ACOUSTIC DAYLIGHT IMAGING: VISION IN THE OCEAN

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ABSTRACT

Sound provides a natural means for exploring the ocean but current sonar systems, as used for example in swath-mapping applications, do not provide directly pictorial images of the ocean depths. Such systems are more akin to radar, which relies on travel-time information to map the environment. A new acoustic technique for providing real-time visual images of the interior of the ocean is currently under development, and the results from initial experiments at sea provide evidence in support of the concept. The imaging process relies on ambient noise, or “acoustic daylight”, as the source of illumination, the underlying idea being analogous to photography in the atmosphere with daylight illuminating the subject. An object in the noise field scatters the incident sound, and the scattered field is focussed with an acoustic lens to form an image on an array of transducers. After signal processing, the acoustic image is displayed as a pictorial image on a television monitor. Acoustic “colour”, characterizing the spectral reflectivity of the object, could be represented as artificially generated optical colour in the display, and a rapid refresh rate should yield moving images much like those from a conventional video camera.

INTRODUCTION

Daylight is strongly absorbed by seawater: below a depth of a few tens of metres the ocean is enveloped in darkness. Lack of visibility seriously impedes exploration of the ocean depths and is one of the main reasons why activities such as seafloor mapping are so slow and costly. Artificial light sources can be used at depth but, like daylight, suffer heavy attenuation by the medium, which limits the effectiveness of all forms of optical illumination to very short ranges. Turbidity, which may be severe in shallow environments, exacerbates the problem, reducing the ranges achievable with optics still further.

Acoustic techniques for probing the ocean are more promising than light, since seawater is essentially transparent to sound. As demonstrated recently in the Heard Island experiment (Baggeroer and Munk, 1992), sound, under the right circumstances, can be transmitted and detected over oceanic path lengths of tens of thousands of kilometres. Traditionally, acoustics is used in two ways in the ocean: “passive” methods involve simply listening for the sound produced by an object, such as a submarine, whereas “active” systems transmit pulses of sound and listen for returning echoes. Swath-mapping sonar is an example of an active system that is used in an exploratory application, in this case leading to the production of contour or topographic maps of the bathymetry (Macdonald *et al.* 1993).

Most acoustic systems used for probing the ocean are based on some form of active technology. Put in familiar terms, this is equivalent to exploring the surface of the earth in pitch darkness using flashlights; or perhaps more accurately, using radar transmissions, which provide travel-time information but no direct visual image. In the circumstances, it is not surprising that ocean exploration is such an arduous activity. Since sonar systems do not yield pictorial images directly, considerable computational effort or a high level of skill and experience is required to interpret their output. Such systems are far from being the underwater equivalent of a conventional photographic or video camera in the atmosphere.

In fact optical imaging, which is so familiar in the atmosphere, has at present no acoustic analogue in the ocean. Conventional images, as formed by the human eye or a photographic camera, are possible because the presence of an object modifies the ambient illumination by scattering the incident radiation. When the scattered light is focussed by an optical lens onto a focal surface (retina or film), an image is created. An essential ingredient in this process is the illuminating field which, under natural conditions in the atmosphere, is daylight. Although it embodies elements and advantages of both, photographic imaging with daylight is neither an active nor a passive technique: the objects being imaged are not inherent radiators, nor is the object space illuminated by an artificial light source.

Photography, both still and video, is an extremely effective method of communicating information, as exemplified in the news media, advertising and television. An analogous acoustic system for the underwater environment could show similar potential but, for reasons which are not entirely clear, has never been developed. This raises the question:

is it feasible to develop an acoustic imaging technique, analogous to daylight photography in the atmosphere, capable of creating pictorial images of objects in the ocean?

ACOUSTIC DAYLIGHT

Ambient noise in the ocean is the analogue of daylight in the atmosphere. Both are incoherent, random fields of radiation propagating in all directions, although the source mechanisms in the two cases are obviously different. The oceanic noise field is produced by numerous natural sources, including breaking waves, bubbles, spray and precipitation (Kerman 1987, 1993), in addition to shipping, offshore engineering activities and marine mammals (Urick 1983). An object in the noise field scatters some of the incident radiation, suggesting, by analogy with photography, that the ambient noise field could be the basis of an “acoustic daylight” imaging system.

