Acoustic effects of the ATOC signal (75 Hz, 195 dB) on dolphins and whales

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The Acoustic Thermometry of Ocean Climate (ATOC) program of Scripps Institution of Oceanography and the Applied Physics Laboratory, University of Washington, will broadcast a low-frequency 75-Hz phase modulated acoustic signal over ocean basins in order to study ocean temperatures on a global scale and examine the effects of global warming. One of the major concerns is the possible effect of the ATOC signal on marine life, especially on dolphins and whales. In order to address this issue, the hearing sensitivity of a false killer whale (Pseudorca crassidens) and a Risso’s dolphin (Grampus griseus) to the ATOC sound was measured behaviorally. A staircase procedure with the signal levels being changed in 1-dB steps was used to measure the animals’ threshold to the actual ATOC coded signal. The results indicate that small odontocetes such as the Pseudorca and Grampus swimming directly above the ATOC source will not hear the signal unless they dive to a depth of approximately 400 m. A sound propagation analysis suggests that the sound-pressure level at ranges greater than 0.5 km will be less than 130 dB for depths down to about 500 m. Several species of baleen whales produce sounds much greater than 170–180 dB. With the ATOC source on the axis of the deep sound channel (greater than 800 m), the ATOC signal will probably have minimal physical and physiological effects on cetaceans.

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INTRODUCTION

The Heard Island Feasibility Test (Munk et al., 1994) of Scripps Institution of Oceanography and the Applied Physics Laboratory, University of Washington, in January, 1991 has generated considerable controversy. The intensity of ensuing negative publicity and public outcry over the possibility of harming marine mammals and other marine animals (Cohen, 1991) has surprised many underwater acousticians. The follow on Acoustic Thermometry of Ocean Climate (ATOC) program, which will broadcast a low-frequency 75-Hz phase modulated, 195 dB re: 1 μPa source level acoustic signal over ocean basins to study ocean temperatures on a global scale, has also drawn considerable criticism from concerned individuals. Aside from the intense emotions engendered against ATOC, one of the difficulties surrounding the controversy is the lack of data on the low-frequency hearing sensitivity of whales, making it difficult to rationally address the appropriate issues.

The initial feasibility stage of the ATOC program calls for installing a source at a depth of approximately 900 m on the Pioneer Seamount off Point Sur in California. This source was installed in December 1995 (Mercer et al., 1996) and a study on its effect on marine mammals is underway (Costa et al., 1996). Another source is to be installed in waters north of the Island of Kauai in the Hawaiian Archipelago, approximately 7 nautical miles from shore at a depth of approximately 850 m. The California source is located close to the routes of gray and humpback whales. Humpback whales migrate from the waters off Alaska to winter in the waters of the Hawaiian Islands, including the island of Kauai.

In order to obtain some data on the potential effects off the ATOC signal on hearing, communications, and the well being of dolphins and whales, the hearing sensitivity of two pelagic cetaceans was measured using the ATOC signal. The subjects were a false killer whale (Pseudorca crassidens) and a Risso’s dolphin (Grampus griseus). The animals were housed, trained, and tested at the Hawaii Institute of Biology Marine Mammal Research facility in Kaneohe Bay, Oahu, Hawaii.

The ATOC signal is a phase modulated carrier that can be described by the equation

\[ s(t) = A \cos(2 \pi ft + \phi [2m_i - 1]), \]

where \( f \) is equal to 75 Hz, \( \phi \) is equal to 88.2092°, and \( m_i \) is a specific sequence of 1’s and 0’s used to create a phase shift of \( \phi \) when \( m_i \) equals 1 and \( -\phi \) when \( m_i \) equals 0. Two cycles of the 75-Hz carrier correspond to a digit and each bit in the \( m \)-sequence determines the phase of a digit. The three signals in Fig. 1 consisting of four two-cycle digits having a duration of 107.7 ms can be used to illustrate how the \( m \)-sequence affects the waveform and power spectrum of the signal. A duration of 107.7 ms corresponds closely to the integration time constant of a dolphin’s auditory system at 100 Hz (Johnson, 1968). In the top signal of Fig. 1, \( m = 1 \) for each digit so that there is no phase shift and the signal is a 75-Hz pure tone. In the middle signal, \( m = 1 \) for the first digit and \( m = 0 \) for the next three digits so that there is one phase shift of 176.4184°. This single phase shift causes the bandwidth of the signal to increase, as can be seen by its power
spectrum. In the bottom signal, \( m = 1 \) for the first digit, \( m = 0 \) for the second and third digit, and then \( m = 1 \) for the fourth digit. Therefore, there are two 176.4184° phase shifts in the bottom signal that cause the spectrum to broaden.

