EFFECTIVENESS OF ACOUSTIC SIGNALS IN ATTRACTING EPIPELAGIC SHARKS TO AN UNDERWATER SOUND SOURCE[1]

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Abstract

Three experimental studies were carried out in the field to determine the effectiveness of various acoustic signals in attracting free-ranging silky sharks, *Carcharhinus falciformis*, into the immediate vicinity of an underwater sound source. These studies were carried out over deep water in the Straits of Florida, miles from the mainland, as well as at a moored buoy in the Tongue of the Ocean, Bahamas.

All of the octave bands of noise used in the tests resulted in attraction, with the level of attraction increasing as the frequency spectrum decreased, respectively, from 500-1000 Hz, to 250-500 Hz, to 75-150 Hz, and finally, to 25-50 Hz. Irregularly pulsed signals were also more attractive than regularly pulsed signals, with the latter increasing in attractiveness as the pulse rate increased from 1, to 5, to 10, and finally to 20 pulses/sec. Additionally, it was established that, at least under certain conditions, sharks can be drawn away from one vessel by transmitting irregularly pulsed, low-frequency signals from another vessel, stationed a few hundred meters distant.

Various behavioral actions of individual sharks, after approaching a sound source, are described. Also various practical considerations, arising from the findings, are discussed.

Introduction

The studies reported here are part of a continuing investigation on the acoustic biology of sharks found in the waters of Florida and the Bahamas.

Previous emphasis on reef and inshore species has provided information not only on their hearing sensitivity and orientation to underwater sound sources (e.g., Banner, 1967, 1972; Nelson, 1965, 1967), but also on the attractive nature of certain sounds (Banner, 1968, 1972; Myrberg, 1969, 1972; Myrberg *et al.*, 1969 a and b; Nelson, 1967; Nelson & Gruber, 1963; Richard, 1968; Wisby *et al.*, 1964). These and other studies (e.g., Evans & Gilbert, 1971; Hobson, 1963; Limbaugh, 1963; Nelson, 1969; Nelson & Johnson, 1970; Nelson *et al.*, 1969) have amply demonstrated that numerous species of shallow-water sharks are attracted to various biological sounds, as well as to irregularly pulsed, low-frequency, instrumental signals, whose characteristics "mimic" the former.

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Little information exists, however, as to: (1) attraction of free-ranging, epipelagic (= "blue-water") sharks to an underwater sound source, and (2) clear, differential attraction by any species to instrumental signals, possessing different frequency and/or pulse spectra. Nelson and co-workers (1969), while stationed at a deep-moored buoy in the Tongue of the Ocean, Bahamas, transmitted intermittent trains of pulses, containing frequencies from 50 to 200 Hz, in the presence of silky sharks, *Carcharhinus falciformis* (Müller & Henle). Although these "blue-water" sharks clearly approached the sound source initially, rapid reduction in response soon followed (12 approaches during first day of testing, followed by few approaches on succeeding days), thus precluding statistical evaluation of the data and clear interpretation.

These authors (Nelson & Johnson, 1970), subsequently carried out a field investigation in the Pacific to determine differential attraction by three species of reef sharks to signals of differing frequency and/or pulse spectra. Unfortunately, insufficient data again precluded valid comparisons. Signals possessing different frequency spectra were also used by Myrberg *et al.* (1969) in an investigation on attracting sharks by sounds. Unfortunately, in this case, their tests were designed to provide information on other factors, and thus they were also inadequate for valid comparisons of signals possessing frequency spectra below 1000 Hz.

The need for adequate information, thus, was evident. Two "blue-water" studies were therefore initiated: one over the deep waters of the Straits of Florida, 20-28 km from the mainland; and the other in the vicinity of the deep-moored buoy in the Tongue of the Ocean, Bahamas, where Nelson *et al.* (1969) had frequently encountered silky sharks (site is 15 km from land and over a depth of 1900 m).

