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The Effect of Monomolecular Films on Low Sea State Ambient Noise

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ABSTRACT. A series of experiments conducted during low sea state conditions show that surface-related ambient noise is significantly reduced beneath monomolecular films. Although the amount of noise reduction varies between experiments, the highest attenuations reach 8 dB for frequencies of 1 kHz and higher. The ambient noise spectra beneath these films generally resemble those of non-filmed lower sea states. Preliminary low sea state experiments, providing simultaneous aural and visual monitoring of the sea surface from a depth of one meter, suggest that, in the absence of whitecapping, films attenuate surface noise by dramatically reducing the number of microbreaks which are associated with bubble entraining noise.

1. Introduction

"I want to know what it says... the sea... what it is that it keeps saying" - Charles Dickens

It has been recently reported [1] that ambient noise generated at the sea surface is dramatically reduced beneath monomolecular films (surfactants) spread on the surface. Figure 1, which contains unpublished data representative of the measurements reported in reference 1, shows the spectral ratios of two omni-directional hydrophones, one of which served as a reference while a monomolecular film (MSF) was deployed over the other. The hydrophones were deployed several kilometers apart during sea state 6 conditions (wind speed > 20 m/s) at a depth of 122 meters. The extent of the film, dispersed from an outwardly spiraling helicopter, was estimated to be about 300 meters in radius. Although experimental limitations reduced the effective frequency range to between 4 and 16 kHz, the spectral ratio of the slicked to reference hydrophone data within this range clearly drops after the film is deployed. Eventually the spectral ratio returns to its original state which corresponds to the observed break up of the film and its drift past the slicked sensor. Where the slick remained coherent there appeared to be less whitecapping, although visibility at the time was generally poor.

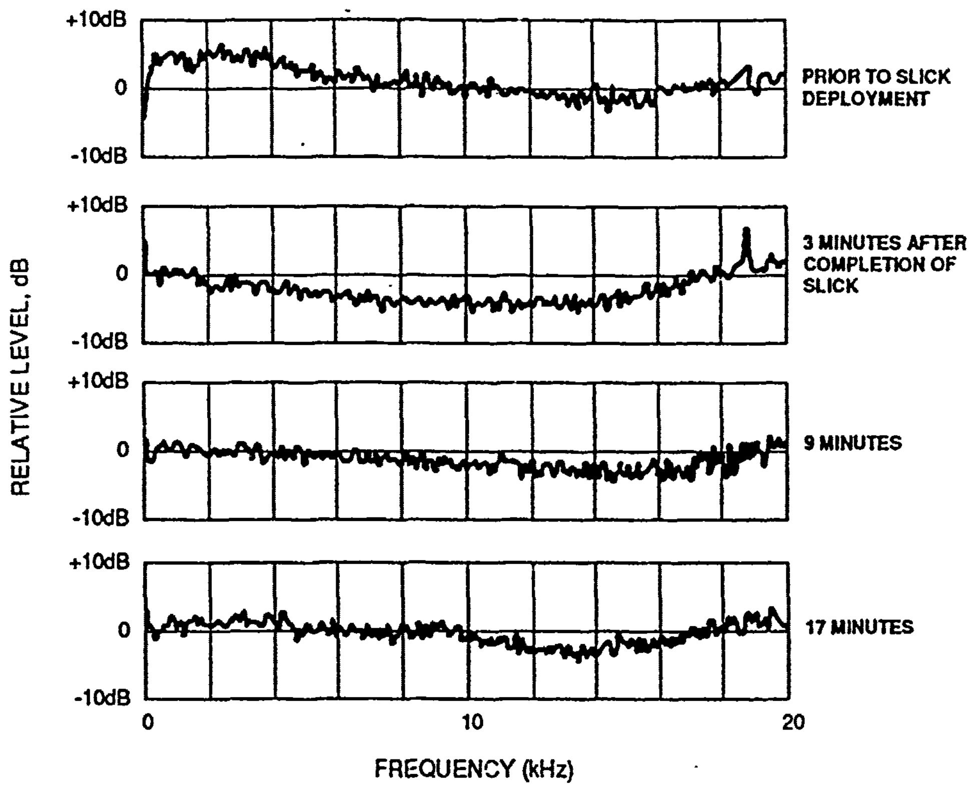

Figure 1. Spectral ratios of test to reference hydrophone data before and after a slick (15 gallons of MSF) was created over the test hydrophone. Both sensors were at a depth of 122 meters in a sea state 6.