To produce an acoustic daylight image, an acoustic lens is required to focus the scattered sound onto a focal surface. The lens could be a reflector, refractor or phased array. Differences in acoustic *intensity* across the focal surface constitute the image, making acoustic daylight imaging an incoherent technique which, unlike holography for example, does not rely on phase information to produce the image. (With a phased array, the phasing is important only for producing beams). Once the acoustic image has been formed, the intensity distribution across the focal surface could be displayed as a familiar pictorial image on a television monitor.

The ambient noise frequencies useful for imaging lie below about 100 kHz, an upper limit dictated by the onset of thermal noise arising from thermal agitation of the water molecules (Mellen, 1952). Thermal noise, a localized, microscopic phenomenon, is not a radiating acoustic field and hence cannot be used for imaging. At a frequency of 50 kHz, near the centre of the usable band, the acoustic wavelength is 3 cm, which is approximately five orders of magnitude greater than the wavelength of visible light. Inevitably, this means that the resolution of acoustic daylight images will be inferior to that of their optical counterparts.

The (dilated) pupil of the human eye is about 10,000 optical wavelengths in diameter, which accounts for the remarkable acuity of human vision. To achieve similar angular resolution with an acoustic daylight system would require an acoustic aperture of the order of 300 m, which is not practical for a variety of reasons. An aperture of 10 metres, that is approximately 300 acoustic wavelengths, is about the largest that could be achieved in the immediate future. An image from such a system, although not of optical quality, would be by no means unacceptable. Moreover, image enhancement techniques offer the prospect of improving the perceived sharpness of the final image.

INCOHERENT IMAGING

The first *in situ* acoustic daylight experiments (Phase I) were conducted in the Pacific Ocean off Scripps pier in southern California (Buckingham *et al.* 1992). The acoustic lens used in the experiments was a parabolic reflector of diameter of 1.22 metres with a single, low-noise hydrophone at the focus. Thus, the system formed a single beam or "look" direction (Figure 1a), corresponding to just one pixel of an image. The surface of the parabolic dish was faced with neoprene rubber, which is nominally a perfect (pressure-release) reflector at the frequencies of interest. Rectangular targets, also faced with neoprene, were placed in the beam at ranges of approximately 10 metres; and noise spectra were recorded with the targets "on" (broadside-on) and "off" (edge-on) to the lens, as well as entirely absent.

Figure 2 is a time/frequency plot showing noise spectra, between 5 and 50 kHz, obtained with the targets in the three possible configurations. It is clear that in the "on" position the targets increased the noise level across the band of interest: the targets were visible in the illumination provided by the naturally occurring ambient noise in the ocean. Even in the "off" configuration, the targets could be "seen", in that they produced higher-energy noise spectra than were obtained with the targets absent. Although this single-beam experiment is a far cry from acoustic daylight image formation, the fact that the intensity in a single pixel responded to the presence of a target in the beam provides the first direct evidence that imaging with ambient noise in the ocean is a physically reasonable possibility. Since the technique works with one pixel, it should only be a matter of technology to extend it to many pixels, and many pixels constitute a genuine pictorial image.

Nominally, the difference between the spectral levels observed with the targets "on" and "off" is 3 dB. However, the "on" spectra show some interesting structure, as illustrated in Figure 2, where regions of relatively high intensity or "hot spots" can be seen centred around 10, 22, 33 and 47 kHz. Apparently, the targets exhibited a frequency-dependent acoustic albedo, with some frequencies being reflected more strongly than others. This effect can be interpreted as "acoustic colour", by direct analogy with optical colour. It is not difficult to imagine that acoustic colour could be displayed as "false" optical colour in an acoustic daylight image (just as infra-red and ultra-violet satellite images are displayed in computer-generated colour), thereby providing visually recognisable information about the acoustic properties of the object being imaged.