The first study compared the relative attractiveness of various bands of noise (pulsed irregularly) to those pelagic sharks encountered during testing. The second study had two aims: (1) to compare the attractiveness of an irregularly pulsed signal relative to that of other signals of the same frequency spectrum but with fixed pulse rates, and (2) to determine if sharks could be drawn away from a small vessel by transmitting specific acoustic signals from another vessel, some hundreds of meters distant.

Differential Attraction of Sharks to Various Bands of Noise

Materials and Methods.—The signals selected for testing were the following octave bands: 25 to 50 Hz, 75 to 150 Hz, 250 to 500 Hz, and 500 to 1000 Hz. The upper frequency limit was based on results from a previous study (Myrberg *et al.*, 1969) and the known hearing range of a few species of sharks (Banner, 1967, 1972; Kritzler & Wood, 1961; Nelson, 1967), while the lower limit was set by the instrumentation used in the study.

Sounds were produced with a white noise generator (H. H. Scott 811B)

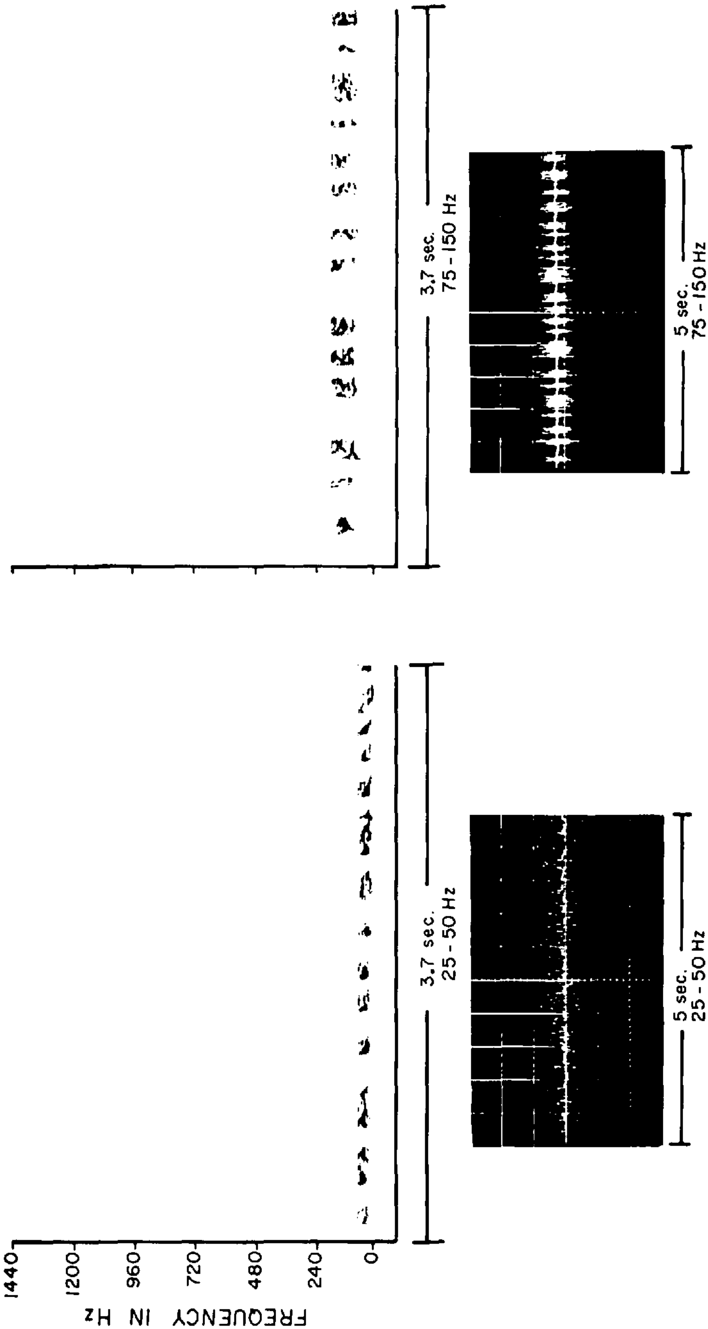

FIGURE 1. Spectrograms and oscillograms of portions of sounds used in "blue-water" playback series (irregularly pulsed).