The calming effect of olive oil on the sea surface is cuneiform old. Alth[illegible]ce-active materials have little influence on large waves and swell, small gravity and capillary waves are quickly attenuated [2,3]. It has been hypothesized [4] that as the sea surface becomes smoother the aerodynamic drag exerted by the wind decreases, thereby reducing the occurrence of whitecaps. A reduction in whitecapping is at least one mechanism by which films could reduce underwater ambient noise. There is evidence [1], however, that the films continue to reduce ambient noise even at low sea states where whitecapping is absent. This is of particular interest since the primary source of ocean ambient noise remains undetermined under these conditions [5,6]. To quote Urick [6]:

> Although it is clear that the sea surface must generate the major portion of the [ocean] ambient noise in this frequency range [.5 - 25 kHz], the process by which it does so is still uncertain. Several processes come to mind, and a number of others have been advanced in the literature. Perhaps the most obvious of these are breaking whitecaps, which must produce crash noise when breaking occurs. Yet whitecaps cannot be the sole source of noise, since measured noise levels increase with sea state or wind speed well below the sea state in which whitecaps begin to appear.

It is the goal of this paper to better document the noise-reducing effect of monomolecular films at low sea states, and to begin to identify the process by which the films cause this reduction. Hopefully this will lead to a better understanding of the sources of underwater ocean noise in general. In section 2 we present experimental data recorded at sea, and in section 3 we discuss this data in the context of identifying the source of low sea state ambient noise.

2. At-Sea Tests

2.1. PRELIMINARY SONOBUOY EXPERIMENTS WITHOUT FILMS

The experiments discussed in Sections 1, 2.1 and 2.2 used U.S. Navy Sonobuoys (AN/SSQ-57A) to monitor underwater noise. These sonobuoys are essentially composed of a battery-powered hydrophone hanging from a balloon-encased transmitting antenna. Their advantage is that they provide a readily available source of expendable, omni-directional hydrophones which are fairly sensitive (approximately -100 dB re 1 volt per μPa) over the frequencies of interest (0.5 to 20 kHz) and can be set to record at a variety of depths. Moreover, since the sonobuoy's radio-transmitter can broadcast the hydrophone's response for up to 8 hours, the acoustic contamination of a large recording platform or ship is avoided.

Figure 2 contains spectral responses (composed of one-minute averages) recorded by two pair of sonobuoys which are typical of most of our data. The sensors were deployed at a depth of 9 meters and transmitted data during sea states ranging from $^1/_2$ (or less) to $2^1/_2$ (wind speed 1 to 6 m/s). Conspicuously present throughout the time series data that corresponds to sea state 1 (curve 2) are brief, highly tonal events. As the wind speed and sea state increase to the point of whitecap generation (wind speed > 5 m/s), the number of these acoustic events can be heard to increase: first merging into an almost continuous babble and finally evolving into a constant

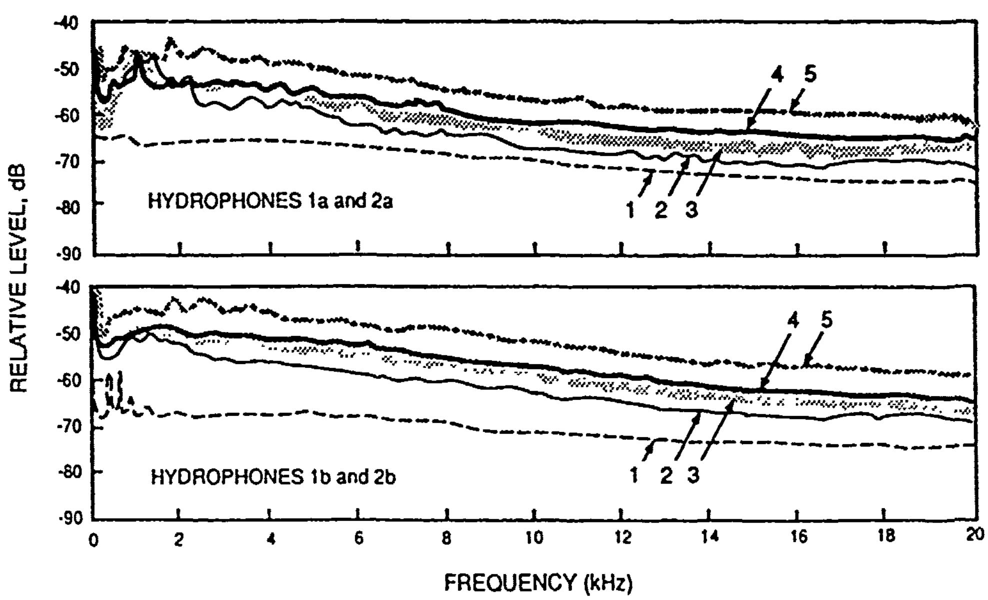

Figure 2. Simultaneous comparisons of spectral data from pairs of hydrophones, all at depths of 9 m, throughout the low sea states of interest (no film present). Lowest levels (dashed lines) are obtained in a sea state between 0 and 1. Remaining measurements were obtained while the sea state was changing from 1 to $2^1/_2$.

hiss. The anomalous spectral shape at the lowest measured wind speeds (curve 1) reflects, in the absence of the intermittent events common to the slightly higher sea states, the electronic noise floor of the sensor.

