

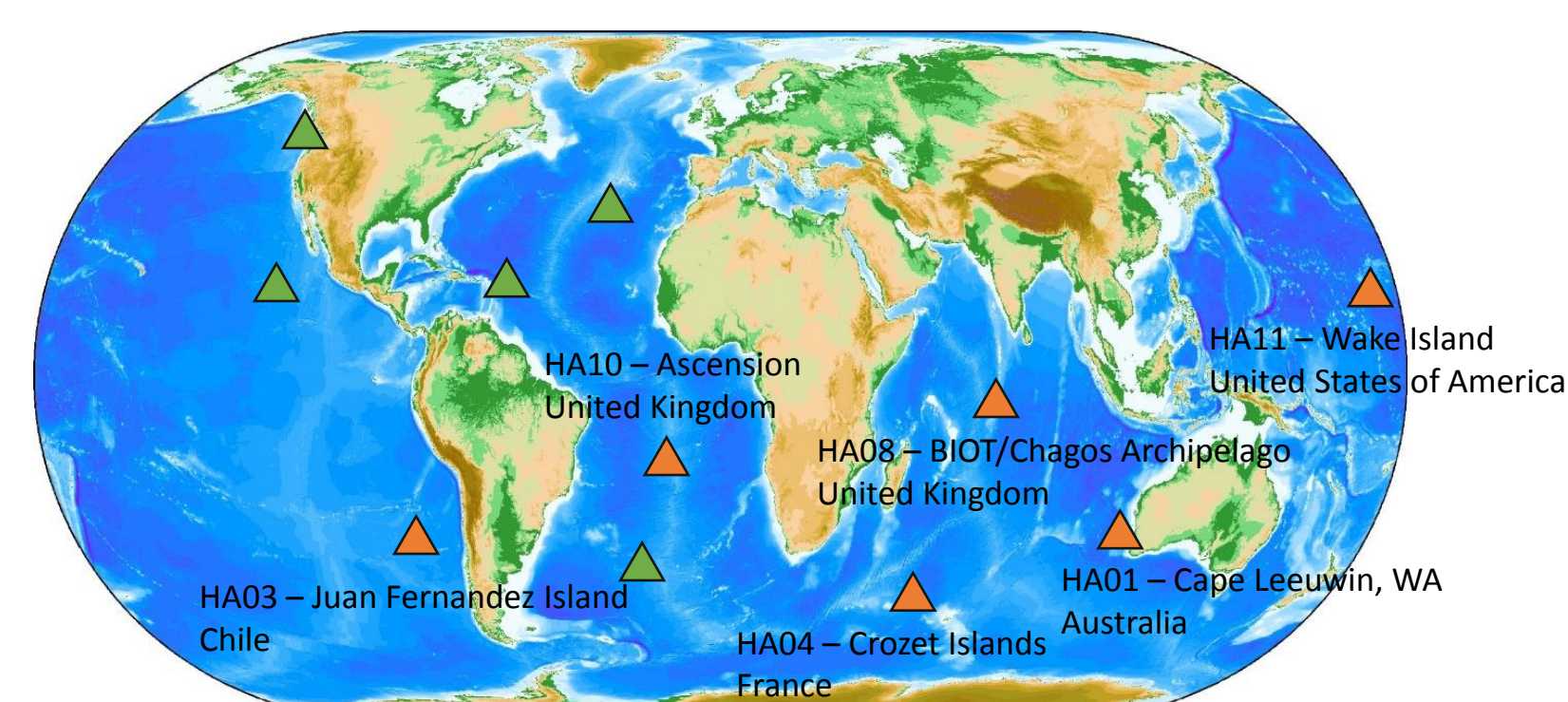


In-situ observation in terms of seismicity suggested that the volcanic activity of Ioto (formerly Iwojima), a volcanic island offshore Japan in the northwest Pacific Ocean, increased in early September in 2018. Discolored waters and a splash were confirmed in the nearshore by a local flyover observation. Although these visual signs evidenced a connection between undersea eruptions and recorded seismic activity, there still remained uncertainty as to what portion of the *in-situ* recorded seismic activity was associated with volcanic tremors vs. undersea eruptive events.