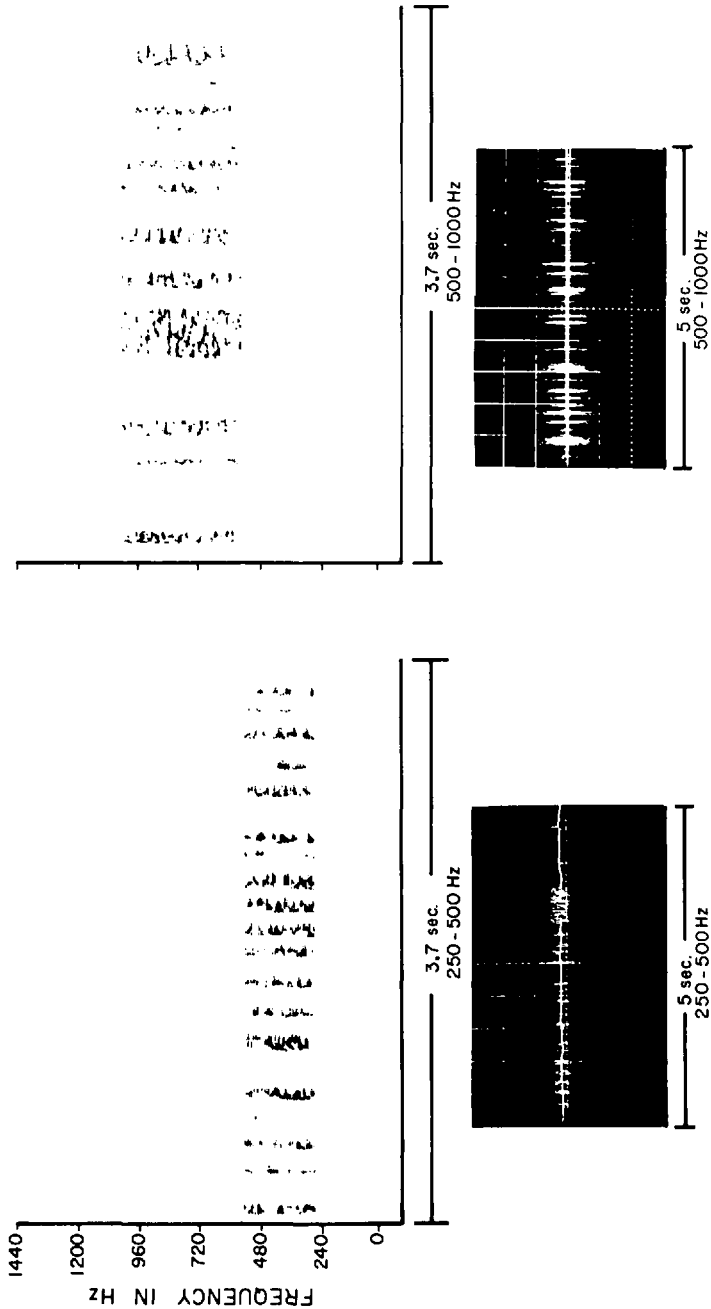

FIGURE 2. Spectrograms and oscillograms of portions of sounds used in "blue-water" playback series (irregularly pulsed).

and a band-pass filter (Krohn-Hite 3100, 24 dB/octave slope). A transientless photoswitch was keyed manually during 3 min of recording (Uher 4000 L recorder), with the resulting rapid and irregular pulses having durations and intervals of 0.05 to 0.1 sec. Each recording was inspected by a spectrograph (Kay Missilyzer) and oscillograph (Tektronix 502, with a C-27 camera) for absence of artifact. Random portions of each band are illustrated in Figures 1 and 2.

Playback equipment consisted of the recorder used for signal synthesis, a 40-watt amplifier (Allen Organ Co., T-50) and an underwater projector (J-11, Naval Research Laboratory, Orlando), which, in turn, was lowered to a depth of 5 m during testing. Sound output was continually monitored by a hydrophone (Chesapeake Instrument, SB154B), through a preamplifier (Ithaco 144L) and then to the audio channel of a video recorder (Sony, TCV 2010), as well as to an oscilloscope or voltmeter.