Momentary variations in the noise level of sensors near the surface have been noted since the earliest underwater noise measurements [7] and have been attributed to individual breaking waves. What is particularly noteworthy about our observations is that these variations occur in the absence of whitecapping and, moreover, their acoustic signature consists of clearly recognizable, individual tonal components, unlike the cacophony of sound from a crashing wave. Using a large underwater array 50 meters beneath the ocean surface, Shang & Anderson [8] also reported evidence of discrete surface noise sources during sea states too low to generate whitecapping. Unfortunately, they were unable to determine the nature of the mechanism generating these sounds.

Ocean ambient noise measurements [7,9] generally agree that the slope of the audible spectrum, beginning around 500 Hz in the absence of shipping noise, exhibits a common -5 dB (to -6 dB in reference [9]) per octave drop throughout most sea states. Presumably this common spectral shape reflects some self-similar process [9]. The sonobuoy used to collect the data in Figure 2b was calibrated from 0.5 to 7 kHz. The corresponding sound pressure levels show good agreement with the traditional Knudsen curves [7]. Sporadic whitecaps appeared as expected between sea states 2 and 3 (curve 5). Sound pressure levels for the lowest sea state (curve 1 in Figure 2b) are below the sonobuoys minimum rated sensitivity.

2.2 LOW SEA-STATE SONOBUOY EXPERIMENTS WITH FILMS

The basic format for the sonobuoy experiments was to deploy them in pairs at identical depths about a kilometer apart. One sensor (referred to as the reference hydrophone) would monitor the true ambient noise throughout the experiment, while the second sensor (referred to as the test hydrophone) would monitor the effect of a monomolecular film spread above it. The goal was to characterize and compare, by simultaneously recording the sonobuoys, the ambient noise produced by otherwise identical environments. Measurements were collected in deep water far from shipping and shore noise.

The chemicals tested were oleic acid, oleyl alcohol (trade name ADOL-85), and a double ethoxylated isosteryl alcohol (trade name AROSURF-MSF). These chemicals are nontoxic, essentially insoluble, biodegradable surfactants. Oleic acid is the surfactant constituent of olive oil, a material whose capillary wave-damping virtues have been extolled at least since the ninth century B.C. [10]. Oleyl alcohol resembles natural ocean slicks in its physicochemical behavior and has been used to simulate them [3]. AROSURF-MSF is used on drinking reservoirs for mosquito control [11]; by decreasing surface tension, the film prevents insects from molting on the water surface. It should be noted (in light of recent world events) that these materials bear little resemblance to crude oil, which is much less effective in damping capillary waves [12].

Throughout our experiments the ocean surface was always sufficiently rippled with capillary waves making it possible to distinguish the boundaries of a deployed film. Since the films were dispensed from a small boat, only a limited area could be covered in each experiment. Therefore, an attempt was made to center the films over the test hydrophone and cover an area with a radius of twice the sensor depth. Previous modeling [1] has shown that extending a film beyond this ratio provides little additional acoustic benefit. It was found that slicks having radii of a least 18 meters could be routinely created, allowing a corresponding sensor depth of 9 meters.

Each experiment used between 5 and 10 gallons of chemical. This quantity is several orders of magnitude greater than the minimum required to form a molecule-thick layer over a circle with a radius of eighteen meters. Since the films are autophobic (they do not spread readily upon themselves), they tend to form when applied in excess tiny reservoirs (micelles) which replenish tears in the films as a result of wind and wave action. After creating a slick, the dispensing dinghy either returned to the launching vessel or proceeded to a location just beyond the slick, where it secured its engine and monitored the position of the sonobuoy's antenna relative to the slick. Hydrophone data was transmitted continuously to the support vessel, which was stationed over a kilometer away with engines secured.

