ACOUSTIC DAYLIGHT — USING AMBIENT NOISE TO SEE UNDERWATER

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ABSTRACT: Detection of targets in the ocean using sound is traditionally achieved with either passive or active sonar. Acoustic daylight is a new technique being developed, which relies on the ambient noise in the ocean to provide the acoustic illumination necessary to detect a target. The presence of a target scatters some of the incident sound which can be collected by a suitable acoustic lens to produce an image of the target. An acoustic daylight imaging system developed at Scripps Institution of Oceanography is described, and images obtained of planar, cylindrical and spherical targets are presented. It was able to image all targets, with varying resolution and contrast between the target and background. In some cases it was able to distinguish between different target compositions through the reflected spectral content. A more sophisticated imaging system being developed by the DSTO will also be described.

1. INTRODUCTION

Traditionally the search for underwater targets by sound has been performed with passive or active sonar. In active techniques sound is projected into the water by the listening platform, and a target in the vicinity scatters some of this sound energy back towards the listener. Passive sonar relies upon the emission of sound by the target, which can be picked up by the listener.

Passive sonar is inherently a covert method. The listener does not emit any sound and so does not provide any acoustic signal by which the target can detect its presence. Since it relies upon sound being emitted by the target, it cannot be used for targets which are inherently silent. Active sonar by its nature flags the position of the searching platform to the target.

In both active and passive sonar the presence of background noise degrades the performance of the detection equipment and so lowers detection ranges.

2. ACOUSTIC DAYLIGHT

In optics there are three ways by which one commonly observes an object. In the first instance, it might emit light. This is how we see the stars. If it isn't a light emitter, but the observer is in dark surroundings, he can shine a torch and thereby see the target from the light it reflects. However, most commonly there is already sunlight present and objects are perceived when they scatter this light. The observer can distinguish between different objects because of the frequencies of light they scatter and/or the intensity of the light scattered by each. We call the first property colour and the second contrast.

In underwater acoustics, passive sonar is analogous to the first optical case. In this instance the object emits sound rather than light. Active sonar is like the second technique in which a torch is replaced by a sound projector. In the mid-1980's Buckingham suggested using the acoustic equivalent of scattered light in which ambient noise provides the source of ensonification. By analogy with optics the proposed method was called "acoustic daylight".

Ambient noise is generated in the ocean by several mechanisms, including distant shipping, breaking waves, and biological sources. In warm shallow waters around Australia's coastline, snapping shrimp are the dominant source, make a snapping sound extending from 500 Hz to more than 200 kHz.

3. FIRST EXPERIMENT

The first acoustic daylight experiment was conducted off Scripps Pier in southern California in 1991 (Berkhout, 1992; Buckingham et al., 1992). In this experiment the noise was produced by snapping shrimp under the pier pilings and from the surf. Targets consisting of 25 mm-thick sheets of 0.9×0.77 m plywood board faced with neoprene rubber were placed on poles 6.1 and 12.2 m from a hydrophone at the focus of a parabolic reflecting dish. As the targets were swivelled on their poles they appeared broadside or end-on to the acoustic lens. Depending on the orientation of the acoustic lens and the targets, the latter reflected the ambient noise or blocked it. It was also noted that the targets reflected some intensities more than others, providing evidence for acoustic colour.

The overall result of this first acoustic daylight experiment was to show that a target can alter the noise field, but being a parabolic reflector with a single hydrophone at its focus, it formed a single beam and so corresponded to just one pixel of an image. To build up an image a multi-beam acoustic lens is necessary. If the system was broadband, it would be able to make use of the acoustic colour characteristic.

4. ADONIS

The first operational acoustic daylight system was designed and built at Scripps Institution of Oceanography, in a research group including Mike Buckingham, Chad Epifanio and John Potter. The acoustic camera was called 'ADONIS', which stands for Acoustic Daylight Ocean Noise Imaging System. It was designed to collect broadband data between 8 and 80 kHz in ambient noise of 20-70 dB re 1 $\mu Pa^2/Hz$. Figure 1 shows its assembly; a detailed description appears in Readhead (1998).

