, which seem the most coherent for the earlier energy, we align 4 prominent peaks in the energy observed in the signals. This is shown in the lower part of figure 2. The third element of the array, W1, is then aligned by constraining the phase velocity to be that observed for the ice signal, 1.46 km/s. Geometrical constraints and the assumed phase velocity then determine uniquely the offset for W1. W1 is clearly not very coherent with either W2 or W3 for this signal, but in general, the bulk of the energy for this arrival appears in the same time window as it does on W2 and W3, with the exception of an early pulse of energy, which could be unrelated. Note that figure 1 is also created with this alignment, and the 8-16 Hz band shows good alignment for the timing of the bulk of the energy, again with the exception of spurious energy early on W1. Attempts to align the early energy on W1 result in unphysical phase velocities, which also leads us to conclude that this early energy on W1 is unrelated. The final alignment of the first arrivals produces a DOA of 246.9° (with the phase velocity fixed at 1.46 km/s). The source for this arrival would then be WSW of the array, in the general direction of the region in which MH370 may have impacted the ocean, and has an arrival time that could be consistent as well. Although the arrival is weak and is interfered by a strong ice source arrival, there is evidence that this could be an arrival from an impact of MH370 with the ocean surface. Figures 3 and 4 show spectrograms aligned with the computed cross-correlation for the latter arrival and the manual alignment of the first arrival. The alignment of energy in these figures also supports the direction of arrival conclusions.