In a second experiment with the Phase I acoustic lens, the neoprene-faced targets were replaced with a vertical screen of bubbles, all of nominally the same size (radius of 0.3 mm). Bubbles are well known to be resonant systems, with a resonance frequency that varies inversely with the bubble radius (Minnaert 1933). For the bubbles forming the screen, the resonance frequency was about 11 kHz. The bubbles were produced by attaching an air compressor to a hose pipe along which small holes had been pierced with a fine needle. The hose pipe was laid on the seafloor, well below the beam of the acoustic reflector to ensure that the bubbles were acoustically quiescent as their buoyancy carried them upward through the beam. [On closure, a bubble undergoes radial oscillations for several milliseconds, during which time it acts as a brief but effective, narrow-band source of sound (Longuet-Higgins 1993). After the oscillations have decayed, the bubble is in equilibrium with its surroundings and remains mute for the remainder of its existence].

Figure 3 shows two ambient noise spectra, as observed with the bubble screen present and absent. It can be seen that with bubbles present the spectrum exhibits a pronounced peak centred close to 11 kHz. Since they are quiescent within the beam, this peak cannot be attributed to the initial pulses of sound made by the bubbles at closure, although it is consistent with the resonant nature of the bubbles: each bubble is excited by the incident (broadband) ambient noise and is driven into radial oscillation around the resonance frequency. The bubble then reradiates sound uniformly in all directions (Devin, 1959), the pressure showing a spectral peak centred on the resonance frequency ($Q \approx 20$ for a bubble of radius 0.3 mm). This scattered field is responsible for the observed peak in the spectrum. Since the bubbles in the screen were almost certainly distributed about the nominal diameter, the observed noise peak is considerably broader than the resonance peak of a single bubble. On the basis of these observations, it appears that the spectra shown in Figure 3 constitute further evidence in support of the concept of acoustic daylight imaging.

The Phase I experiments, with the single beam lens, are now complete and construction of a multi-element acoustic lens (Phase II) is currently in progress (Figure 1b). Again, the lens is a reflector but with the single sensor replaced by an array of 128 hydrophones in the focal surface. The geometry of this arrangement is such that each sensor element corresponds to a single beam, thus providing 128 pixels in the final image. In passing, it is interesting to note that this Phase II lens, which forms multiple beams through the geometrical disposition of the dish and transducer array, is a very unusual example of sonar system design, although it has an analogue in the long focal length mirror lens that is popular for conventional photography. Looking further into the future, the reflector will be replaced with a phased array of about 1000 elements (Phase III), perhaps mounted on the hull of a remotely operated vehicle (Figure 1c). Such a design would provide relatively high resolution images of 1000 pixels and a mechanical “zoom” capability achieved through the mobility of the platform.

THEORETICAL MODELLING

Although the idea of incoherent imaging with ambient noise is appealing and the analogy with optical imaging provides an intuitive basis for understanding the physical processes involved, it is difficult to quantify the imaging process. A number of questions are of interest, including the effect that the anisotropy of the noise has on the image. This issue was not addressed in the Phase I experiments because of difficulties in measuring the directionality of the noise field, although circumstantial evidence suggests that Scripps pier itself acted as a significant noise generator.

A full wave-theoretic analysis (Buckingham 1993) of acoustic daylight imaging has been developed in which the target is assumed to be a spherical object with pressure-release surface. Concentric with the target sphere is a noise sphere of infinite radius on which the acoustic sources are distributed. The directionality of the noise field is controlled by selecting the area of the noise sphere covered by the sources. The acoustic lens is modelled as a line array of hydrophones at half-wavelength spacing, arranged endfire-on to the target. A central feature of the analysis is the derivation of a new, closed-form approximation for the Green’s function of the field scattered from the pressure-release sphere. This approximation makes the statistical analysis of the field tractable, allowing a solution to be developed in a form that is easy to evaluate on a desktop computer.

The response of the line array to the scattered field is expressed in terms of a “visibility” function, V, defined as the ratio in dB of the total field (incident plus scattered) to the incident field alone. This is essentially the quantity that was measured in the original Phase I experiments. Provided the contrast is sufficient - say, with positive value (front lighting) greater than 3 dB or negative value (backlighting) less than -3 dB - the object should be visible against the background.