It consisted of an approximately planar array at the focal plane of a 3 m reflecting dish. The dish was comprised of neoprene foam on a fibreglass base and provided

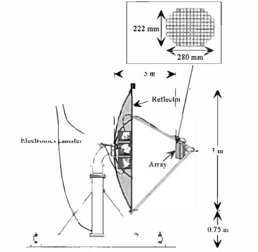

Figure 1. Side view of ADONIS. The array layout is shown in the inset.

approximately 18 dB gain. Beamwidths varied from 3.4° at the lowest frequencies, to 0.6° at the highest frequencies. The field of view was 10° in the horizontal and 8° in the vertical. The whole assembly could be rotated around a vertical mast, providing 360° coverage in the horizontal.

The array was made by EDO Corporation and consisted of 130 piezoelectric hydrophone elements arranged in an elliptical pattern as shown in the inset in Figure 1. Each element was 20 mm × 20 mm EC-76, a US Navy type-V lead zirconate titanate, with a sensitivity over most of its frequency range of -188.8 dB re 1 V/μPa.

Electronic gain of 100 dB was provided in multiple stages. Preamplifiers were incorporated into the array housing before transfer of the data to the underwater electronics canister. Here the signals were further amplified and pre-whitened. Rather than send the amplified sinusoidal data to the surface, 16 spectral estimates were sent instead. This cut down the data rate appreciably. Multiplexers were then used to serially transmit the data to an analogue to digital converter board in a computer on the surface where it was stored on hard disk. The computer also contained a digital signal processing board which processed the data for display on a video monitor. Moving images were displayed with an update rate of 25 Hz.

5. DEPLOYMENTS

ADONIS was deployed under a moored barge in 7 m of water in San Diego Bay in August 1994 and October-November 1995 as shown in Figure 2. Planar, cylindrical and spherical targets were imaged. The panels were fixed to a 3 m × 3 m frame and were mostly 1 m x 1 m sheets of 3.2 mm thick aluminium faced with 6.4 mm thick closed-cell neoprene foam, with the foam side facing the acoustic lens. The panels were also reversed and compared with 6.4 mm thick aluminium, 3.2 mm thick corrugated galvanised iron, and 6.4 and 12.7 mm thick plywood coated with a thin layer of resin or 5 mm of fibreglass.

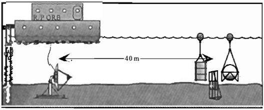

Figure 2. Deployment of ADONIS under R/P ORB.

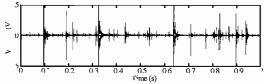

Figure 3. Time series of ambient noise collected by ITC6050C hydrophone.

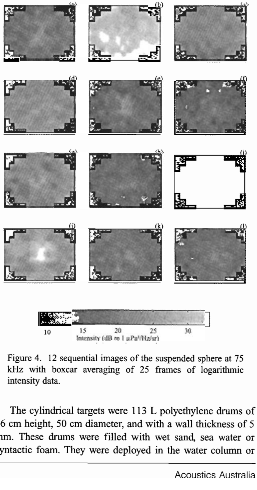

Figure 4. 12 sequential images of the suspended sphere at 75 kHz with boxcar averaging of 25 frames of logarithmic intensity data.

The cylindrical targets were 113 L polyethylene drums of 76 cm height, 50 cm diameter, and with a wall thickness of 5 mm. These drums were filled with wet sand, sea water or syntactic foam. They were deployed in the water column or dropped onto the sea floor. The spherical target was a hollow, air-filled titanium sphere of 70 cm diameter and a wall thickness of 15 mm. It was held in a metal cage in the water column and made negatively buoyant by the addition of lead weights.

Since San Diego Bay was shallow and calm, there were almost no breaking waves. The dominant sources of acoustic noise in the 8-80 kHz frequency range came from harbourside industrial activities, shipping traffic, sea mammals and snapping shrimp. The noise field was highly anisotropic, aiding in the illumination and detection process. It also had large temporal variations, as shown in Figure 3 by the 1 s time series of noise data collected by an ITC 6050C hydrophone. Figure 4 shows the effect of this non-stationarity in the noise field on 12 sequential images, representing 17 ms of data spread over 0.5 s, of the spherical target. Intensity variations of more than 20 dB are evident. By temporal averaging over 1 s and adjusting the colour axis for each image to account for the differing mean intensities, stable images were produced.