The vessel used for the study was the R/V OBSERVER, a 13-m houseboat (Thunderbird Corp.) outfitted for video-acoustic studies and diver operations.

Selection of test sites in the Straits of Florida was based on distance from the mainland (20 to 28 km), depth of water (exceeding 200 m), absence of nearby vessels, and reasonable sea state (0 to 2). After arrival at a given site, all engines were stopped and the vessel began to drift slowly northward with the Gulfstream, parallel to the mainland. Two observers floated astern of the vessel, each holding onto lifelines. Once testing began, these men reported the arrival and departure of any shark within their visual range to a third person, stationed at the stern. A temporal record of such events was thus maintained, as well as any behavioral activities of interest and species-identification, if provided. On occasion, film and video records were obtained, using hand-held cameras. A cage was used during the last half of the study because of an apparent increase in rapid approaches by large sharks. The presence of the cage (either floating or submerged to a depth of 5 m) and the occasional use of SCUBA did not appear to affect the data whatsoever, based on a comparison of the number of attractions recorded prior to using these necessary aids and the number recorded thereafter.

A minimum of four test sessions was conducted during a given day of testing, each session consisting of four transmissions (each test signal, once, for a period of 3 min) and appropriate control (silent) periods of equal duration which bracketed each transmission, if necessary. A 1-min rest period, separating a given test and control period, was used whenever sharks were present during the test period. This allowed sharks to leave the area of surveillance before the control period began. Only rarely was it necessary to extend the duration of rest periods so that the following control period would, indeed, reflect differences in the presence of sharks

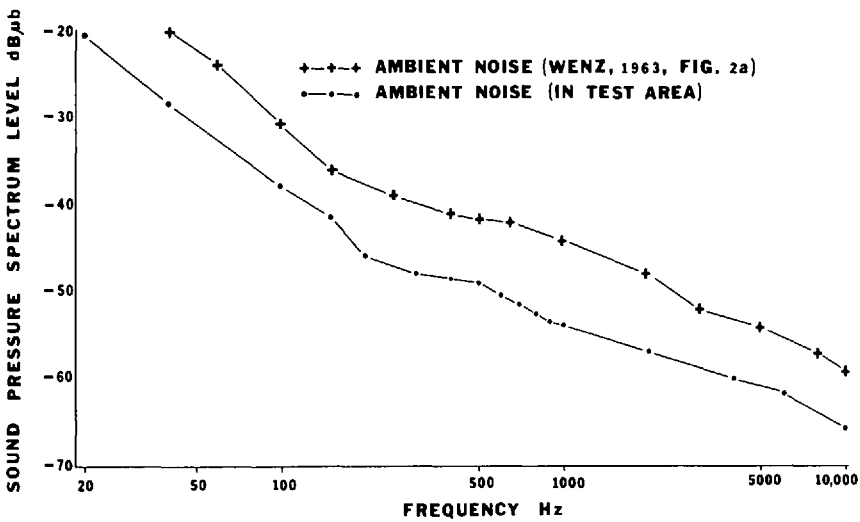

FIGURE 3. Spectrum-level, ambient-noise measurements carried out under conditions similar to those present during "blue-water" tests. Measurements are compared with those of Wenz (1963).

during periods of transmission and periods of "quiet." The four sessions conducted on a given day allowed each signal to hold a different position in the playback sequence, at least once (the position of each signal during the first session on a given day was chosen at random). Generally, only a few minutes separated the first and second and the third and fourth sessions, but a break of at least an hour separated the second and third sessions. If, at any time, sharks became so prevalent that possible habituation might well affect further testing, it was a simple matter to move rapidly some km distant to another location. The few sharks (1 to 3) that generally were encountered during all sessions on a given day of testing, the lengthy break between the second and third sessions (period of rest needed by observers), and finally, the distance generally covered by drift throughout a day of testing (15 to 25 km) reduced considerably, in our judgment, the chance that habituation was, in fact, playing a significant role in the distribution of our data.