Figures 3 through 7 contain one-minute averages of the simultaneous spectral data recorded before and after slick deployment for the reference (unslicked) and test (slicked) sensors, both of which were deployed at a depth of 9 meters. The data in Figures 3 through 5 were collected about 150 kilometers west of San Diego (latitude 32°29', longitude 118°29') from June 30 through July 4, 1988. The water was 1500 meters deep. The remaining measurements comprising Figures 6 and 7 were obtained in the Sea of Cortez (latitude 27°38', longitude 111°38') on February 20, 1989, where the water depth was over 1000 meters. These data plots are representative of the larger noise reductions achieved with the films. It should be noted that there are an equal number of data sets, for the same films and approximate sea states, which resulted in noise reductions of generally similar shape but of considerably less magnitude (only 3-4 dB noise reduction). Another interesting anomaly is that deploying twice the volume of film over an area did not result in greater ambient noise reduction. It is possible that the additional time required to dispense the larger volume of chemical allowed the sensor to drift further from the center of the slick. Considering the lack of control over a film's shape, size, and position relative to the underlying sensor, as well as the difficulty of duplicating sea conditions, additional data will be necessary before such conflicting results can be resolved.

2.2.1. *Sonobuoy/Film Measurement - June 30, 1988.* Figures 3a and b show simultaneous measurements for the reference and test hydrophones, both before and after 10 gallons of oleic

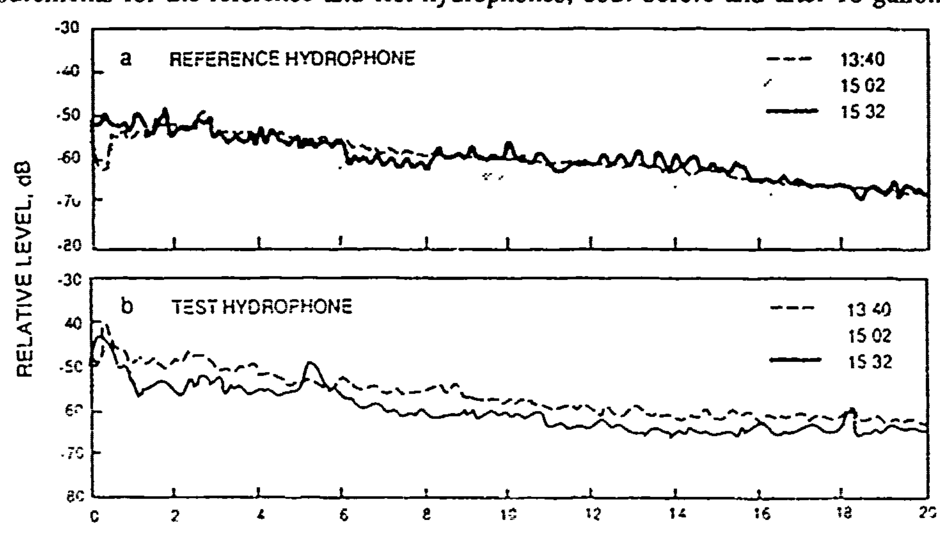

Figure 3. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of oleic acid) was created over the test hydrophone. The film was dispensed at 14 30 on 6/30/88, wind speed was about 3 m/s and both sensors were 9 m beneath the sea surface

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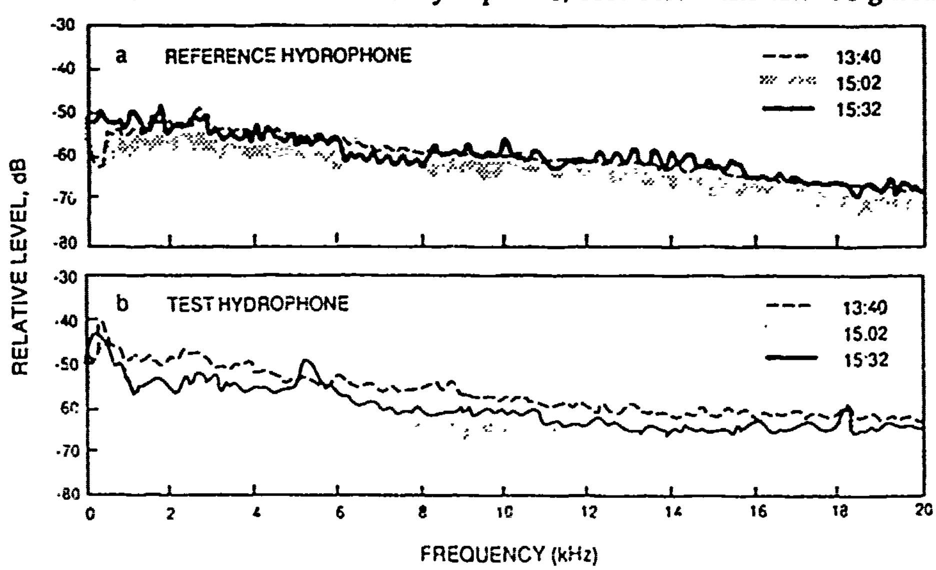

Figure 3. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of oleic acid) was created over the test hydrophone. The film was dispensed at 14.30 on 6/30/88, wind speed was about 3 m/s and both sensors were 9 m beneath the sea surface.