Theoretically, the visibility is found to be fairly insensitive to the anisotropy of the noise under front lighting conditions, showing values of several dB, which is consistent with the observations in the Phase I experiments. This is encouraging, since it implies that the acoustic daylight imaging technique is robust in that it does not depend critically on the detailed structure of the noise field. Under strong back lighting conditions, the visibility function goes strongly negative (in dB), indicating a high acoustic contrast with the background, in which case the object is in silhouette. The onset of shadowing, as predicted by the wave-theoretic theory, is consistent with arguments based on simple geometrical (ray) acoustics.

NUMERICAL SIMULATION

Whereas the analytical theory provides a quantitative estimate of acoustic daylight imaging, it does not yield visual simulated images. To remedy this situation a numerical model has been developed (Potter 1993), based on Kirchoff-Helmholtz scattering and a far-field assumption, that simulates the process of acoustic daylight imaging. Objects of various shapes, illuminated by realistic noise fields, can be handled by the numerical code to provide images that should be representative of a working acoustic daylight system.

An example of a simulated acoustic daylight image is shown in Figure 4a. The object in the foreground is a 1 metre diameter steel sphere located in a shallow ocean channel. The perspective is that of an observer located at the same depth as the target sphere, looking straight down the channel. Overhead is the sea surface and below is the sea floor. A great deal of visual information about the acoustic properties and geometrical form of the target, as well as the geo-acoustic character of the environment, is contained in this picture. To interpret the information requires some thought, since such images are currently so unfamiliar. However, of all the human senses, vision is the most highly developed, providing more information about the external world than the other senses combined; and the human brain has evolved to become remarkably efficient at recognising visual cues. As our experience with acoustic daylight images grows, the acoustic messages contained therein, as exemplified by Figure 4a, should become relatively easy to read, as is the optical information in a conventional photograph.

In Figure 4a breaking waves, acting as natural sources of sound on the sea surface, are represented as overhead (bright yellow) parallel dashed lines, which can be seen below (dull red) reflected in the bottom. The source lines are mapped as arcs onto the surface of the sphere, thereby giving a visual indication of the shape of the target. If the sphere were pitted, then the imperfection would show up as a deformity in the mapped curve; or if the object were, say, ellipsoidal the mapped lines would be correspondingly elongated. These mappings, of course, are specular reflections of the sources in the surface of the target. In the ocean, the actual surface sources would be more randomly distributed than those shown in Figure 4a, but this would not affect the overall illumination significantly, although it would change the detailed structure of the reflections from the target. Nevertheless, shape information could be gleaned visually from these more random mapped reflections in much the same way as in the present example.

Apart from the specular reflections, the shape of the object in Figure 4a is also apparent from subtleties in shading. On first viewing the image, the shading is perhaps the main factor that identifies the object as a sphere, which serves to illustrate how well the eye-brain combination has adapted to interpreting two-dimensional images of three-dimensional objects. Shape inferred from shading is, of course, commonplace when viewing a photograph, but is only just being exploited in the latest computer-generated swath mapping sonar displays (Nishimura and de Moustier, 1993). Acoustic daylight imaging offers shading as a natural, intrinsic feature of the new technique.

The sea floor in Figure 4a has been modelled as a fast fluid sediment with a critical grazing angle of 28˚ (for sound incident from above). Thus, noise rays with grazing angles less than 28˚ are totally reflected from the bottom, whilst rays with higher grazing angles penetrate the interface and are lost to the water column. With such a bottom relatively little acoustic energy travels upwards at grazing angles steeper than 28˚. This is indeed evident in Figure 4a from the dark shadow on the lower half of the sphere. The edge of this shadow, which is very sharply delineated, corresponds precisely to the critical grazing angle of the bottom.

Looking straight down the channel, on either side of the equator of the sphere, the image is almost black, indicating that very little noise travels horizontally. This is consistent with the fact that most of the energy propagating in the horizontal originates in far distant surface sources and thus is subject to severe attenuation by the medium. On looking slightly above the horizon the surface becomes brighter, an effect which continues with increasing elevation, until the nearby, overhead sources appear brightest of all.