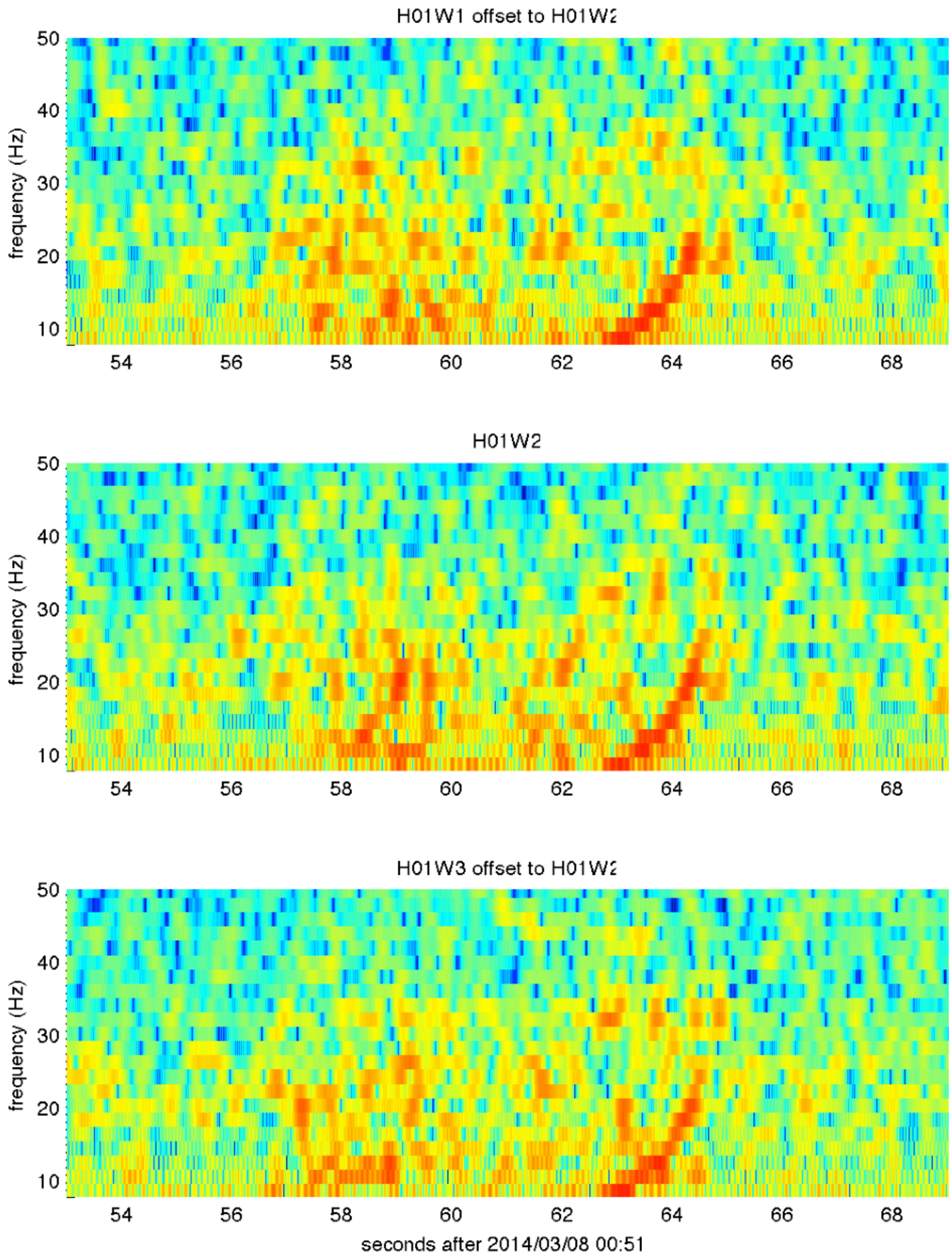

Figure 3. Spectrograms, 8-60 Hz, around 2014/03/08 00:52 UTC for hydroacoustic array H01. The spectrograms for the three elements of the array are aligned on the computed cross-correlation offsets for the latter arrival (the large-amplitude highly

dispersed arrival between about 63 and 65 seconds after 00:51). Note the apparent lack of alignment for the earlier energy.