Although very similar record levels were used during synthesis of the various test signals, we believed that slope characteristics of the ambient noise, as well as the probable differences in signal attenuation would result in differing distances of propagation for each signal, relative to noise. To prevent possible errors during testing, however, the same gain was used for all transmissions. At the termination of the study, the propagation charac-

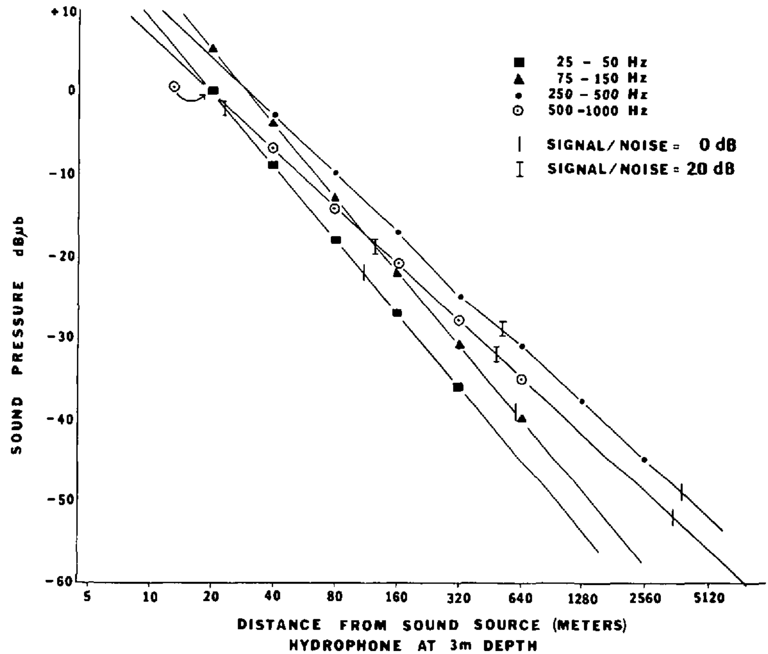

FIGURE 4. Sound-pressure levels (dBμb) at 3-m depth for increasing distance from source (J-11). Levels were measured to a distance of 80 m and extrapolations were made from that point on.

teristics of each signal were determined under similar sea and wind conditions to those encountered during testing. The J-11 was placed at operational depth, and signal transmission was picked up by a carefully suspended, calibrated hydrophone (F-37, NRL, Orlando) and passed through the Ithaco preamplifier and band-pass filter to either a voltmeter or oscilloscope. On return to the laboratory, spectrum level corrections were applied to the data. Ambient noise levels were also obtained in the test areas and these were compared with already published curves. This information thus provided us with the approximate distances that our signals traveled until each fell to specified levels relative to spectrum-level ambient noise (i.e., signal/noise = 0 and 20 dB).

Results.—To provide greater ease in understanding the data and their interpretation, the acoustical portion of the study will be considered first. Our ambient noise data (Fig. 3) compared well with the combined data given by Wenz (1963: fig. 2a) for "shallow water" conditions (200 m depth) and moderate ship noise, as well as those obtained by Arase & Arase

TABLE 1
ATTENUATION OF TEST SIGNALS PER DISTANCE DOUBLING (IN dB)
(Sound projector located at 5-m depth; hydrophone placed at three different depths)

Hydrophone depth (m)	Frequency (Hz) 25–50					75–150					250–500					500–1000				
	Distance doubling, starting 5 m from source																			
	1	2	3	4	x̄	1	2	3	4	x̄	1	2	3	4	x̄	1	2	3	4	x̄
3	11	12	9	9	10.2	10	10	9	9	9.5	6	7	8	7	7	6	6	7	7	6.5
10	9	8			8.5	8	7			7.5	6	6			6	8	8			8
20	9	8	7	7	7.7	8	8	8	8	8	8	6	6	6	6.5	9	7	7	7	7.5