During the same period, a large number of underwater acoustic (hydroacoustic) signals were recorded by the Comprehensive Nuclear-Test-Ban Treaty's (CTBT) International Monitoring System (IMS) hydroacoustic (HA) station HA11 Wake Island. A set of three hydrophone sensors forming a triplet makes it possible to compute the back-azimuth uniquely for wave packets with a good signal-to-noise ratio. As a result, the IMS hydrophone triplet data could discriminate the hydroacoustic signals associated with the Ioto volcanic activity. We analyzed the data of the IMS hydrophone triplets during the month of September 2018 and compared them with *in-situ* seismic observations in Ioto for the same period.

The direction-of-arrival (DOA) was estimated using cross-correlation analysis, suggesting that approximately 200 signals were detected as originated from Ioto. The arrivals from Ioto determined by the IMS HA station correlated well with the *in-situ* observations in Ioto. The present study suggests that two-thirds of the hydroacoustic signal arrivals were associated with volcanic tremors and one-third with the undersea eruptions.

IMS Hydroacoustic Network & Hydrophone Triplet



Underwater hydrophone stations / T-phase stations

Figure 1. CTBT IMS hydroacoustic network.

The hydroacoustic network is part of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty (CTBT) and has 11 stations. Of the 11 hydroacoustic stations, five (denoted by green triangles) are T-phase stations which use seismometers to pick up water-borne signals from acoustic events coupled in the crust of coastal areas. The other six (orange triangles) are cabled stations that utilize underwater hydrophones. All the cabled stations have two triplets of underwater hydrophones suspended in the water column, in a horizontal triangular configuration with a separation of 2 km, except for HA01 at Cape Leeuwin, Australia which has only one triplet.

The present study is concerned with the IMS hydroacoustic (HA) hydrophone stations, which have been installed since the early 2000's. The hydrophone stations are based on islands and connected by electro/fiber-optic cables to the hydrophone triplets. The triplets are deployed up to 200 km from the island. All hydrophone sensors are located in the Sound Fixing And Ranging (SOFAR) channel axis at a depth of 600 m to 1200 m, suspended by subsurface floats. Hydrophones record the pressure change in the water caused by passing hydroacoustic waves, such as H-waves and T-waves.

