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Underwater signals from confined explosions in very shallow water

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ABSTRACT

Certain offshore structures require pipelines to the shore, which are generally buried beneath the seafloor in a shallow trench. If the seabed is rock, creating a trench can require blasting, which is done with explosions confined in boreholes drilled into the rock and covered with stemming. A desalination plant is under construction at Binningup, Western Australia. The seabed contains a sand layer (of variable thickness) over Tamala limestone, and five confined blasts were fired in the limestone to create trenches for an outfall and two inlets. The seafloor depth was 10 m at the blast positions. The underwater acoustic signals were monitored by hydrophones out to sea, and the signals from one of these blasts have been selected for detailed analysis. The data for peak Sound Pressure Level from the confined charges are in good agreement with a synthesis of empirical formulae due to Arons (1954), Gilmanov (1984) and Oriard (2002). The characteristics of the acoustic ground wave were affected by a high-density sub-bottom stone rather than the Tamala limestone layer that lies above it. The interface to the dense stone is around 10 m below the seafloor, and is observed to have a wave speed (presumably shear) of 2620 m/s. The blast contained six explosions, and the Sound Exposure Level (SEL) was observed to decrease from 158 to 149 dB re µPa^2.s as range increased from 840 to 2400 m. The SEL spectra have peaks at around 50 to 60 Hz, which can be attributed to the delay of 16 ms between explosions, and minima at around 200 Hz, which appear to be attributable to a second low-frequency cut-off in the vicinity of 600 Hz.

INTRODUCTION

A desalination plant is under construction at Binningup, Western Australia. In accordance with the Marine Blasting Management Plan produced for the Southern Seawater Desalination Project, Dempsey Australia Pty Ltd fired five confined underwater blasts during March and April 2010. The purpose of the blasts was to create trenches in the partially rock seabed, for pipes from the planned desalination plant to an outfall and two inlets. The conditions for approval by the federal Department of Environment, Water, Heritage and Arts included the following clause: “all marine blasting must be sound monitored at a distance of 2 km from the blast source…” (DEWHA 2010). According to the approval, the purpose of this condition is to ensure that physical harm, including temporary hearing threshold shift, to cetaceans and marine turtles will be unlikely.

The subject of this paper is the first blast (Blast 1), which comprised six explosions. The aim is to describe this blast and the acoustic signals received by hydrophones deployed out to sea, in order to take a first step toward predicting the latter, given a description of the former.

THE BLASTS

A picture of the surface effervescence and the shot-firer’s barge (taken during a much larger blast) is shown in Figure 1. The picture was taken when the effervescence reached its maximum extent. One of the boats from which hydrophones were deployed can be seen in the distance. The closer small boat was associated with the blasting, but was performing other duties.

Figure 1. Blast effervescence near the shot-firer’s barge off the coast at Binningup. The effervescence shown here was caused by a blast 12 times larger than the blast examined in the present paper.

For each of the blasts, cylindrical cartridges of explosive were placed in holes drilled into rocky areas of the seabed. Each full cartridge was 70 cm long, 5.5 cm in diameter and contained 1.9 kg of explosive emulsion. A Surface Delay Detonator (SDD), which did not trigger the cartridge, was placed above the seafloor near the top of each hole. Each SDD consisted of a detonator placed inside a plastic clip connector for mechanical protection (Maxam Australia 2008). The detonator contained 0.24 g of heavy-metal azide explosive which, since the TNT equivalence of such azides is approximately 0.4 (Cooper 1994, Kleine et al 2003), would be equivalent to around 0.1 g of TNT. A Down-Hole Detonator, which did trigger the cartridge and was connected to the SDD by a flexible shock tube, fired 500 ms after the SDD. The times (delays) at which the explosions were fired were 16 ms apart, so that the waterborne shock waves would not coherently superimpose on each other.

The first blast was 506 m offshore where the seafloor depth was 10 m. It comprised six confined explosions in a rectangular array of three in the east direction (1.5 m burden) by two in the north direction (2.0 m spacing). The two holes at the centre burden each contained 1.66 cartridges beneath 70 cm of stemming, and the other four holes contained one cartridge beneath 60 cm of stemming. Angular gravel (1 cm size) was used for stemming. The point of initial ignition was the south-west corner of the rectangle.