2.2.3. *Sonobuoy/Film Measurement - July 4, 1988.* Ambient noise comparisons at the same location for a film composed of 5 gallons of oleyl alcohol are shown in Figure 5a and b. Engine problems delayed the slick deployment. During this delay the sea state increased significantly (with wind speed changing from 4 to 6 m/s) before post-slick data could be recorded. This is reflected in Figure 5a, where the reference sensor's spectrum increased about 6 dB between 18:52 and 19:41. At the same time, the output of the test hydrophone (Figure 5b) remained approximately constant below 12 kHz and decreased about 2 dB at higher frequencies. Subsequent measurements taken at 20:10 show that, while the reference hydrophone continued to record the same high noise levels, the test hydrophone's output increased by nearly 6 dB from 1 to 20 kHz. By 20:22, neither sensor's spectral output had changed (the rising noise floor in Figure 5b was due to a gradual weakening of the transmission signal). Consequently, we presume that by 20:10 the slick had either broken up or drifted past the test sensor. The spike in the post-slick spectra around 11.5 kHz was due to an echo sounder from an unrelated experiment. As expected (since the film can only affect noise sources on the ocean surface), the magnitude of the 11.5 kHz spike does not vary between pre- and post-slick measurements, even as the plots show a decrease in the background noise.

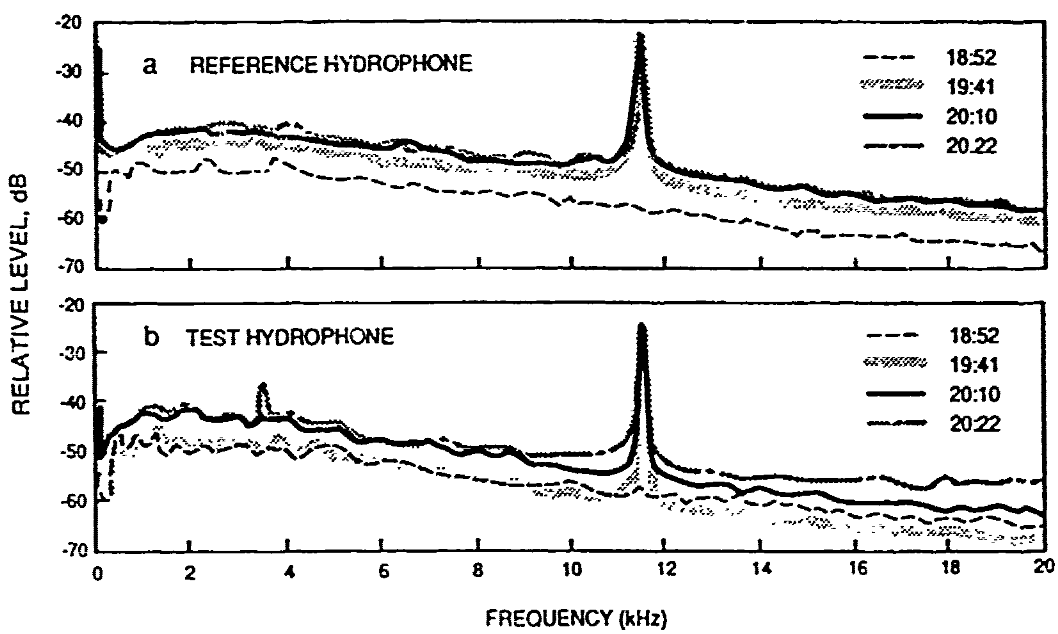

Figure 5. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 5 gallons of oleyl alcohol) was created over the test hydrophone. The film was dispensed at 19:00 on 7/4/88, wind speed was increasing from about 4 to 6 m/s during the experiment and both sensors were 9 m beneath the sea surface.

2.2.4. *Sonobuoy/Film Measurement - February 20, 1989 (mid-morning).* This was the first of two experiments conducted in the Sea of Cortez, each using the same original slick (composed of 10 gallons of MSF), but under different sea states. This experiment (Figures 6a and b) took place between 9:40 and 10:02 when wind speeds (measured 10 meters above the ocean's surface) averaged 3 meters/sec. Immediately after deploying the film (9.50), a nearly constant 5 to 6 dB reduction in ambient noise was observed for frequencies beginning at about 1 kHz. However.