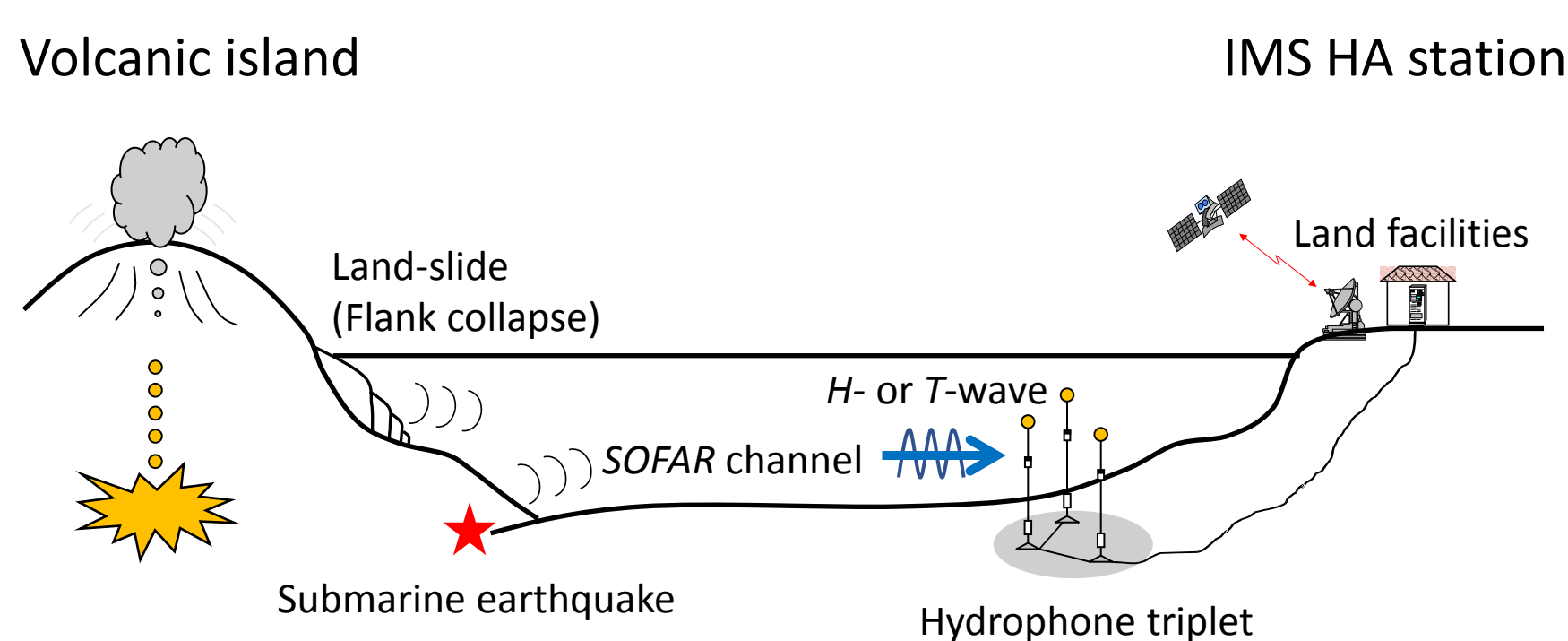


Figure 2. Overview of an IMS hydrophone triplet and events which generate underwater sound.