In addition to the planned delay of 16 ms between explosions, there were further small delays due to two factors:

- the SDDs were joined by signal tubes whose lengths could vary between 2 and 4 m (the straight-line distances between detonators that were joined were either 2.0 or 2.5 m). Since the ignition in the signal tube propagates at 2000 m/s, the resulting delay per connection would have varied between 1 and 2 ms; and
- the 1.5-m hole-to-hole spacing in the eastern direction (“burden”), which would cause a delay of up to 1 ms per burden, depending on the direction of propagation.

Since ignitions were commenced from the western side of the array, these two delays would have added together for signals propagating westward, in that signals from the eastern side started later, and were further away from hydrophones to the west.

Method of Monitoring

Three hydrophones, named A, B and C, were deployed from boats approximately due west of the blast, at ranges of 840, 1410 and 2410 m respectively (to the nearest 10 m). For Hydrophones A and B the data acquisition system comprised a Harrison in-line 12 dB attenuator, a Reson EC6061 preamplifier, and a sound-recorder in a Toshiba laptop computer. The system for Hydrophone C comprised a preamplifier and laptop. A sampling rate of 96000 /s was used.

The sea surface condition was estimated at 3 on the Beaufort scale, for which the corresponding wind-speed interval is 7 – 10 knots, and there was no noticeable current. The hydrophones were each deployed with 5.0 m of cable below the sea surface, and since conditions were mild, their actual depths below the mean surface would have been close to 5.0 m all the time. The seafloor depth along the acoustic propagation paths increased from 10 m at the blast to 12 m at hydrophone A, remained constant from A to B, and then increased to 13 m at hydrophone C.

RESULTS

Pressure waveform of whole signal

The pressure waveforms of Blast 1 from the three hydrophones are shown in Figure 2, offset along the ordinate axis by their respective ranges. The initial group of 6 weak pulses are from the SDDs. Time is relative to 5 ms prior to the pulse from the first SDD. Since the amplitudes are not corrected for different attenuations in the three data acquisition systems, the amplitudes from one hydrophone to another cannot be compared. The main pulse commences 500 ms after the first detonator pulse. For each hydrophone, the main pulse begins with a sharp increase and contains four sharp peaks over a duration of 70 ms before it descends into reverberation. Much of the main pulse is relatively incoherent. The detonator pulses from hydrophones B and C are not as clear as those from hydrophone A (the detonator pulses from the three hydrophones will be shown more clearly in a later figure).

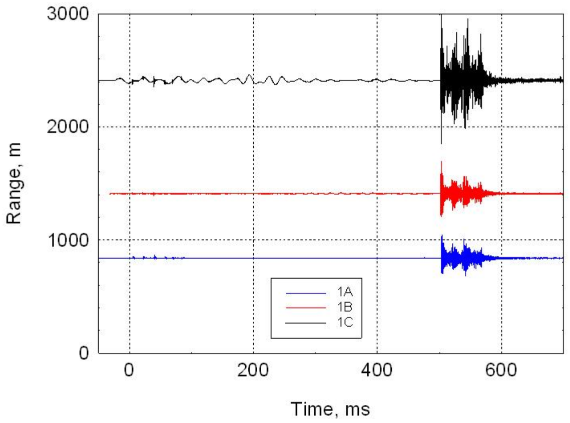

Figure 2. Pressure waveforms from Blast 1, offset by the hydrophone ranges. Time is relative to 5 ms prior to first detonator pulse. Amplitudes are not corrected for different attenuations in the three data acquisition systems.

Pressure waveforms of detonator pulses and ground wave

The precursors to the main signals received at the three hydrophones are shown in Figure 3, again offset along the ordinate axis by their respective ranges. The SDD pulses are evident in the three waveforms. It is not known why the third SDD gave a stronger signal than the other five.