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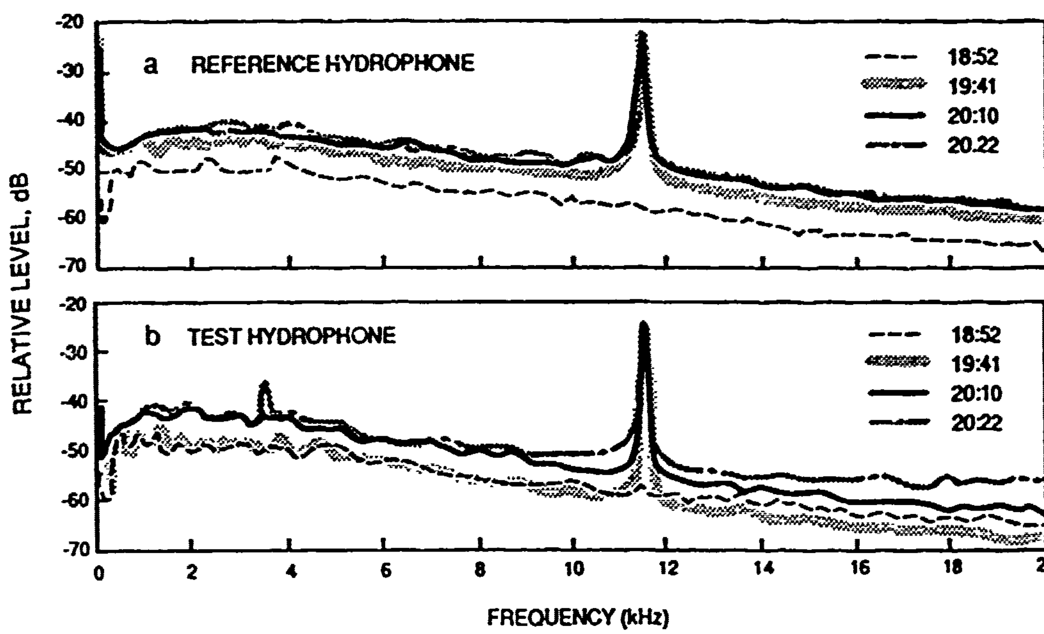

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2.3 LOW SEA-STATE SSNI EXPERIMENTS WITH AND WITHOUT FILMS

The Synoptic Surface Noise Instrument [13,14] (SSNI), built by Garr Updegraff and Victor Anderson and pictured in Figure 8, was designed to provide simultaneous in situ acoustic and video monitoring of the ocean surface from a depth of one meter. The instrument is tethered one kilometer from a support vessel to provide acoustic isolation. The housing contains a surface-pointing video camera, along with sensors to measure the instrument's depth, tilt, roll, and compass orientation. The depth of the SSNI is remotely controlled by extruding a piston to change its buoyancy. Four Clevite hydrophones, each sampled at 20 kHz, are mounted on the instrument's three arms so that the position of individual noise sources can be triangulated relative to the camera's view of the surface, which roughly covers a square meter. A surface buoy, tethered 30 meters from the SSNI, provides a continuous record of wind speed and direction at 1.5 meters above the ocean's surface.

Simultaneous acoustic and video recordings collected from the SSNI show unequivocally that, during low sea states when whitecaps are absent, surface noise is generated by small wavelet spills which entrain air bubbles. Such spills, which produce sound for about a second, may leave no foam at the surface to record their passage. The time series recorded by the instrument's hydrophones show that a spill's sound is actually composed of distinct sinusoids which start abruptly and then decay within milliseconds – the unmistakable signature of freely resonating air bubbles. Unfortunately, these bubbles measure a few millimeters or less and are too small to be resolved by the instrument's camera. Medwin & Beaky [15] have reported similar resonating bubble oscillation sounds in the laboratory by creating windless artificial wave breaks.

Figure 8. Synoptic Surface Noise Instrument (SSNI).

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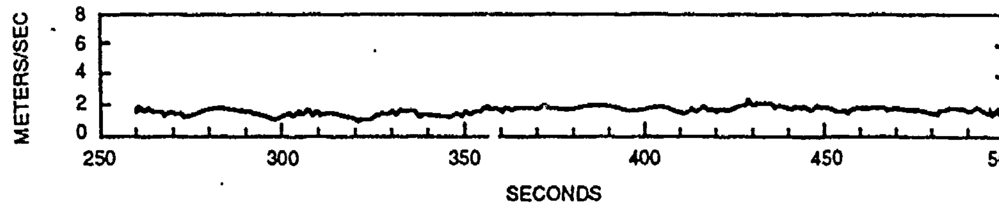

Figure 9a. Sample of a four-minute time series of wind speed (one-second averages, obtained 1.5 m above the ocean surface) during an SSNI deployment on the morning of 2/20/89.