TABLE 2
DIFFERENTIAL ATTRACTION OF SHARKS BY IRREGULARLY PULSED, INSTRUMENTAL SIGNALS OF DIFFERENT FREQUENCIES

Session	Frequency band of signal	No. of sessions	Surface area covered by signal (S/N = 0)	Surface area covered by signal (S/N = 20)	Total no. of sharks attracted	Actual no. of sharks per session	Predicted no. of sharks attracted per session*	Discrepancy (Predicted no. ÷ actual no.)
Test								
	25–50	85	0.036 km²	0.0018 km²	29	0.34	0.34	0
	75–150	85	1.044 km²	0.046 km²	13	0.15	8.68	57.8
	250–500	85	43.32 km²	0.81 km²	20	0.24	152.93	637.2
	500–1000	85	36.75 km²	0.69 km²	12	0.14	130.27	930.5
Control								
	No signal	177	—	—	12	0.007	—	—

* If all signals were as attractive as the 25- to 50-Hz signal (areas arbitrarily chosen are those having S/N = 20).

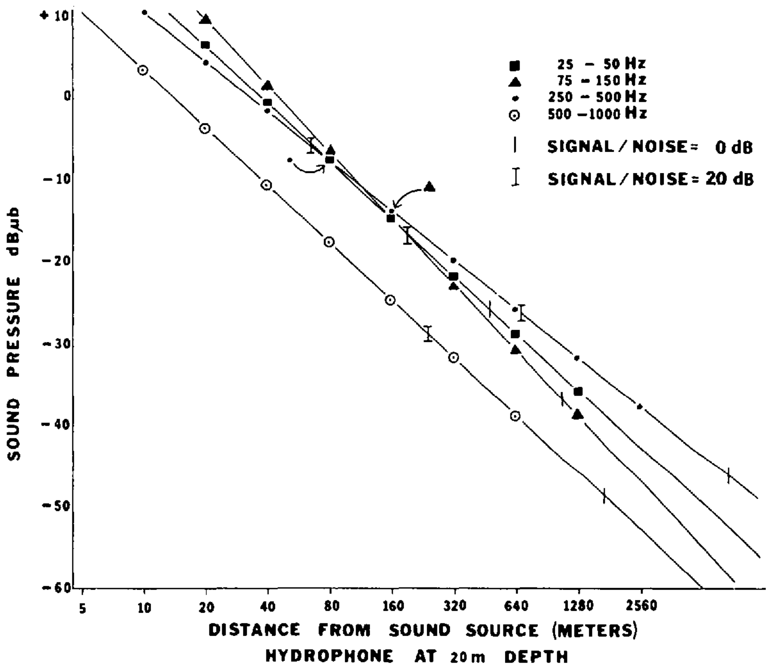

FIGURE 5. Sound-pressure levels (dBμb) at 20-m depth for increasing distance from source (J-11). Levels were measured to a distance of 80 m and extrapolations were made from that point on.

(1967) at a depth of 60 m under similar wind conditions. The rate of sound attenuation per distance doubling for each signal (normally 6 dB for free-field, spherical spreading) is seen in Table 1. Low frequencies propagated least well near the surface and attenuation was somewhat greater than expected near the source for all frequencies.

Plots of the measured sound levels obtained at specific distances from the sound source (up to 80 m) resulted in straight-line functions for each signal (Fig. 4, 3-m depth; Fig. 5, 20-m depth). Then, using the known attenuation rates and the measured ambient noise levels at the middle frequency of each test band, we determined the distance at which the signal should attenuate to spectrum level ambient noise (signal-to-noise ratio = 0 dB), as well as the distance where each signal should attenuate to 20 dB above that level. This latter ratio was chosen because of its apparent importance regarding threshold determinations which have been carried out on sharks and teleosts by various individuals (Banner, 1967, 1972; Buerkle, 1969; Cahn *et al.*, 1969; Myrberg *et al.*, 1969). When these distances were plotted, it was apparent that the 25- to 50-Hz signal, at 20-m depth,