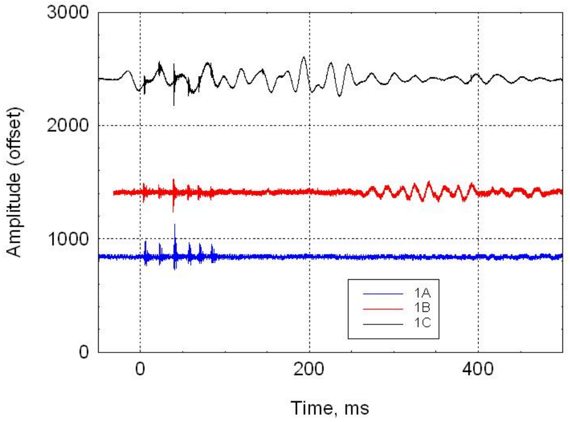

Figure 3. Precursors to the main signals from Blast 1, offset by the hydrophone ranges. Time is relative to 5 ms prior to first detonator pulse. Amplitudes are not corrected for different attenuations in the three data acquisition systems.

Although no low-frequency (fast) ground wave (Pekeris 1948, page 94) associated with the main pulse was evident at hydrophone A, they were evident at the longer range hydrophones. At hydrophone B the ground wave began at 240 ms prior to the main pulse, which placed it well after the detonator pulses. At hydrophone C the ground wave started 517 ms prior to the main pulse, so that it overlapped the first detonator pulse by 33 ms. The six detonator pulses can be seen superimposed on the ground wave in Figure 3.

Later in the paper, results for the peak Sound Pressure Level (SPL) of the detonator pulses will be presented. In view of the ground wave overlapping these pulses from hydrophone C, that waveform was high-pass filtered with a low-frequency cut-off at 160 Hz. The result, together with the unfiltered waveform, is shown in Figure 4.

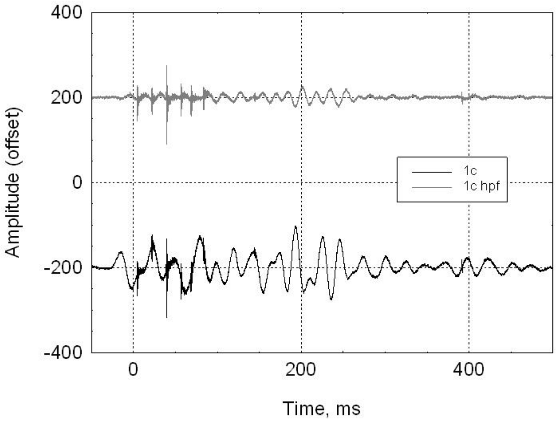

Figure 4. Wideband and high-pass filtered waveforms of the detonator pulses and ground wave from hydrophone C. KEY: black – wide-band; grey – high-pass filtered.

SEABED PARAMETERS INFERRED FROM PULSE CHARACTERISTICS

If the seabed is uniform with depth, then the wave speed in the seabed (sound or shear) can be determined without ambiguity from the travel time of the ground wave (Brekhovskikh, 1960, page 402). If the seabed contains layering, then the speed so obtained will be that of one of the layers, but its depth, and the wave speed in the layer overlying it cannot be determined from the ground wave. Nevertheless, knowledge of the wave speed at any depth is of value. Determining the travel time of the ground wave requires knowledge of the travel time of the main pulse, the high-frequency part of which travels at the speed of sound in the water. The prevailing sea surface temperature in the region was 20 °C (BOM 2010), and since there had been moderate winds blowing during previous days, the water layer would have been well mixed and isothermal. Assuming the salinity was the standard 3.5%, the corresponding sound-speed (Cw) would be 1520 m/s, and the travel times of the ground wave to hydrophones B and C would have been 686 and 1069 ms. Since the ratio of these times does not equal the ratio of the ranges, it is necessary to allow an offset for travel to an interface beneath the seafloor (as is done for head-wave analysis). Applying this method of analysis yields a seabed wave speed (Cb) of 2620 m/s. The depth of this interface can be determined if the wave speed in the overlying layer is known.

The low-frequency cut-off (Fc) for propagation in shallow water treated as a waveguide is equal to the frequency of the ground wave at its commencement (Brekhovskikh, 1960, page 403). For Hydrophones B and C these have been estimated by performing spectral analyses of the first 45 ms of the ground wave, and found to be 56 and 26 Hz respectively. The former is probably caused by the peak due to the 16 ms delay between explosions, leaving 26 Hz as the likely waveguide cut-off frequency. The expression for cut-off frequency is (Brekhovskikh, 1960, page 372):

$$Fc = Cw /[4 H \sqrt{(1 - Cw^2 /Cb^2)}]$$

where H is the depth of the main reflecting interface. Inverting this into an expression for H and substituting the above values for Fc, Cw and Cb yields H = 18 m. This indicates that the main reflecting interface at low frequency is around 8 m below the seafloor.