Ioto Volcanic Island & IMS HA11 Wake Island

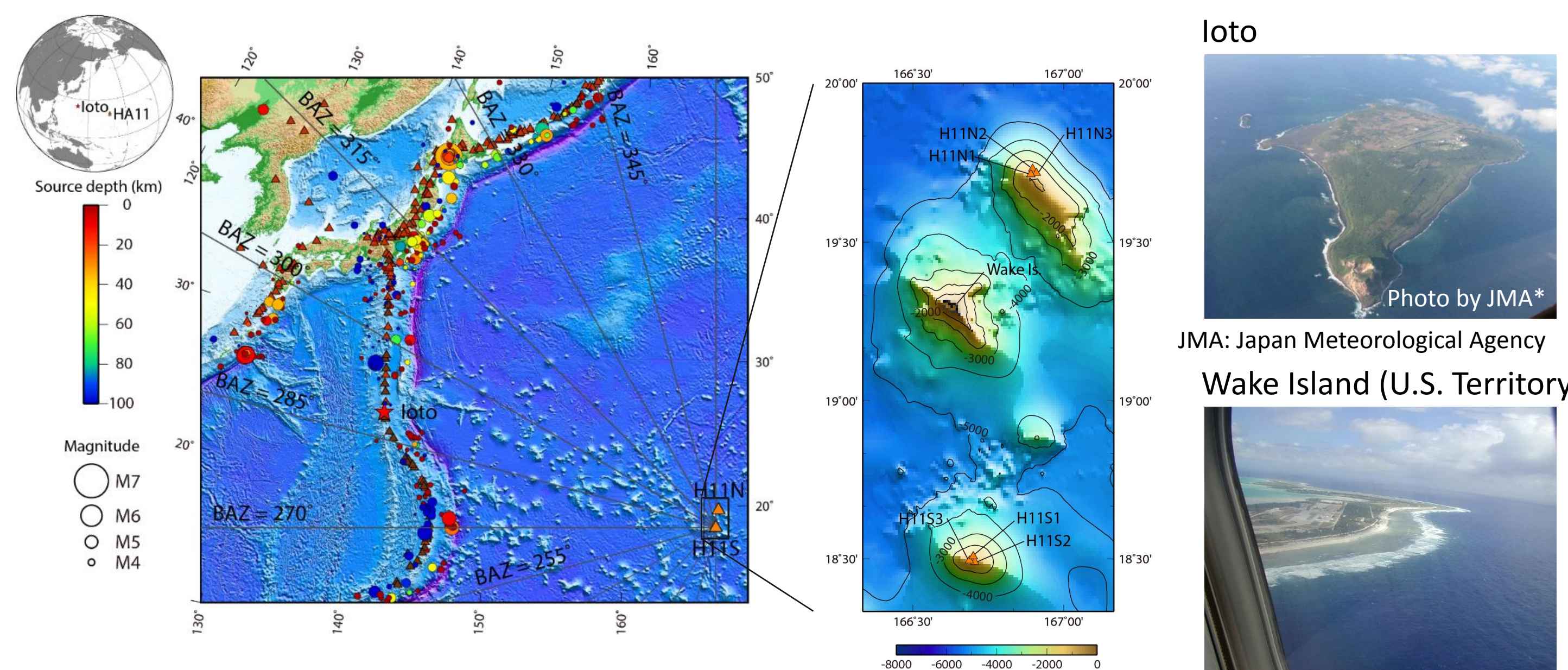


Figure 3. The northwestern Pacific Ocean area covered by the present study.

Figure 4. Flyover photos of Ioto and Wake Island.

The location of Ioto island (formerly Iwojima) volcano is denoted by a red star, and the IMS HA11 hydroacoustic station triplets at Wake Island are denoted by orange triangles. HA11 comprises two triplets of hydrophones, referred to as H11N and H11S. The distance between Ioto and HA11 is about 2,700 km. Circles mark the locations of the 6,165 earthquakes recorded in the area during the month of September 2018, their color and size represent source depth and magnitude, respectively. Dark and bright red triangles locate above-surface and submarine volcanoes, respectively, as registered by the Smithsonian Institute. Radial marks are back-azimuths (BAZ) from H11S.