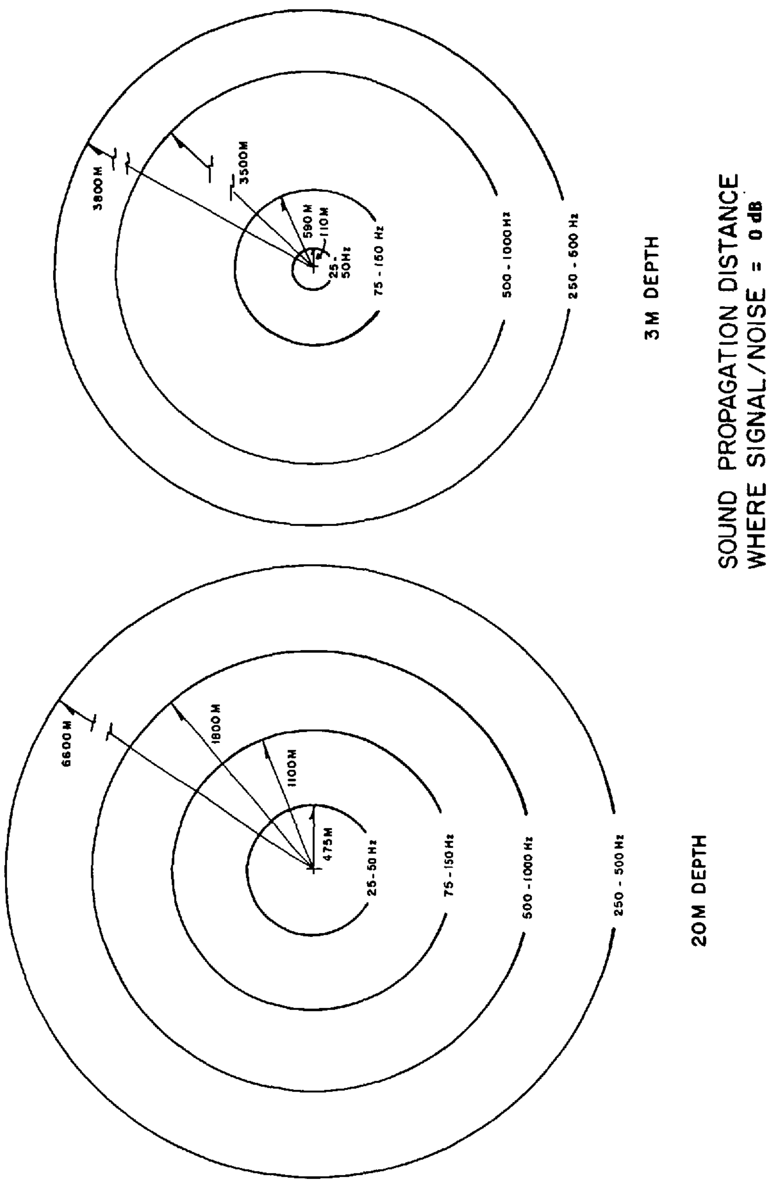

FIGURE 6. Sound propagation distances for sounds used in "blue-water" tests. Each circle refers to distance at which a given sound attenuated to the level of ambient noise (S/N = 0).