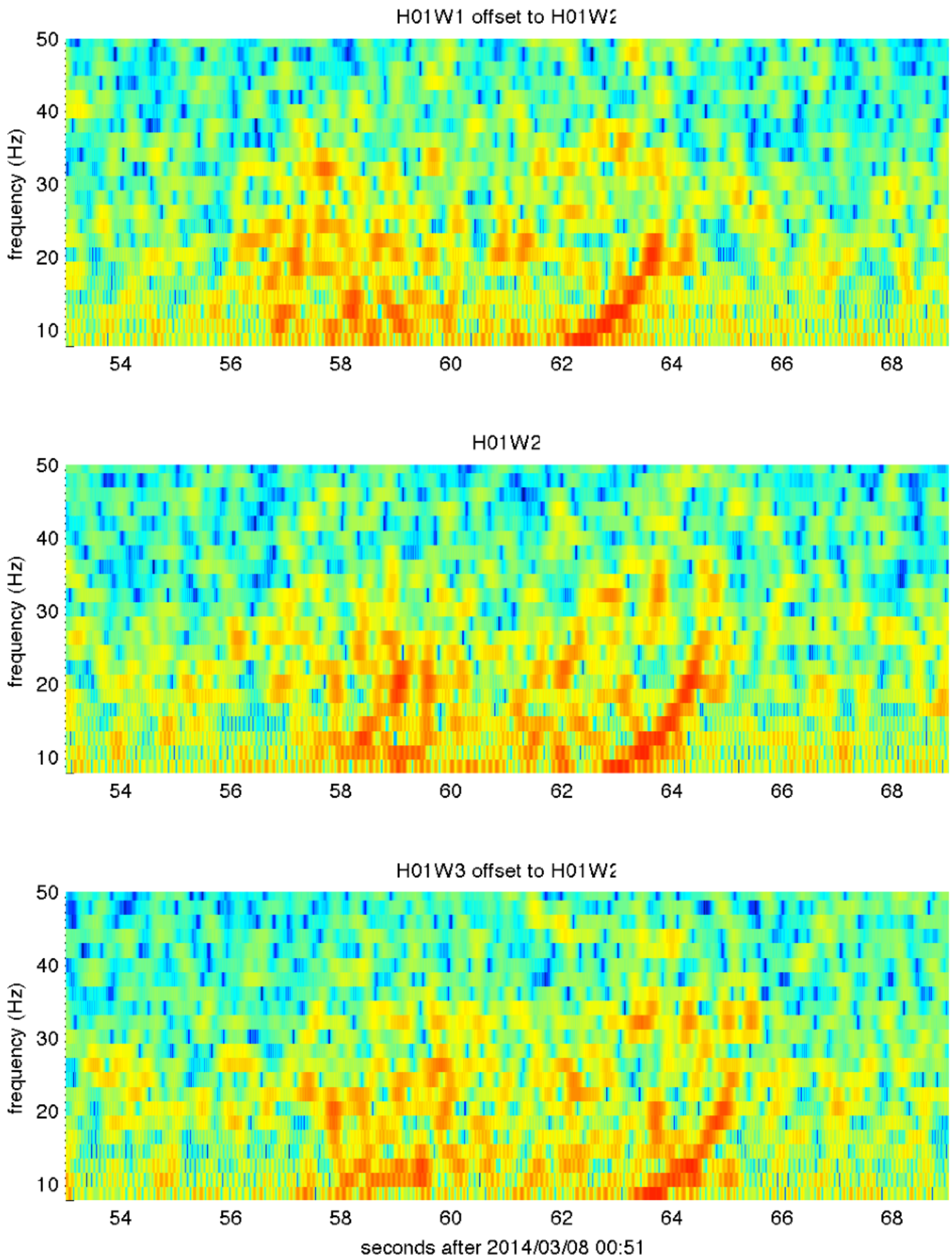

Figure 4: Spectrograms aligned according to manual alignment of early features. Apart from some early energy on H01, features of the earlier energy appear better aligned, particularly between W2 and W3 elements. All elements now show

features between 57.8 and 58.5 and again between 59 and 60 that appear to be well aligned. A feature between 58 and 58.5 may show some evidence of identical dispersion on elements W2 and W3.

H08

H08 is a hydrophone station that is quite a bit further from the potential impact region than H01. We started with the same type of time scan as we did on H01, applied to the southern 3-element array form H08. However, this analysis revealed a long set of two large-amplitude, broadband, repeating signals, one at approximately 10-second intervals and one at approximately 8-second intervals, that dominate the record throughout. These signals continue for hours both before and after the time of interest, and, as can be seen in the figure, are very broadband. In addition, they are larger in amplitude, relative to background, than the signals of interest observed on H01. These signals preclude any possibility of identifying any signal from the impact that might have arrived at H08. The signals arrive from two separate directions. They are both coming from the sea so they are either anthropogenic (airgun surveys or something similar) or biogenic (whales, for example).

A sample of H08 data is shown in figure 5. The same 5 filters are used as were used for H01 data in figure 1. The large amplitude signals appear at approximately 10-second intervals. The smaller amplitude signals are at about 8-second intervals and can be seen progressively interfering with the larger signals. To see this most clearly, look at element S2 at 10-20 Hz. The small signal clearly follows the large one at about 3707 (seconds after 2014/03/08 00:00), has about the same arrival time as the large one at 3715, arrives before the larger signal at 3723 and is almost completely before the larger signal at 3731, and these are 8-second intervals (the large arrivals are at 3704, 3714, 3724, 3734, which are 10-second intervals). The traces in figure 5 are aligned on the expected direction of arrival (and a fixed phase velocity of 1.46 km/s, as observed at H01) for a source in the vicinity of the MH370 expected impact. It is readily apparent that neither of the repeating signals arrivals are from that direction, and that they arrive from 2 different directions. The DOA for the larger 10-second signal is 29.8°, and the observed phase velocity is 1.485 km/s. For the smaller 8-second phase, the DOA is approximately 117° (determination is less reliable due to interference from larger signal). Therefore, H01 will not be useful for investigation of potential arrivals from an MH370 impact. H08 also has a northern array, but it would be blocked by Diego Garcia Island for any arrivals coming from the vicinity of the expected impact site.