In light of this finding, it is of interest to consider the geology of the seabed, which along the south-west coast of Western Australia is generally Tamala Limestone. According to Wikipedia (2010) "This rock consists of calcarenite wind-blown shell fragments and quartz sand. As a result of a process of sedimentation and water percolating through the shelly sands, the mixture later lithified when the lime content dissolved to cement the grains together." According to websites of merchants dealing in dry Tamala Limestone, its dry bulk density is around 1550 kg/m^3. Since non-porous calcite has a density of 2710 kg/m^3, the corresponding porosity is 0.428. In marine Tamala limestone the non-stone volume is assumed to be saturated medium sand, which itself has a porosity of 0.38 (Richardson and Briggs 1993) and therefore a density of 2070 kg/m^3. The density of the resulting three-phase medium will be 0.428 × 2070 + (1 – 0.428) × 2710 = 2436 kg/m^3. From Hamilton (1980), the sound and shear speeds in calcareous sediment that corresponds to this density are approximately 4000 and 2100 m/s respectively.

The equation for Fc assumes that the sound speed is constant (Cw) from the sea surface to the depth H. Due to the Tamala limestone layer, the effective Cw will be somewhat higher than 1520 m/s, and the value for H will therefore be somewhat higher than 18 m.

VARIATION OF PEAK SOUND PRESSURE LEVEL WITH RANGE

Hydrophone A was an HTI-96-MIN, made by High Tech Incorporated (Mississippi, USA) and B was a Z3B made by Harris Transducer Corporation (Connecticut, USA). According to the makers' specifications, the low-frequency (LF) sensitivities of hydrophones A and B are -202 and -195 dB re V/μPa respectively, and their resonance frequencies are both around 30 kHz. Over that band, A's sensitivity is presumed to be constant to within ± 1 dB, while B's has a minimum 3 or 4 dB below its LF value at around 4 kHz, and oscillates twice around the LF value until 30 kHz. Hydrophone C, which is of unknown make, contains a 60-mm diameter piezoelectric annular sphere inside an 80-mm diameter rubber sphere. Based on its size, hydrophone C is intermediate to the spherical hydrophone types ITC1001 and ITC1032 made by International Transducer Corporation (California, USA). By interpolating between the maker's specifications for these two types, it has been estimated that C's resonance frequency is around 26 kHz, and its sensitivity lies between -194 and -191 dB re V/μPa. On the basis of results obtained (to be presented later), it seems likely however that C's sensitivity would be around -190 dB re V/μPa. This value has been adopted, and given a tolerance of ± 3 dB. The sensitivities of the three hydrophones have been assumed to remain at their LF values over the whole frequency band used for analysis, which extends to 32 kHz.

Using the sensitivities above, the peak SPLs of the main pulses have been computed, allowing for the attenuations in the data acquisition systems. The results are shown in Figure 5. The prediction of the author's synthesis of results presented by Arons (1954), Gilmanov (1984) and Oriard (2002) for a confined explosion is also shown (the curve notated by "AGO"). This particular curve applies if the explosive charge meets the following conditions:

- it is a cylinder, 5.5 cm in diameter, and at least 27.5 cm in length (Gilmanov found that, as a function of charge length, the waterborne SPL saturates when the charge length exceeds five charge diameters),
- its density is 1140 kg/m^3, and
- it has 60 cm of stemming over it.

In addition, this model requires that each charge be fired at a unique delay, and the propagation path be unimpeded by obstacles. The individual explosions in Blast 1 complied with these properties, and it can be seen that the results at the three ranges are close to the curve.

Also shown in Figure 5 are the peak SPLs of the SDDs, together with a curve obtained from Aron's (1954) formula for unconfined explosions, applied to a charge of 0.1 g TNT. It is presumed that the detonators being inside a plastic clip connector of high mechanical resistance (Maxam Australia 2008) caused the pulses to be 10 to 20 dB below the Arons curve.