Identification of Undersea Eruptions

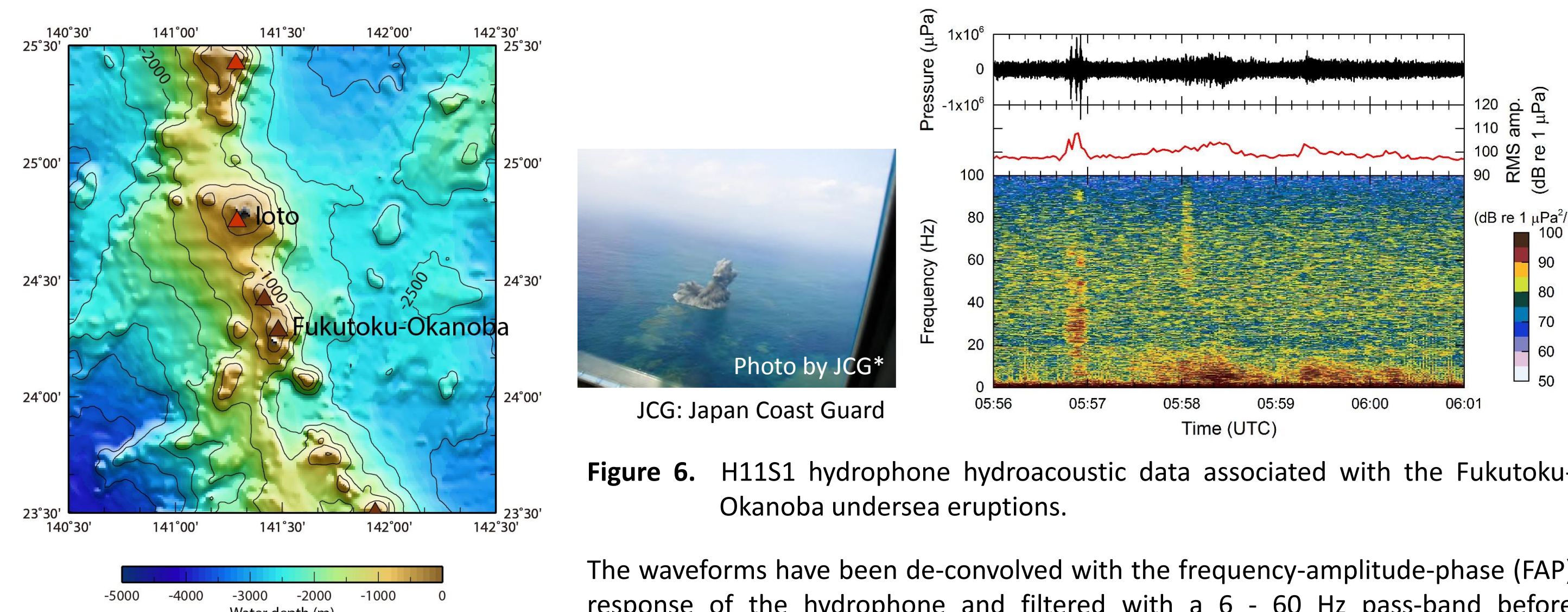


Figure 5. Locations of Ioto and Fukutoku-Okanoba.

Figure 6. H11S1 hydrophone hydroacoustic data associated with the Fukutoku-Okanoba undersea eruptions.

The waveforms have been de-convolved with the frequency-amplitude-phase (FAP) response of the hydrophone and filtered with a 6 - 60 Hz pass-band before displaying the time-series. The lower panel shows the H11S1 hydrophone spectrogram during the 03 February 2010 Fukutoku-Okanoba undersea eruption. The root-mean-square (RMS) amplitude, using 2-s bins, is also shown. A flyover observation identified that an undersea eruption took place at 05:27 UTC on 03 February 2010. Based on time of arrival and back-azimuth it was possible to associate the signal received at 05:56:50 UTC with this visually observed Fukutoku-Okanoba undersea eruption. The successive longer-lasting (> 2 min) low frequency (< 20 Hz) signal is typical of an earthquake and is not associated with the eruption.

The hydroacoustic signals associated with the Ioto undersea eruption are the ones recorded at 09:23:12 UTC and 09:25:15 UTC. A longer duration low-frequency signal preceding the volcanic arrivals is identified at 09:21:00 UTC with a back-azimuth of 140° (i.e. off from the direction of arrival of signals originating from Ioto), and is thought to be associated with an earthquake or undersea volcanic activity from a location different than Ioto. The left figure shows the Power Spectral Densities (PSDs) of ambient noise and the Ioto undersea eruption.