The \( m \)-sequence is used in conjunction with cross correlation processing to precisely determine the time of arrival of the signal after it has traveled several thousand miles across the ocean. Changes in the integrated ocean temperature can be determined by examining changes in the arrival time. A correlation type received will also be helpful in extracting the signal out of noise. However, using such a scheme for the signal affects the bandwidth of the signal. Therefore, the hearing threshold of a marine mammal will probably be lower with the ATOC sound than with a 75-Hz pure tone since the broadening of the spectrum may cause energy to spill into critical bands that are adjacent to the one at 75 Hz.

I. METHODS

A go/no-go experimental procedure was used in measuring the animals’ sensitivity to the ATOC signal and to other pure-tone signals. A trial began with the subjects swimming into a stationing hoop facing a J-13 transducer two meters from the hoop, as depicted in Fig. 2. When the subject stationed properly, the experimenter activated an underwater light alerting the animal to expect an acoustic signal. The underwater light remained on until the cessation of a trial. For a signal present trial, a signal was projected 1 s after the activation of the light. If the signal was audible to the subject it would back out of the hoop and touch a response paddle (go response). For a signal absent trial, the animal was required to remain in the hoop until the experimenter presented an audible 12-kHz bridge tone to release the animal from station (no-go response). The subject received a food reward for correct responses and did not receive reinforcement for wrong responses. A modified Gellerman series (Gellerman, 1933) was used for the signal presentation schedule in which an equal number of signal present and signal absent trials were conducted per ten trial block with the stipulation that the signal condition not be the same for more than three consecutive trials.

An up–down staircase procedure was used to determine the subject’s threshold of hearing. After a ten-trial warm-up period in which a constant supra-threshold level signal was used, the signal level was reduced by 2 dB for every correct signal present response until the animal made its first miss, which constituted a reversal. The signal level was then progressively increased in 1-dB steps until the next correct signal present response was made. Thereafter, the signal level was changed in 1-dB steps depending on the animal’s response during signal present trials. A session continued until ten reversals occurred. A threshold was defined when the average signal level per session at the reversal points for two consecutive sessions was within 3 dB.

The simulated ATOC signal was generated using a DATEL PC-420 12-bit arbitrary waveform generator board with the 32 736 points of an \( m \)-sequence signal stored in on-board memory and clocked out continuously at a rate of 1200 Hz. When the experimenter activated the signal-present switch of a signal shaping circuit, the DATEL PC-420 output was amplitude modulated with a 3-s trapezoidal pulse having a 0.3-s rise and fall time to produce the stimulus signal. The signal level was controlled by a rotary attenuator. Pure-tone signals were produced in a similar fashion with the signal gated on and turned off by modulating a continuous signal with the trapezoidal pulse. The signal level at the hoop station was calibrated with an International Transducer Inc. ITC-1032 spherical hydrophone connected in a differential mode to a Princeton Applied Research PAR-113 low-noise amplifier and an oscilloscope.

II. RESULTS AND DISCUSSION

The mean and standard deviation of the Grampus’ thresholds were 142.2 \( \pm 1.7 \) dB for the 75-Hz pure-tone signal and 140.8 \( \pm 1.1 \) dB for the ATOC signal. The Pseudorca’s thresholds were 140.7 \( \pm 1.2 \) dB for the 75-Hz pure-tone signal and 139.0 \( \pm 1.1 \) dB for the ATOC signal. The difference between the threshold for the 75-Hz and ATOC signals for both animals was significant to the 0.01 level (paired \( t \)-test). These thresholds are plotted in Fig. 3 along with other low-frequency pure-tone thresholds for the same two animals obtained by Nachtigall et al. (1995) and for another Pseudorca measured by Thomas et al. (1988). The data of Nachtigall et al. (1995) are included here to compare the
75-Hz threshold with other low-frequency thresholds and to illustrate the fact that the auditory system of these odontocetes is adapted for high ultrasonic frequencies. The pure-tone thresholds are similar to those obtained by Johnson (~1967) for *Tursiops truncatus* and for Johnson *et al.* (~1989) for *Delphinapterus leucas* at frequencies close to 75 Hz. These odontocetes are relatively insensitive to low-frequency sounds; *Pseudorca* has a maximum sensitivity of approximately 39 dB re: 1 μPa at 65 kHz (Thomas *et al.*, 1988), which is 100 dB better than at 75 Hz.