6. IMAGES

Figure 5 collects together a number of images formed during the deployments of ADONIS (Epifanio, 1997; Epifanio et al., 1999; Readhead, 1998). Most images consist of a boxcar average of a 10 s time series, corresponding to 250 frames. Often several frequencies have been averaged, and these are noted by specifying the range of frequencies. In most cases the resultant intensities are mapped into the jet colour map after bi-cubic spatial interpolation, in which the output pixel values are calculated from a weighted average of pixels in the nearest 4-by-4 neighbourhood.. This map grades from blue at low intensities to red at high intensities.

Bar target

Figure 5a shows the scene falling within the field of view of ADONIS, based on the known location, size and range of the target frame, and the field of view of ADONIS. The horizontal line in the background delineates the horizon, with the sea surface above and the sea bottom below. Three neoprene-coated aluminium panels form a bar on the target frame at a range of 38 m.

Figure 5b presents an image for the high frequencies of 57-75 kHz. The data corresponded in time to the use of an angle grinder for hull maintenance on a vessel moored along the pier. Acoustic noise was injected into the water for several seconds at a time, greatly increasing the ambient noise level, and raising the acoustic contrast from a more usual 3.5 dB to 9 dB at these higher frequencies.

Fenestrated cross

With the angle grinder still injecting noise into the water, the panels were rearranged to form a fenestrated cross (Figure 5c). Again all target panels are clearly defined and visible with an acoustic contrast of 9 dB for 57-75 kHz data (Figure 5d). Even the hole is visible in the image, with a contrast of 4 dB between it and the panels.

A different source of ensonification was provided by a boat passing behind the target. Figures 5e and 5f show two images formed from boxcar averaging 1 s (25 frames) of 57-

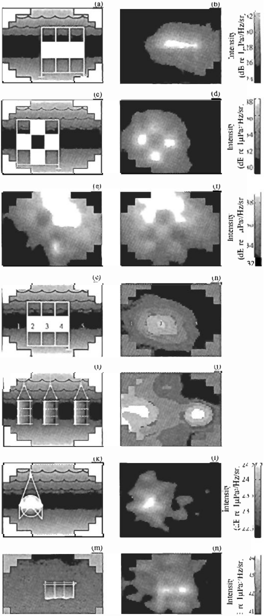

Figure 5. Sketch of field of view of ADONIS for a) bar target, c) fenestrated cross, g) multi-metal panels, i) suspended drums, k) suspended sphere and m) bottom drum. Acoustic daylight images for b) bar target, d) e) and f) fenestrated cross, h) multi-metal panels, j) suspended drums, l) suspended sphere and n) bottom drum.

75 kHz data. The two images are separated in time by 1.2 s. The boat is passing from right to left behind the cross, with Figure 5e showing the boat just to the right of the cross, and Figure 5f showing it almost directly behind the cross. The target panels block some of the boat noise, creating four holes in the noise field with an inverse contrast of more than 3 dB. Some of the boat noise passes through the hole in the cross. These images show that passing boats can be used as a source of opportunity to silhouette targets.

Multi-metal panels

To test the potential of acoustic daylight to discriminate between targets based on differences in both reflected intensities and frequencies, three metal targets were placed in the frame: 3.2 mm thick aluminium covered with 6.4 mm neoprene foam, with the metal side facing ADONIS, 6.4 mm thick aluminium, and 3.2 mm thick corrugated galvanised iron. Figure 5g shows the panels forming a bar in ADONIS' field of view, with the aluminium/neoprene panel labelled as 2, the thicker aluminium panel as 3, and the galvanised iron panel as 4.

In Figure 5h linear trapezoidal colour mapping has been employed in which red, green and blue correspond to low, medium and high frequencies, respectively. The aluminium/neoprene panel is seen with a reddish tint, indicating its propensity to reflect only lower frequencies well. The galvanised iron panel appears bluish, corresponding to its good reflectivity of only the higher frequencies. The thick aluminium panel reflects well at all frequencies and appears whitish. Note also that the luminosity of the three panels is well above the background.