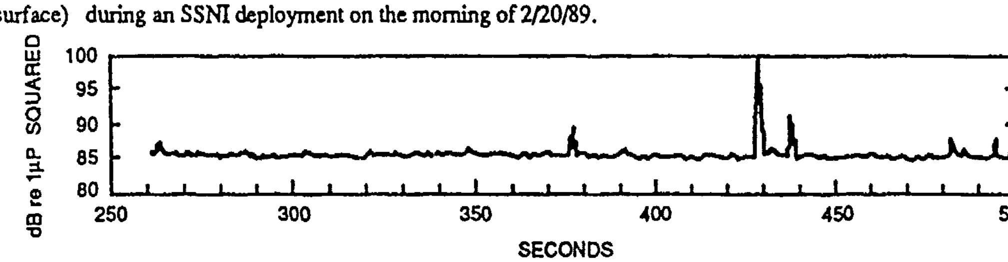

Figure 9b. Sample of a four-minute time series of mean square acoustic pressure (one-second averages, obtained about 2 m below the ocean surface) during an SSNI deployment on the morning of 2/20/89.

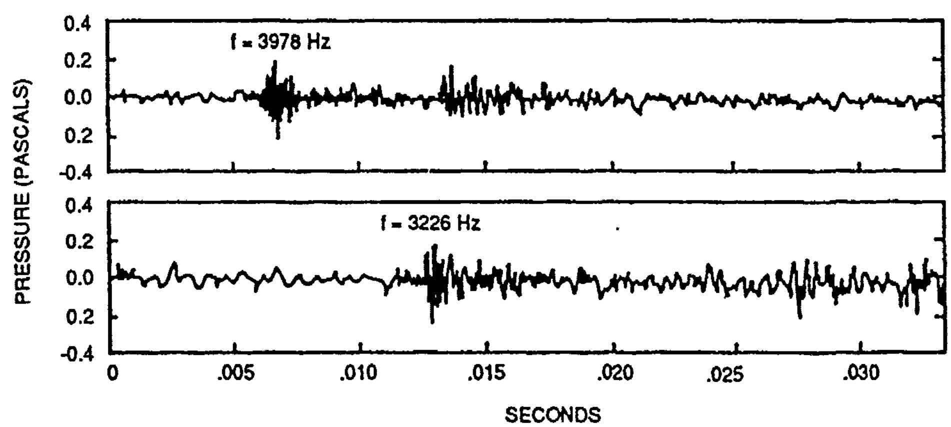

Figure 9c. Two consequtive 1/30-second sections of the acoustic time series occurring about 378 seconds into the previous (Fig.9a,b) recording. Where possible the frequency of the larger oscillations have been marked.

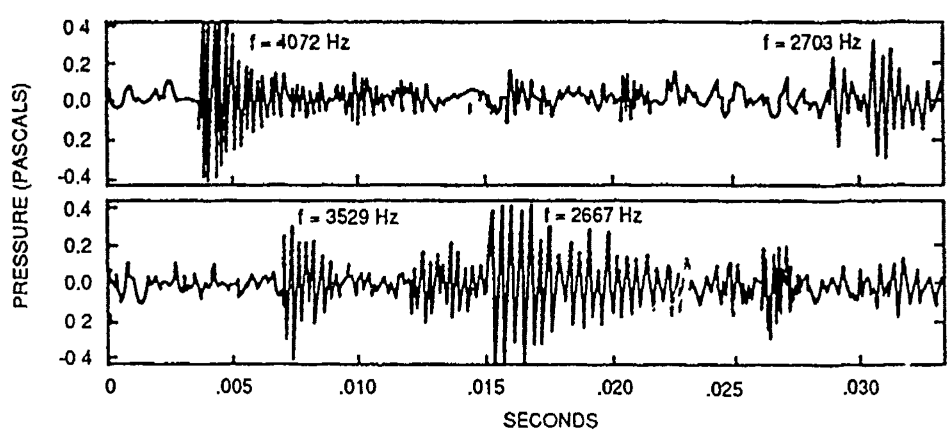

Figure 9d. Two consecutive 1/30-second sections of the acoustic time series occurring about 438 seconds into the previous (Fig.9a,b) recording. Where possible the frequency of the larger oscillations have been marked.