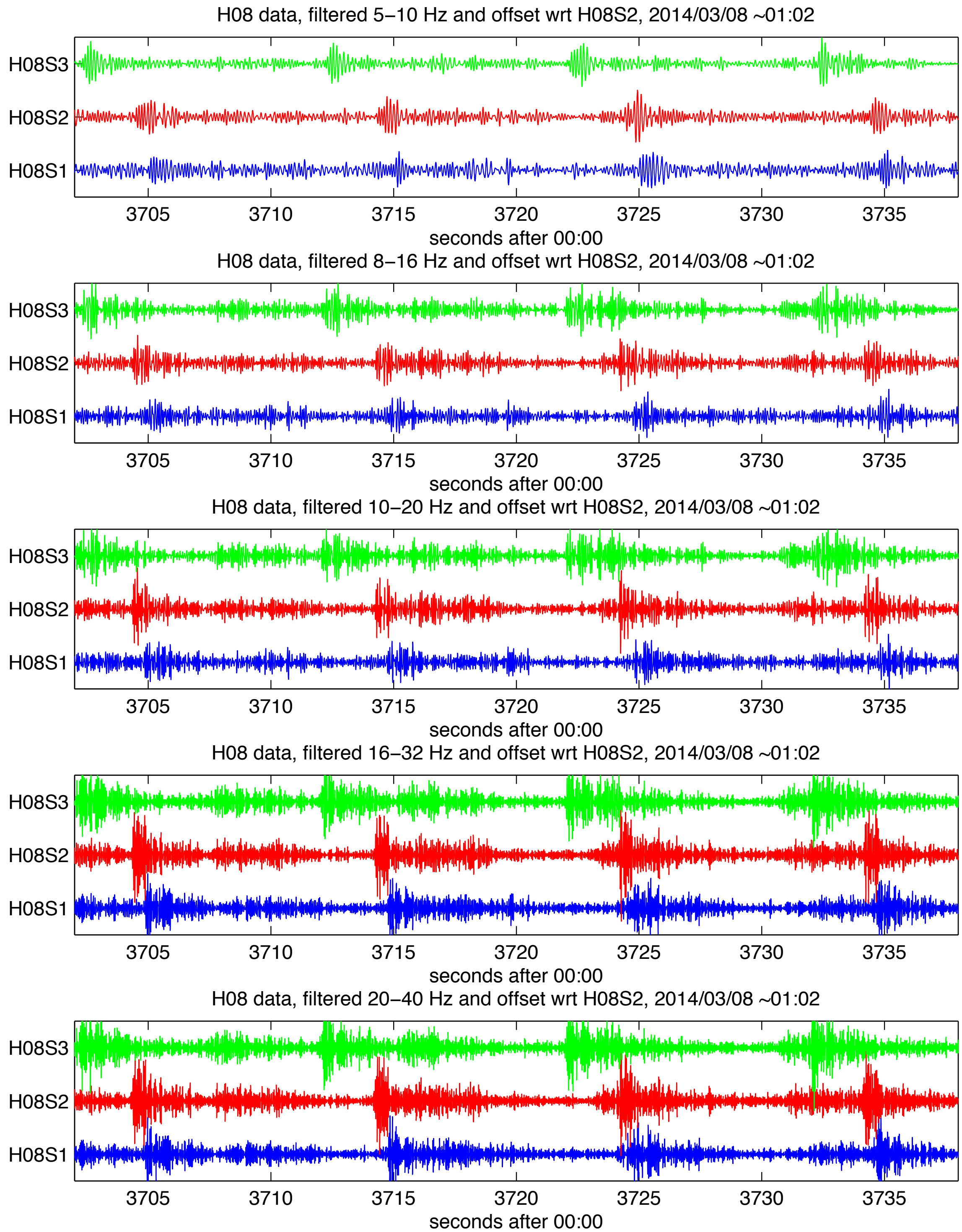

Figure 5: H08 data near expected arrival time. Data are shown filtered into 5 1-octave bands, same filters as figure 1. Note large amplitude signals repeating at 10-second intervals and smaller amplitude signals at 8-second intervals. Also note the broadband nature of the signals, having significant signal-to-noise ration in all bands from 5 to 40 Hz here. These signals completely obscure any other signals that may be present.

AIS

As expected, AIS is a noisy site. It is close to shore on an island often buffeted by large breakers and exposed to strong winds. We again scanned the waveforms, looking for any signals that might stand out from the noise in any characteristic; however none could be found. Part of the problem is that the station has a low sample rate (20 samples per second) that precludes examining the waveforms in the band of interest, 10-20 Hz (as indicated by the signal of interest observed at H01), since the Nyquist is only at 10 Hz. One could well expect that if the suspected impact signal is not above the noise below 10 Hz at the hydrophones of H01, it then could not be above the noise when converted to a T phase, even without the excessive noise at these frequencies at AIS. As for higher frequencies, since AIS is likely closer to a potential impact site, then frequencies above 20 Hz may be above noise here that are not above noise at H01. But again, the low Nyquist frequency precludes any opportunity to investigate that possibility.