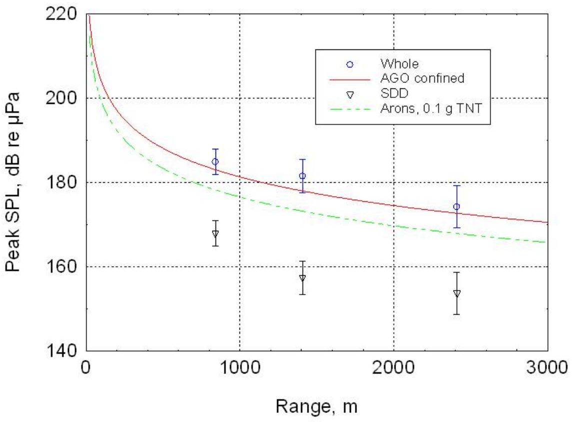

Figure 5. Peak Sound Pressure Levels of the Blast-1 main and detonator pulses from the three hydrophones. KEY to curves: red – author's synthesis of results from Arons, Gilmanov and Oriard ("AGO") for a confined explosion; green – result for unconfined 0.1-g TNT charge, from Arons (1954).

VARIATION OF SOUND EXPOSURE LEVEL WITH RANGE

For a given time interval, SEL is the energy per unit area of the waveform over that time interval, although in underwater acoustics it is the integral of pressure-squared (unit µPa^2.s) rather than the integral of intensity (Joule /m^2). For each main pulse, an integration interval was defined, and SEL was computed by summing the squares of the waveform over that interval (after allowing for the gains in the data acquisition system). The resulting data for SEL of the main pulse at each hydrophone are shown as a function of range in Figure 6 (the blue marks). The decrease in SEL from the closest to the furthest hydrophones is 9 dB. Functions of the form

$$SEL(r) = A - 20 \log r - B\, r /1000$$

have been fitted to the data, in which the second term corresponds to spherical spreading, and the coefficient B is equivalent to a damping rate (in dB /km). The function of best fit to the main pulse is

$$SEL(r) = 217 - 20 \log r - 0.01\, r /1000.$$

An aside on hydrophone sensitivity is pertinent here: if C's sensitivity were set to -193 dB re V/µPa (rather than -190), then the SEL at 2410 m would be 3 dB higher, and in the corresponding function of best fit the coefficient B would be negative (-1.8 dB /km).

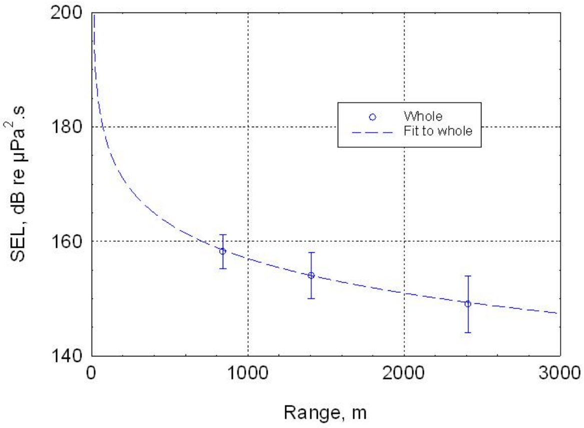

Figure 6. Sound Exposure Levels of the Blast-1 main pulses from the three hydrophones.

SPECTRAL ANALYSIS

Although the wide-band results are the parameters of practical interest, a physical explanation can be obtained only by examining effects at different frequencies. The spectrum of a pulse was computed by taking a Fast Fourier Transform (FFT) of a portion of the signal starting before the main pulse and ending when the signal had returned to the noise level (as seen by inspection of the raw wide-band signal). The mean square FFT was computed over each of the 31 third-octave bands from 31.5 Hz to 31.5 kHz. A segment of noise, selected so as to be free of noise spikes and pulses from the blast, was analysed in the same manner, and its mean square FFT was subtracted from the signal. The resulting spectra of the main pulses from the three hydrophones are shown in Figure 7.