A sonobuoy/film experiment was conducted earlier, between 9:40 and 10:02, when the sea state was about 1. The reference hydrophone snowed a 2 dB decrease in ambient noise as the sea state slowly decreased. The test hydrophone, after a film composed of 10 gallons of MSF was deployed overhead, simultaneously recorded a 6 dB reduction in ambient noise for frequencies above 1 kHz (see Figures 6a and b).

2.3.5. *SSNI Measurement - February 20, 1989 (early afternoon).* The SSNI data was recorded between 11:59 and 12:29 during a sea state estimated to be 1/2. The wind was blowing from 90 degrees at around 1.3 meters per second, as measured by the wind buoy. Long period swell height was negligible. Only one wavelet break, which took place at 12:02, was noted during the entire recording. This dramatic change in surface activity, from just one hour earlier (described in the previous paragraph), for such a small change in wind speed is consistent with numerous references [15] to ocean noise being instantly sensitive to the onset of winds. A sonobuoy/film experiment was performed from 13:29 to 14:05 in a sea state of 1/2 or less, and showed no film effect on the ambient noise field (see Figure 7). In light of the SSNI's recording, we believe this lack of noise reduction beneath the slick is due to the absence of microbreaks for the film to suppress.

2.3.6. *SSNI Measurements - with Films.* On one occasion a test was conducted during sea state 2, in which the SSNI recorded data both before and after a 2 gallon oleyl alcohol slick was applied above it. Unfortunately, it hasn't been possible to compare average acoustic power before and after the slick application because of propeller cavitation noise from nearby ship traffic. However, following the slick's application there was a conspicuous reduction observed in the intermittant sound associated with microbreaking. In an effort to objectively quantify the film's effect on the naturally occurring intermittent surface noise (which comprised only a small percentage of the total data recorded), the following procedure was adopted. First, rms values from 1 to 2 minutes of videotape audio were averaged in order to estimate the steady shipping background noise. Then a threshold was set at twice this rms value. In order to discriminate against short-duration sounds of unknown origin (presumably biologics) in favor of the generally one-second microbreak sounds, a 6-millisecond hold time was employed. By using this approach, it was found that after the slick was applied the number of intermittent noise events was reduced by nearly 80%. Regrettably, neither a reference sonobuoy nor a calibrated wind anemometer were available during this test.

3. Discussion

Figures 3 through 7 indicate that the low sea state ambient noise spectra from 1 to 20 kHz, generally associated with a slope of -5 (to -6) dB per octave, can be significantly reduced beneath monomolecular films. Although the amount of noise reduction varied between experiments, the reduction is generally independent of frequency and surfactant. Consequently, the noise level beneath a film resembles natural ambient noise, but at a considerably lower sea state than that existing outside the slick's influence.

Measurements in concert with Updegraff & Anderson's Synoptic Surface Noise Instrument [13,14] suggest that the noise reduction provided by the films result from a decrease in the number of small scale breakings within the slick. Phillips [16] had previously proposed that "micro-scale breaking", which he recognized as being more common than whitecapping, would be significantly reduced where a film was present. However, it had been generally assumed that the microbreaking process did not entrain air [17,18]. The recent measurements of Updegraff & Anderson have shown this perception to be patently false. In fact, by analyzing a single energetic microbreak, they have reported [14] a spectrum with a near -5 dB slope over the frequency range of their instrument (0.5 to 8 kHz).

Our data establishes that monomolecular films significantly reduce ambient noise in sea states 1/2 through 6. It is tempting to speculate that the films undermine some noise source that is common over this range of conditions. Updegraff and Anderson have analyzed [14] the acoustic energy, as a function of frequency, from 81 individual bubble oscillations which were recorded during low sea states. They have found evidence that the -5 dB per octave, wind-dependent, ambient spectral noise slopes of the Knudsen curves [7] are caused by the shorter lifetimes of high frequency bubbles, rather than significantly lower peak pressures. Independently, Medwin & Beaky [15] recorded the average of some 100 individual bubble events in a laboratory, where spilling breakers were generated by a plunger. They also found a spectrum that slopes downward at about 5 dB per octave from 1 to 20 kHz.

In light of the common -5 dB per octave noise slopes at both high and low sea states, and because ambient noise levels in these cases are reduced by similar degrees under surface films, it seems plausible that they share a common noise source: the creation of bubbles by breaking waves. Only at the very lowest sea states (< $^1/_2$), when no micro-breaking is evident, do the films have no effect measurable by our sensors. We believe that the films reduce ambient noise at all other sea states by decreasing the number of breaking waves. At high sea states (>2) the films may also inhibit possible bubble entrainment by spray and breaking capillary waves [19].

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