Figure 6 shows a sample of the waveforms around the time of the expected arrival. It was chosen to show one of the common noise bursts (at about 00:36) observed at this station. Several of these appear in the record every hour, so this is not unique and likely represents a local nature noise source, such as large waves crashing on a nearby shore or something similar. The waveforms were filtered at 2-9 Hz to eliminate most of the longer period ocean noise while retaining all available data above 2 Hz (and below the effects of the anti-aliasing filters at the station). We performed a polarization analysis on the data to look for any signals that might appear both above noise and with the correct DOA. The expected DOA here is approximately 137°. The polarization results for approximately the same time intervals as the waveforms in figure 6 are shown in figure 7. As can be seen, the large noise burst has a DOA (labeled ‘az’ on the figure) of approximately 40 degrees, which is about 100 degrees off from that expected. It is also similar to most of the background noise. Rectilinearity (labeled ‘rect’ on the figure, a measure of how closely the particle motion conforms to a plane wave, on a scale of 0-1, with 1 being a perfect plane wave) is slightly elevated for this phase, but not particularly distinct from the background noise. The incidence angle (labeled ‘inc’ on the figure, and is the angle the 3D DOA vector makes with respect to horizontal plane in a vertical plane that includes the vector) is also not distinct from the background noise. In all three measures, the polarization is not distinct from the background noise, indicating that this noise burst is merely a large-amplitude version of the background.

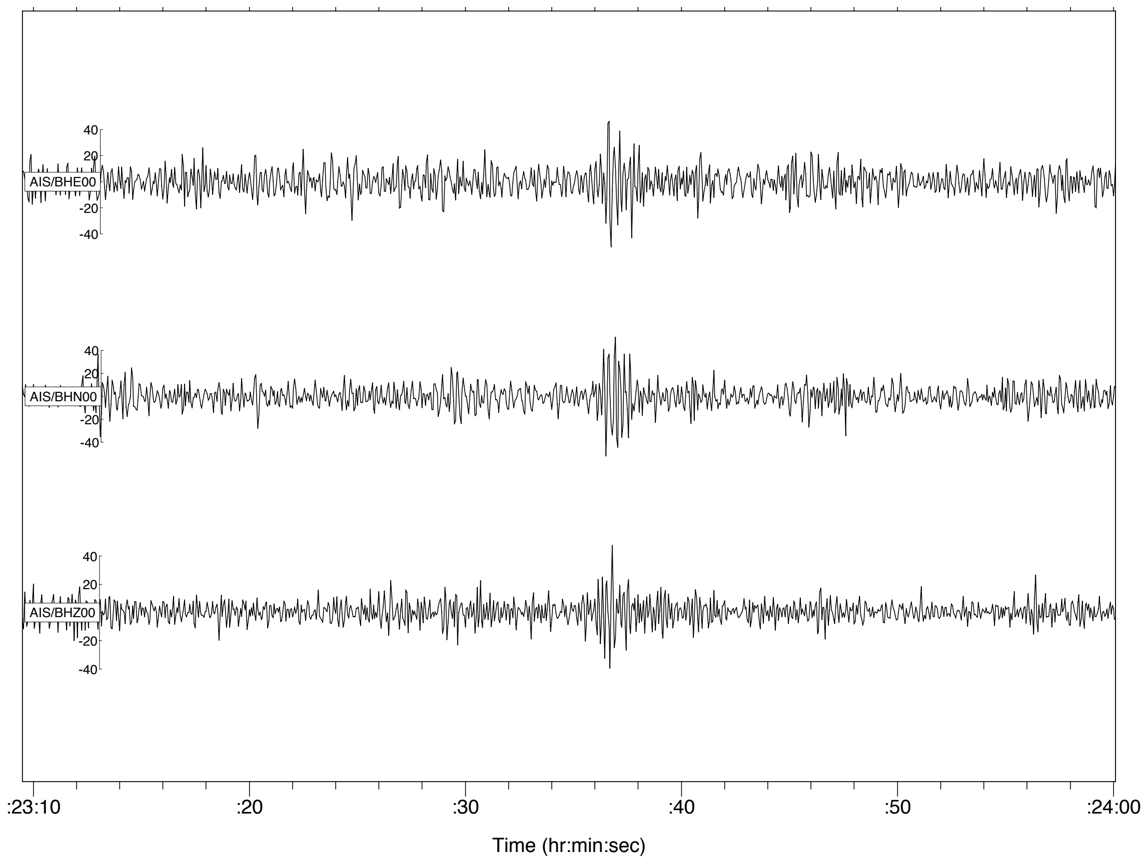

Figure 6: Waveforms from the seismic station at Amsterdam Island (AIS), filter at 2-9 Hz. For the channel names, "BH" indicates a broadband seismometer recorded at high gain, the "00" indicates that these are all components of a single instrument designated "00", and the "E, N and Z" indicate the component of motion: E is positive east, N is positive north and Z is positive down. Time is given as hour:minute:second after 2014/03/08 00:00 UTC.