Suspended drums

The panel targets presented a planar surface normal to the look direction of the acoustic lens. Cylindrical targets would only present a line normal to the look direction, and so would represent more of a challenge for imaging. Figure 5i shows the arrangement of the suspended drums as seen by the acoustic lens. The order of the drums from left to right was foam, water and sand-filled. Figure 5j shows the image with linear trapezoidal colour mapping depicting the different frequency components. The foam-filled drum reflected well at all frequencies as it had a much lower acoustic impedance than water. Thus it appears white. The sand-filled drum had a higher impedance than water, but allowed a greater penetration of low frequency sound as the sand was wet. Some of this energy could reflect off the rear wall of the drum back towards the acoustic lens. Absorption in the wet sand ruled out significant penetration to the rear wall and back by the high frequencies. As the sand-filled drum does not reflect high frequencies as well, it lacks a strong blue component and appears yellow. The water-filled drum has a slight blue tinge, indicating that it only reflects the higher frequencies to any significant degree. It was only weighed down by its 10 kg cage. When moving, the rusty metal parts of the drum cage and supporting shackle rubbed together, producing sound. This was most noticeable when large boat wakes passed over the targets. Hence the water-filled drum and shackle were probably not observed by scattered ambient noise, but by self-noise.

Suspended sphere

A sphere presented only a small patch normal to the look direction, and so was an even more difficult target to image. Figure 5k shows the field of view seen by ADONIS at the 20 range. The images formed from the upper three frequencies, 57-75 kHz are shown in Figure 5l. The acoustic contrast is more than 2 dB.

It is noticeable in Figure 5l that the equator and upper hemisphere of the sphere is visible, but that the lower hemisphere is not seen. The equator is illuminated by noise propagating in a horizontal direction from behind ADONIS, but the upper and lower hemispheres would not be visible by such noise, as it would be reflected up or down, away from ADONIS. The upper hemisphere may have instead been illuminated by noise scattering off the surface towards the sphere, and then back in the direction of ADONIS. There would be considerably less scattering of sound off the muddy bottom, and so the lower hemisphere would be much less illuminated. It is also notable that the image of the sphere is similar to the simulated image shown in Potter (1994).

Bottom drums

In all target deployments reported so far, the acoustic contrast has been between the noise scattered by the target and that scattered by or originating in the surrounding water. A more difficult test was to try and image the drums when on the sea floor. In this case the contrast would be between noise scattered by the drums and the mud.

ADONIS was tilted so as to point to the sea floor. Figure 5m shows the field of view of ADONIS with the foam-filled drum on the sea floor. The corresponding image is shown in Figure 5n for the upper frequencies (57-75 kHz). The drum is clearly visible, with an acoustic contrast of 4 dB. These values are comparable with or better than for the drum when in the water column, partly because there is less background noise around the drum. The possibility of the sea floor and drum forming a propitious corner reflector arrangement cannot be ruled out either.

Most of the images shown in Figure 5 were of stationary targets, for which 10 s boxcar averaging was used. For the moving vessel producing the silhouetting in Figure 5e and f, 1 s boxcar averaging was used. This averaging was also found to be suitable when imaging swimming divers, or when rotating ADONIS so that it panned past the stationary targets. An alternative averaging method which was also found to be suitable was exponential temporal averaging in which the most recent frames carried the most weight

7. BEYOND ADONIS

ADONIS' design bore some similarity to that of a modern conventional optical telescope. The reflector provided high gain, and by geometrically combining the incoming acoustic signals, data processing was simple. However, the apparatus suffered from several limitations common to geometrical systems. Because it used a spherical reflector it was afflicted with spherical and chromatic aberration. Like a telescope it had a restricted field of view, although at 10° it was fairly broad. The penalty for this broad field of view was low resolution. Since it was used in the near field, it could only resolve objects within its limited depth of field, rather like that of a camera. In addition to these geometrical limitations, the way in which the signal processing was implemented meant that most of the acoustic data was not used. This limited the testing of post-processing algorithms.

The next step is to build a phased array, which will remove some of the above problems. All the data can be used. and with dynamic focusing at different distances, the depth of field limitation is removed. Since summation of the signals reaching the various hydrophones is done mathematically to form the image, aberrations are not a problem. Increasing the resolution is obtained by sampling to higher frequencies or increasing the aperture of the array. To achieve a beamwidth of 1° requires a filled array of 10,000 elements, or a Mills Cross with 200 elements. The latter has large sidelobes in the orientation of the cross arms. A random sparse array of the same number of elements has the same total sidelobe energy, but it is more evenly spread in all directions (Steinberg, 1976). The computational load is high, since 64 Mbytes/s of data is acquired if 12-bit sampling is used for frequencies to 80 kHz. This can be compared to ADONIS' modest 3 kbytes/s.

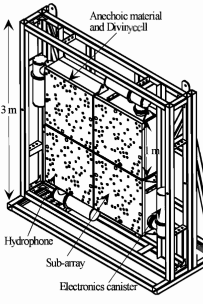

Figure 6. Design of DSTO's array.