From the interpretation of the image in Figure 4a it is apparent that the colour, although artificial, is indicative not only of the reflectivity of the target but also characterizes the spectral content of the incident noise field. Two factors influence the “colour” of the noise, the spectral content of the sources and attenuation in the channel. Obviously, narrow band sources are analogous to monochromatic light, the effect on the image being much the same as that achieved by placing a coloured filter on a photographic lens. The second factor, attenuation, is more interesting because it does not have an analogue in the atmosphere, since light does not suffer significant absorption over typical visual ranges. An ocean channel, on the other hand, acts as a low pass (acoustic) filter, the effect being to bias the illumination towards low frequencies. The farther the noise travels in the channel the more pronounced the effect becomes. Even the lowest frequencies will be removed over sufficiently long ranges and the corresponding portion of the image will appear dark, as illustrated on the horizon in Figure 4a. It may well be possible to turn absorption to advantage, since it yields considerable visual information about the acoustic properties of the channel.

In addition to the pronounced shadowing and reflection effects, the image in Figure 4a shows a number of subtle features that relate to the acoustic properties of the sphere itself. Thus, even this simple example of acoustic daylight imaging contains an abundance of information, making interpretation of the image an interesting and challenging task. At this point, to avoid misrepresentation, it should be said that the resolution of the image in Figure 4a is artificially high, at 90,000 pixels, a number which could probably not be achieved in practice.

Figure 4b shows the same image but degraded to 100 pixels, which is close to the quality expected of the Phase II system currently under construction. No image enhancement has been applied in this case, except for a simple interpolation between pixels, which introduces some smoothing. Obviously, the sharpness of the high-resolution image has been lost and the dynamic range has been reduced but the most prominent features of Figure 4a have been retained. For instance, the dark shadow on the lower half of the sphere can still be seen, the bright waistline is apparent, and the shading on the upper half of the sphere is also evident. Nevertheless, it would be desirable to see some improvement in image quality, at least to the level where the shape of the target could be recognized unequivocally.

When the number of pixels is increased by an order of magnitude, to 900, corresponding to the Phase III system, the acuity of the image is improved significantly and the dynamic range is retained (Figure 4c). The target is easily recognisable as a sphere and all the important details in the high resolution image of Figure 4a are visible, only slightly degraded, in the 900 pixel version of Figure 4c. This degree of quality is believed to be achievable with a practical acoustic daylight imaging system.

With as many as 900 channels, it should still be possible to achieve a rapid refresh rate in real time, allowing moving images to be created. Acoustic daylight imaging would then be the direct analogue of video photography, giving rise to moving, colour pictures originating in ambient sound rather than ambient light. This would provide the facility of vision wherever required in the ocean.

CONCLUDING REMARKS

Simple experiments in the ocean support the concept of imaging with naturally generated ambient noise, a conclusion that is consistent with theoretical and numerical models of the new imaging technique. Potential applications of acoustic daylight imaging include surveying the ocean bottom, monitoring entrances to harbours and fjords, and surveillance of offshore structures and pipelines, to say nothing of many naval concerns. Indeed, the technique is useful whenever vision in the ocean is required. For two reasons - attenuation in the ocean and lack of angular resolution - the system is effective over short ranges of up to about 0.5 km. Within its operating envelope, the acoustic daylight technique should produce images that show (visual) colour, related to the spectral content of the noise and the acoustic reflectivity of the objects being imaged. Since these images can be refreshed rapidly, the final effect should be much like a conventional, moving video image on a television monitor, but with somewhat poorer resolution.

Improvements in resolution could be achieved by increasing the aperture of the acoustic lens, a solution which is likely to be prohibitively costly and anyway would make the underwater "camera" unduly cumbersome. An alternative approach is to consider image enhancement algorithms, which, to be useful, would have to run in real time, and would produce images with the appearance of improved resolution. (Strictly, the resolution of such images is not actually improved, they are just perceived as sharper by a human observer, which is all that is required). Automated image recognition is a related problem, which for certain applications is particularly important. Neural networks, operating on the raw data or extracted feature vectors rather than the acoustic daylight images themselves, may satisfy this requirement. Algorithms dedicated to the recognition of acoustic daylight images are currently being considered.

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