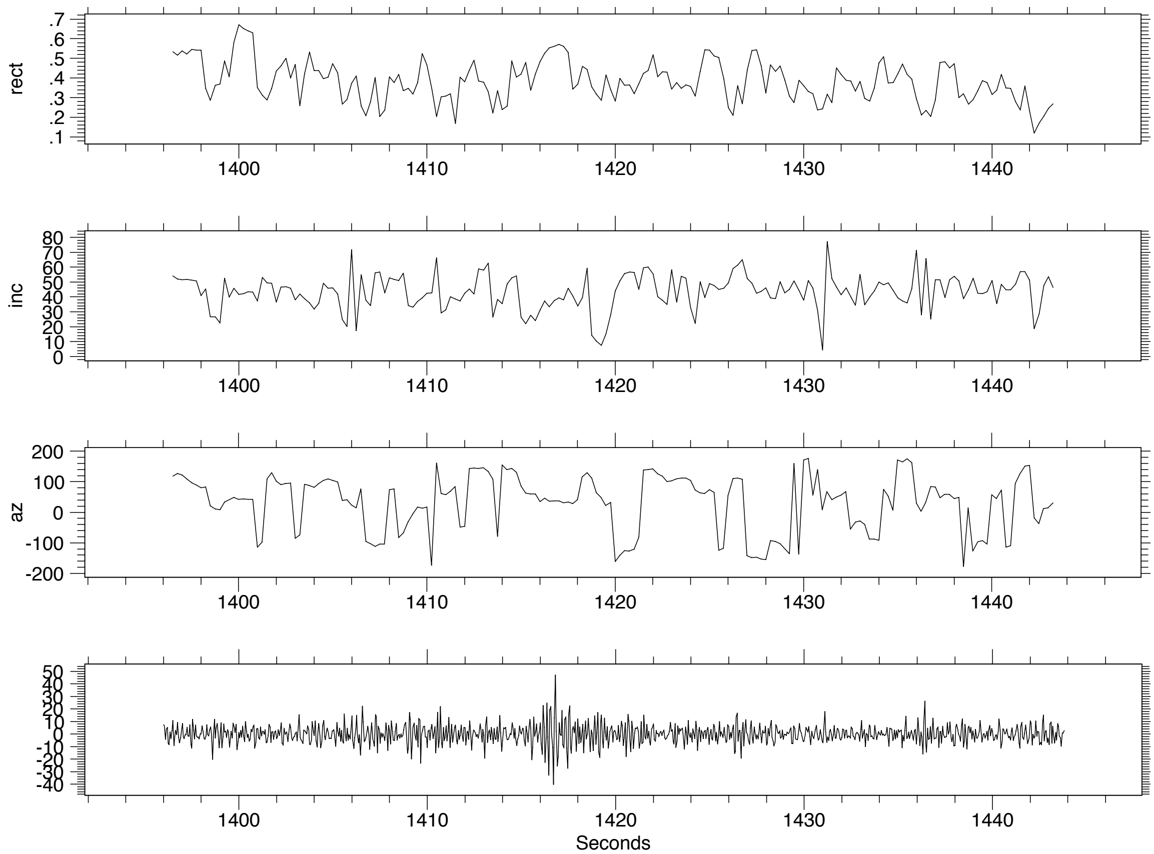

Figure 7: Polarization analysis of Amsterdam Island (AIS) seismic data. Data have been pre-filter to 2-9 Hz. The plots, in order from top to bottm, show rectilinearity, incidence angle, DOA and the seismogram from the vertical component. Time is given in seconds from 2014/03/08 00:00 UTC.

Given that no reasonable signals seem to be present above the noise and from the roughly expected azimuth, it is worth examining the orientation of the station to confirm that it is correctly oriented and would provide accurate azimuths. To do this we chose a large teleseism that is close to the day in question for an analysis to confirm the orientation of the instrument. We chose a M6.5 event near Japan, in the subducting slab of the Philippine Sea plate NW of Okinawa in the Ryukyu Islands. This event occurred on 2014/03/02 at 20:11:23 UTC at the geographic coordinates 27.431°N 127.367°E and a depth of 119.0km (magnitude, location and time from the USGS National Earthquake Information Center).