The effects of the ATOC signal on these animals can be considered by examining the propagation loss profile of the ATOC source. The transmission loss profile for the proposed Kauai location was obtained with a computer program that used a finite element parabolic equation (FEPE) solution (Collins and Westwood, 1991) to the two-dimensional wave equation and a vertical sound velocity and a bottom depth profile appropriate to Kauai. The transmission loss profile for the case in which the signal is traveling directly toward shore is shown in Fig. 4, where the black line denotes the bottom contour. This figure illustrates the complexity of the propagation conditions caused by the signal reflectioning off the surface and bottom. The propagation condition reflected in Fig. 4 is probably the most severe in terms of affecting marine mammals since the signal is propagating toward an up-
ward sloping bottom which can reflect the signal back into the water column.

In order to obtain a more detailed understanding of the sound field close to the location of the source, some of the values used to generate the transmission loss profile were used to calculate the sound-pressure levels as a function of depth and range. The results are shown in Fig. 5, with sound-pressure level depicted as a function of depth at different horizontal ranges from the source. The curve at \( R = 0 \) was obtained by summing the upward moving direct signal with a 180° phase shifted downward moving surface reflected signal, with both components undergoing spherical spreading losses. The \( R = 0 \) curve suggests that small cetaceans such as Grampus and Pseudorca swimming directly over the ATOC source will not hear the transmitted sound unless the animals dove to a depth of approximately 400 m. If these animals were at a horizontal range greater than 0.5 km, the level of the ATOC signal will be below their hearing threshold at any depth.

The curves of Fig. 5 also indicate that for ranges greater than 0.5 km, the maximum sound-pressure level above a depth of 560 m is approximately 130 dB. As the range increases beyond 2 km, the sound-pressure level will become progressively lower. The in-air equivalence of an underwater sound-pressure level of 130 dB can be determined by equating the intensity (power/area) of an acoustic signal in both media. It would not be meaningful to directly compare the acoustic pressure in both media because the large difference in the density causes the acoustic power or intensity to be very different. Acoustic intensity is defined as

\[
I = \frac{p^2}{\rho c},
\]

where \( \rho \) is the density and \( c \) is the sound velocity of the medium. The product \( \rho c \) is known as the specific acoustic impedance and is approximately equal to \( 1.5 \times 10^6 \) Pa s/m in water and 416 Pa s/m in air. Therefore, an underwater acoustic signal of 130 dB is equivalent to 3.16 Pa with an intensity of \( 6.7 \times 10^{-6} \) W/m². Letting the intensity of the underwater acoustic signal be equal to the intensity of an airborne acoustic signal, the resulting airborne acoustic pressure will be 0.053 Pa or 94.4 dB re: 1 \( \mu \)Pa. Airborne sounds are typically expressed in dB re: 20 \( \mu \)Pa and the acoustic pressure using this reference has the notation SPL following the dB value.

Therefore, 94.4 dB re: 1 \( \mu \)Pa in air is equal to 68.4 dB SPL and is equivalent to a 130 dB re: 1 \( \mu \)Pa underwater acoustic signal. An automobile traveling at 35 mph produces a sound of approximately 72 dB SPL 50 ft from it (Kryter, 1985).

An obvious question at this point is the possible effects of the ATOC sound on large baleen whales. One way of addressing this question is to consider sounds that whales themselves make near their conspecifics and to compare these sounds with the ATOC sound field shown in Figs. 4 and 5. It is unfortunate that there are almost no data available on the hearing sensitivity and frequency range of hearing for baleen whales. The frequencies and sound-pressure levels of low-frequency sounds produced by some baleen whales are shown in Table I, with the data extracted from a table in Richardson et al. (1995). From Table I it is clear that some whales produce low-frequency sounds that have levels at 50 m that are greater than 130 dB, and levels on the order of 150 dB are not uncommon. If these whales are not physically harmed by conspecifics producing levels of sounds on the order of 150 dB at 50 m, then the ATOC sound at a sound-pressure level of 130 dB or less will probably be relatively harmless to them physically. Furthermore, the bandwidth of the ATOC sound is relatively narrow and would not be as effective in masking as would the broader bandwidth sounds normally produced by some whales themselves.

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