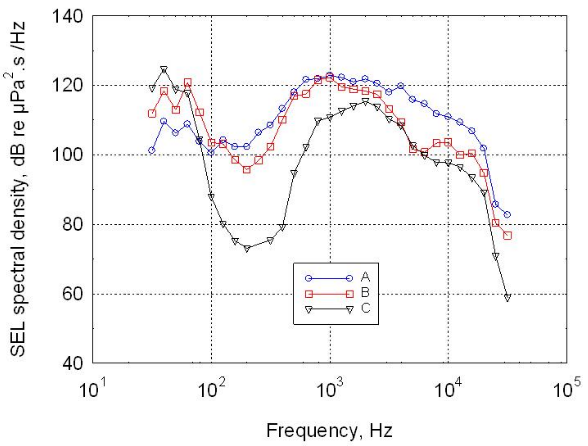

Figure 7. Spectra in third-octave bands of SEL of the Blast-1 main pulses from the three hydrophones. KEY: Blue – hydrophone A; red – hydrophone B; black – hydrophone C.

The 31.5 Hz band was selected as the lowest band since the preceding band (25 Hz) did not contain a FFT component in two of the noise segments, and the 31.5 kHz band was selected as the highest band since the Signal-to Noise ratio in the next band (40 kHz) was insufficient. The frequency axis in Figure 7 is a logarithmic scale. Frequencies in third-octave steps are equi-spaced along a logarithmic scale, and there are 10 steps in each frequency decade.

The result for the 250-Hz band from Hydrophone C is missing, due to the signal being less than the noise.

The FT-squared is equivalent to energy spectral density: the unit of the former is (μPa /Hz)^2, which is equivalent to μPa^2.s /Hz, the unit of the latter. The areas under the curves (when transformed to (μPa /Hz)^2 from the decibel representation) yield the wideband SELs shown in Figure 6, in accordance with Parseval's Theorem.

The spectra of the main pulses from hydrophones B and C each have minima at 200 Hz (hydrophone A's occurs at 100 Hz). This indicates that the propagating high-frequency signals are subject to a low-frequency cut-off in the region of several hundred Hertz. An explanation is that low frequency sound penetrates the seabed with little attenuation and interacts with the high-density stone, whereas high frequency sound suffers higher attenuation and the waterborne signals are due to reflection at the seafloor. High frequency sound will propagate strongly only if its frequency exceeds the cut-off frequency defined by the seafloor, which has an average depth of 11 m. If we assume a nominal value of 600 Hz for Fc, then the above expression for Fc yields Cb = 1522.5 m/s. This is only slightly higher than Cw, but such a small difference is required to yield the observed cut-off frequency. For the given geology of Tamala limestone (sand and stone), it is unlikely that the sound speed would have such a low value, but it is a possible value of the shear speed.

The sampling rate of 96000/s that was used will yield accurate results only at frequencies up to around 40 kHz, since the FT at frequencies higher than 48 kHz cannot be computed. The fall-off in the spectra above 10 kHz indicates that the effect of neglecting these high frequencies in computing SEL should be negligible. It also indicates that uncertainty in the hydrophone sensitivities above 30 kHz should have little effect on SEL.

The features of interest in Figure 7 are the peaks in the 40 and 63 Hz bands, the minima at 200 Hz, and the broad peaks at around 1 to 2 kHz. The peak at 63 Hz can be attributed to the delay of 16 ms between successive explosions. The broad peak at 1 to 2 kHz would be due to the signal comprising a large number of sharp pulses whose durations are in the vicinity of 0.5 to 1 ms.

CONCLUSIONS

The data for peak SPL from confined charges are in good agreement with a synthesis of empirical formulae due to Arons, Gilmanov and Oriard.

A high-density sub-bottom stone determined the characteristics of the low-frequency ground wave. This interface is around 10 m below the seafloor, and has a shear speed of 2620 m/s.

For a blast of six explosives, the Sound Exposure Level decreased monotonically from 158 to 149 dB re μPa^2.s as range increased from 840 to 2400 m.

The spectra of SEL have peaks in the 63 Hz band, which can be attributed to the delay of 16 ms between explosions. They have minima near 200 Hz and exhibit a low-frequency cut-off in the vicinity of 600 Hz. The latter indicates that an acoustic wave speed in the Tamala limestone should be only slightly higher than the sea water sound speed, and is thus presumed to be the shear speed. The spectra also have broad peaks at 1 to 2 kHz, which can be attributed to the signal consisting of spikes whose individual durations are around 0.5 to 1 ms.

ACKNOWLEDGMENT

Graeme Paine of Dempsey Australia Pty Ltd planned the blasts and co-ordinated their execution. He also arranged for the author to set up and participate in the measurements of the acoustic signals.

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