The P-wave from this quake would be expected to be strong in approximately 1-5 Hz at this range. We observed an arrival around 1-2 Hz at the expected P wave time of approximately 20:23:21, but signal-to-noise ration was only about 2, which is insufficient to get a good horizontal polarization, especially for near-vertical incidence as this arrival would be. However, The dominant crustal surface waves near 20 seconds (0.05 Hz) would be well excited by this event and are also well below the microseism frequency band that creates so much noise at AIS. A plot of the waveforms with a 1-octave filter across 20 Hz is shown in figure 8. As can be seen in the figure the north and east components show clear Love and Rayleigh waves well above the noise. The amplitudes on both horizontal components for both waves are roughly equivalent as would be expected for an approximately 45° DOA, clockwise from north. In addition, the motion of the Love wave is NW-SE as expected, and the horizontal motion of the Rayleigh wave is NE-SW, also as expected. This confirms the orientation of the station.

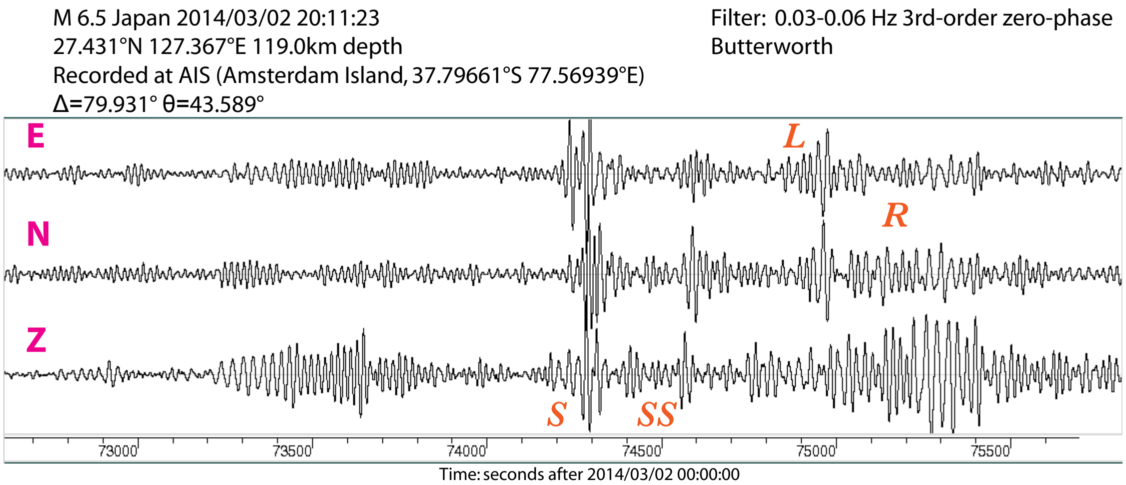

Figure 8. Orientation analysis of AIS using the M6.5 Japan quake from 2014/03/02. E, N, and Z label the 3 components of the instrument. S and SS are body-wave shear arrivals. L and R are the Love and Rayleigh surface waves, respectively. Waveforms have been filtered in a 1-octave band around 20 Hz.

Further information regarding possible flight paths indicated that a time of arrival at AIS of approximately 00:26:30 might be possible. For completeness, we looked at this time in more detail as well. We applied the same tools, including polarization, and careful review as we have done above. No useful signals were discovered; the time includes only the common noise found at this site. Figure 9 shows approximately 1 full minute of data around 00:26:30, filter in 4 bands. The 4 bands from top to bottom are octave bands 2-4, 3-6, 4-8 and 5-10 Hz. The Nyquist frequency is 10 Hz, so it is unnecessary to attempt any higher bands. The figure shows the relatively constant background at 2-4 Hz that is similar to what is seen at all lower frequencies as well. As the frequencies get higher, the more impulsive signals from wave strikes and similar weather-driven phenomena become more prominent. But none of this energy corresponds to seismic body waves that would be expected from the conversion of hydroacoustic energy in the SOFAR channel to seismic energy at the island's offshore slope. Very likely, small signals from converted hydroacoustic phases will be completely obscured in this much noise. The only signal that is not noise in the figure is a seismic surface wave, Rg, visible at about 00:26:25, identified as a surface wave from its dispersion. This would be from some small seismic source on the island, and not from a more distant ocean surface impact.