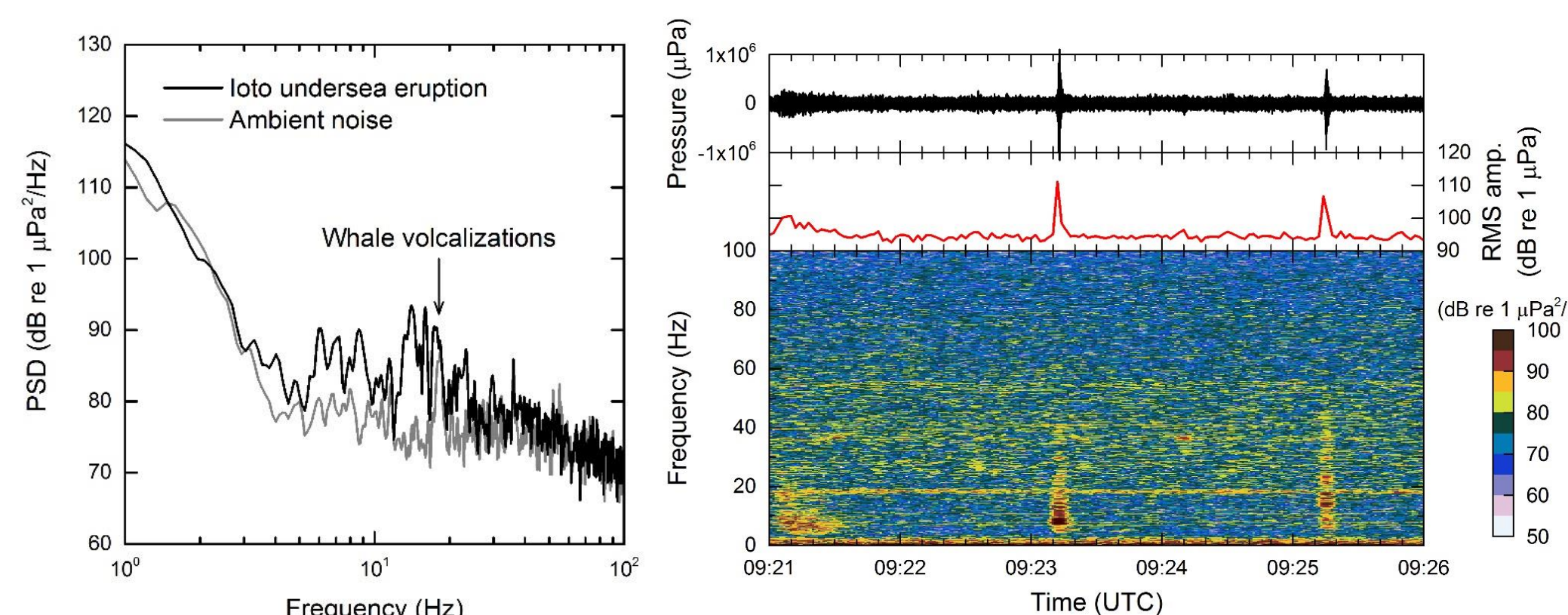


Figure 7. An example of a typical recording associated with the Ioto undersea eruption on 08 September 2018 (centered at 09:23:12 UTC and 09:25:15 UTC) following the same template used in Figure 6.