8. DSTO'S ARRAY

The Defence Science and Technology Organisation (DSTO) is currently building a random sparse phased array of 2 m × 2 m aperture, which has 256 hydrophone elements. It is modular, comprising four identical sub-arrays, each 1 m × 1 m and with 64 elements. Figure 6 shows the design. The sub-arrays are held in a 3 m × 3 m galvanised iron frame, each being rotated by 90° with respect to each other to maintain the maximum randomness. The hydrophones are ITC 8257 units, which are sensitive between 10 and 150 kHz. They have preamplifiers of 60 dB fixed gain, leading to a sensitivity of -132 dB re 1 V/μPa over most of the frequency range. They are glued into stainless steel holders, which in turn are screwed into the face plate of a stainless steel box. To eliminate sound from penetrating from the rear of the array, the boxes are air-filled. Divinycell foam and an anechoic material reduce reflections of sound coming in from the front and reflecting from the box back towards the hydrophone elements. The hydrophone cables run through the box to an electronics canister.

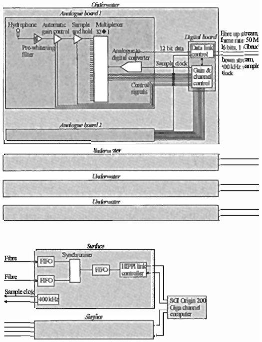

Figure 7. Block diagram of electronics for DSTO's array.

Figure 7 is a block diagram of the electronics processing. The signal from each hydrophone is amplified and pre-whitened. Based on experience with ADONIS where passing boats could swamp out the electronics, the next amplification stage incorporates automatic gain control. Each signal passes through a sample and hold stage and a group of 32 hydrophone signals are multiplexed before being 12-bit digitised at 400 kHz each. The digital stream from all 64 hydrophones is repackaged and sent to the surface via an optical fibre cable at a rate of 1 Gbaud. At the surface the data streams from two arrays pass through FIFOs, are synchronised, pass through another FIFO and are sent via a HIPPI link controller to an SGI Origin200 Gigachannel computer. Data from all four arrays is logged at a continuous rate of 154 Mbytes/s on a RAID array of 20 hard disks.

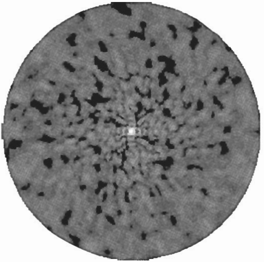

Figure 8. Point spread functions at 100-108 kHz.

Due to the very high data rate the data is post-processed. The first stage is beamforming. As the array is yet to be completed, in place of actual data the anticipated performance of the array is demonstrated by an example of a point spread function in Figure 8. This shows the image which would be formed at 100-108 kHz of a point target located at a range of 50 m, 0° longitude and 0° colatitude when ensonified by a point noise source, such as a snapping shrimp, located 40 m from the target at 0°. The beamwidth to the 3 dB points is 0.35°, and the highest sidelobes contained within ±10° are down by 15 dB. In reality the image would be degraded by other extraneous background noise. At 140 kHz the beamwidth has improved to 0.16°.

DSTO arrays will be deployed onto the floor of Sydney Harbour in the first instance, where depths are typically less than 20 m. The array has been designed to operate to water depths of 40 m, depths being constrained by the pressure on the oblong sub-array boxes. It is not intended that this array be hung from a vessel, but based on experience gained with this array a more mobile design will be built in the future. At water depths of less than 40 m around Australia's coastline the dominant source of ambient noise to 150 kHz is from snapping shrimp, although in Sydney Harbour additional contributions from industrial noise and boat traffic are expected.

9. CONCLUSIONS

Acoustic daylight potentially has a number of advantages over conventional active and passive sonar. Like a passive sonar, it can look for specific signals within one of its beams. It can also look for silent targets and does not have a degraded performance in regions of high ambient noise. In fact, since it uses the ambient noise, it should have an enhanced performance in such regions. Since it does not produce its own sound, it should have a lower power consumption than an active sonar, and so is suited to use on an underwater remotely operated vehicle. Its covert nature has important tactical advantages. Since it produces a pictorial image, with sufficient resolution it should be easier to interpret than current sonar system displays, which require trained operators. The introduction of false colour to the images should ease discrimination between different targets.

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