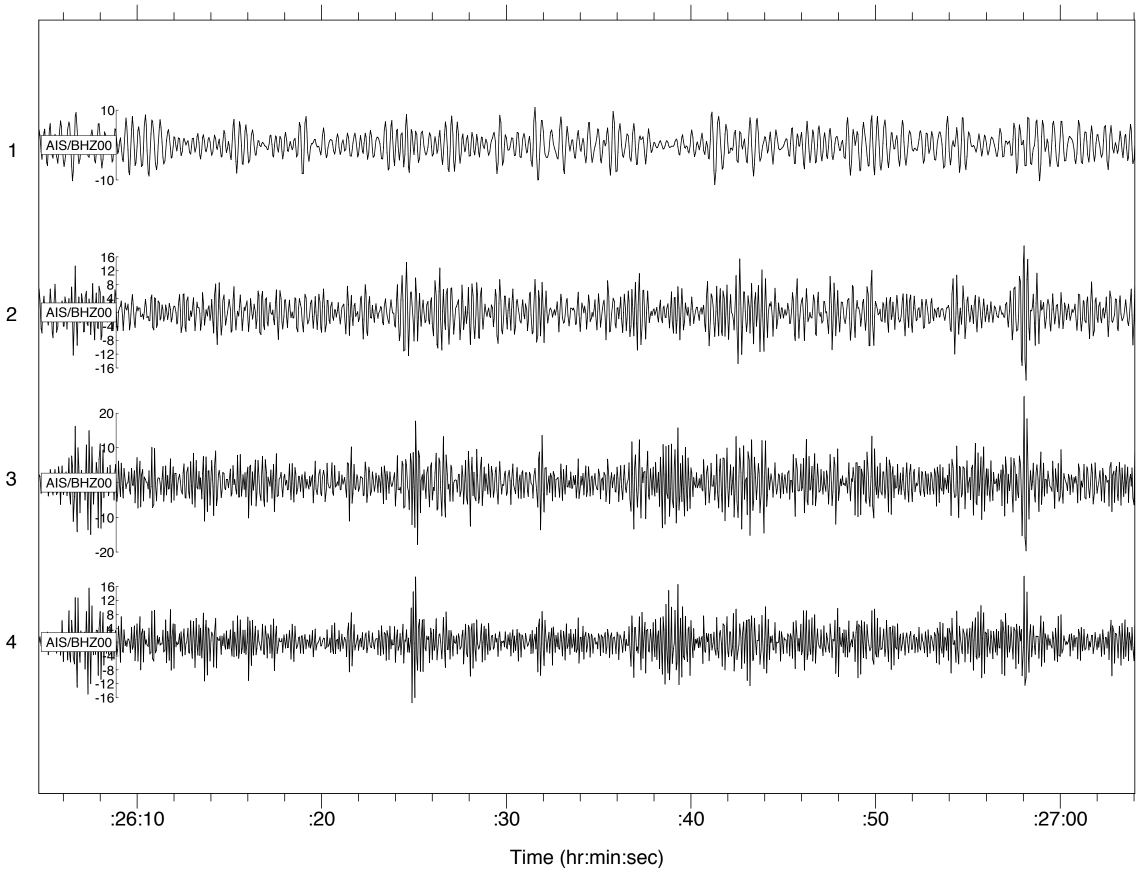

Figure 9. This figure shows a closer look as the seismic waveforms from around the time 00:26:30 at AIS. The vertical component is shown filtered to 4 1-octave overlapping bands. The time interval displays a variety of large-amplitude noise.

Conclusions

The seismic and hydroacoustic data readily and openly available for analysis are quite limited. Only Three potentially applicable station were identified: H01, H08 and AIS. Of these, H01 has a very interesting and potential applicable arrival. H08 is contaminated by a long series of large-amplitude repeating and interfering signals that completely obscure any possible applicable arrival. AIS is contaminated by natural noise sources and has a sample rate sufficiently low as to likely exclude any signals of interest. Thus, at most, we were able to identify a candidate arrival from only a single station. This arrival also has problems in analysis, since it is interfered with by a large-amplitude arrival that follows it with only a small delay. That arrival is clearly associated with some sort of ice event from Antarctica. Continued analysis and further confirmation of the arrival at H01 would only be possible if there are additional sources of data that are either not open or not readily available. The arrival at H01, if it is indeed from the impact of MH370, would indicate that the impact is toward the southern portion of the broad search area previously declared and likely south of the area in which possible pings were briefly recorded.

In addition it is concluded that the southern Indian Ocean is insufficiently monitored for events of any type, including events of interest for the CTBT. Relatively small but significant explosions could prove to be difficult to detect, locate and identify in this region due to the shortage of useful stations and the likelihood that one or more stations could be rendered useless for monitoring purposes by various types of common noise sources in their vicinity.