Discrimination between Volcanic Tremors & Undersea Eruptions

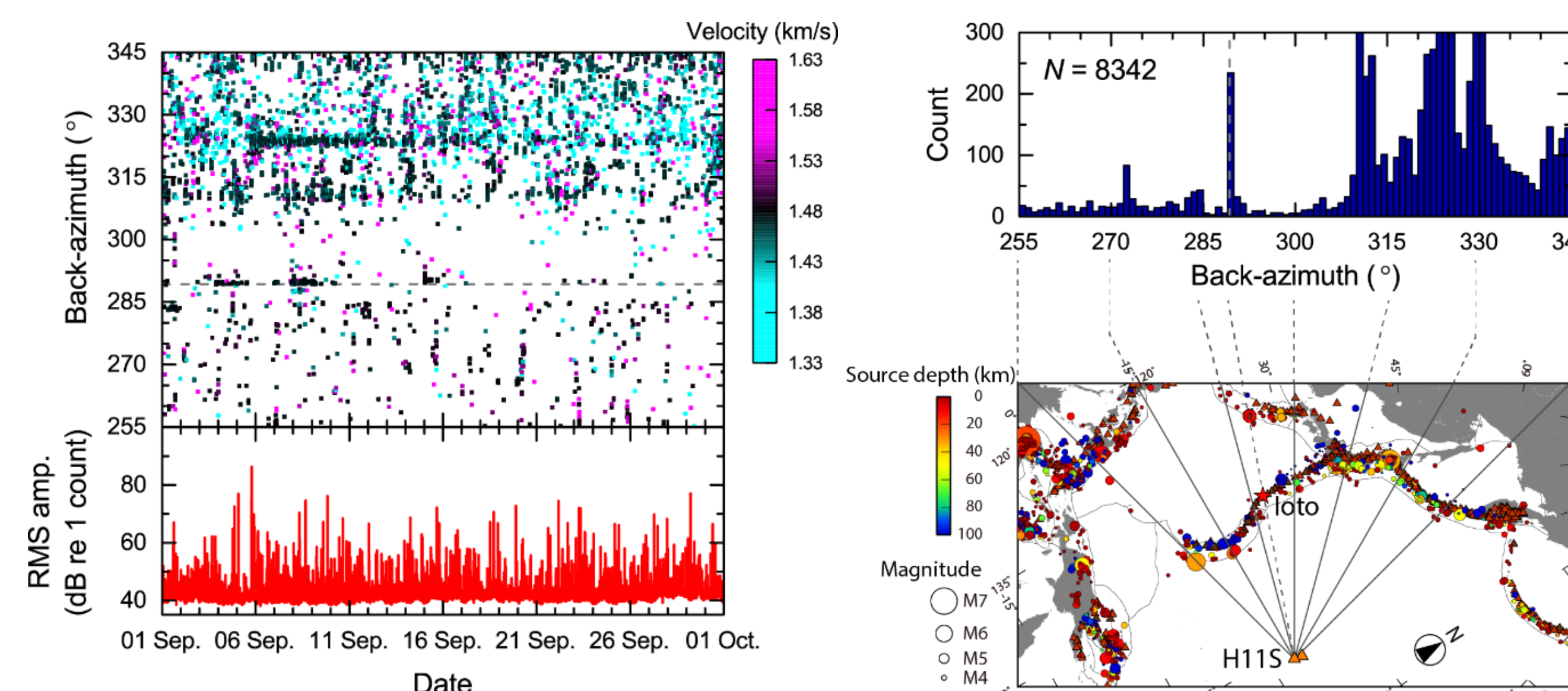


Figure 8. Cross-correlation analysis of data with a band-pass filter between 6 and 60 Hz during the entire month of September 2018.

Figure 9. Histogram of signals detected by H11S.

Back-azimuth between 255° and 345° of the signals detected by H11S, together with the RMS amplitude of the band-pass filtered signal, are shown in Figure 8. Each of the 8,342 dots is calculated over a 20-s time window. The dashed line represents the true back-azimuth to Ioto. The back-azimuth suggests that the Ioto volcanic activity had two separate periods of high activity between the 03 and the 10 September with a 2-day gap. Hydroacoustic signals associated with the 05 September earthquake at Hokkaido (back azimuth 324.3° to the epicenter) and its aftershocks were clearly detected at H11S. These seismic source arrivals are found until the end of the analysis period, albeit that they decrease in number with time.

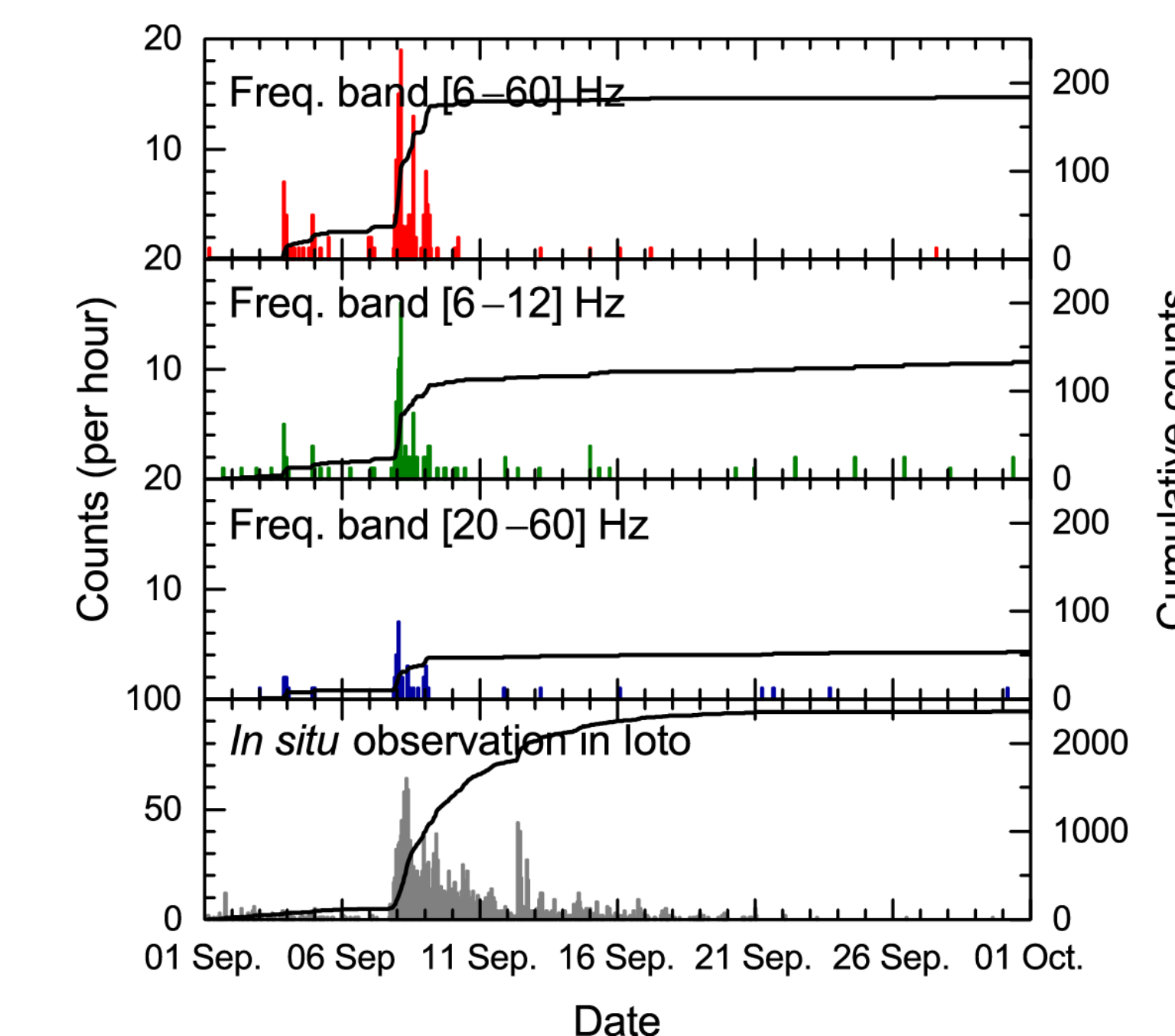


Figure 10. Comparison of hydroacoustic far-field arrivals determined at H11S and Ioto *in-situ* seismic measurements.

The curves in the top three panels of Figure 10 show the cumulative detections of H11S hydroacoustic signals in three different frequency bands. The curve in the bottom panel shows the equivalent cumulative detections for the Ioto *in-situ* seismic signals. Histograms show counts per hour. The total number of signals detected within the full frequency band, i.e. between 6 Hz and 60 Hz, is 184; this number representing both volcanic tremors with frequency band between 6 Hz and 12 Hz and undersea eruptions in the band between 20 Hz and 60 Hz. This total number agrees closely with the sum of the 133 volcanic tremors and 54 eruptions detected based on discriminating the arrivals by their bandwidths.

Conclusions

1. The detections at HA11 from the Ioto undersea eruptions in 2018 were supported by a flyover observation at Fukutoku-Okanoba in 2010.
2. Estimation of the direction-of-arrival (DOA) of the signals recorded at HA11 by cross-correlation analysis made it possible to identify hydroacoustic arrivals from the volcanic activity at Ioto.
3. The total number of hydroacoustic signals from Ioto determined by processing the IMS HA station data and the number of the volcanic events recorded *in-situ* at Ioto showed good correlation.
4. Using the time-frequency characteristics of the arrivals, the present study made it possible to discriminate between volcanic tremors and undersea eruptions, suggesting that two-thirds of the arrivals recorded at HA11 were associated with volcanic tremors and one-third with undersea eruptions.

Acknowledgements

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