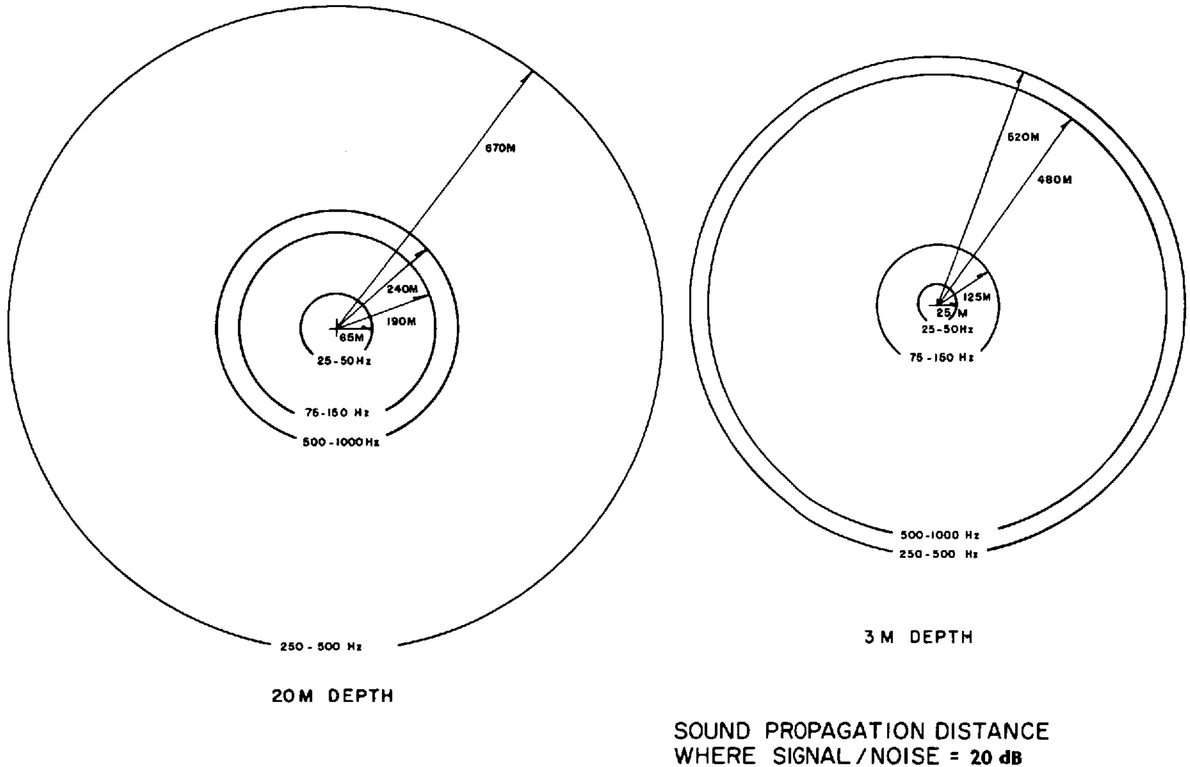

FIGURE 7. Sound propagation distances for sounds used in "blue-water" tests. Each circle refers to distance at which a given sound attenuated to a level of 20 dB above spectrum-level ambient noise ($S/N = 0$).

reached only 65 m before attenuating to 20 dB above ambient, while the 250- to 500-Hz signal reached out 670 m, more than 10 times the distance reached by the former signal. These areas for all test signals are shown in Figures 6 and 7. The circles shown in these figures provide only a two-dimensional picture; it would be more realistic, but far more complicated, to provide a three-dimensional view. The latter would appear as partial spheres with their tops and bottoms flattened because of the surface and bottom. The center of each sphere would contain the sound source. The volume inside the boundaries of such a figure would represent the area from which sharks could be attracted, assuming that appropriate frequency thresholds were located somewhere between S/N ratios of 0 and 20 dB.

Table 2 summarizes the results obtained on attraction of sharks during the period of study (tests were run during every month except May, October, and November). Seventy-four sharks were sighted during all periods of transmission. Species-identification of many of these sharks was difficult, but those identified were silky sharks, *Carcharhinus falciformis*, ranging from 1.5 to over 3.5 m in total length. Many sharks arrived on the scene swimming rapidly and on a "beeline" course to the sound projector. Only when within the last few meters did they veer off and begin circling either the projector or the divers.

The 12 sharks noted during the control periods (3 min of silence preceding given test periods) were individuals which had, no doubt, remained in the vicinity after being attracted to a source during the previous test. This also gave us a rough idea of the relative number of sharks which remained in our vicinity once signals were no longer transmitted. The length of time that a given shark remained at a site during signal transmission varied; some stayed for only 20 to 30 sec before moving on, while others remained for the full 3 min, continually circling either the projector, the divers, or the cage. A shark was never seen by any member of our field team during the many lengthy, quiet periods which preceded or followed a day of testing.

It is obvious, when one takes into account the surface areas covered by the various signals, that the 25 to 50 Hz, irregularly pulsed signal was, by far, the most attractive. The other signals did, however, have "power" to attract, this "power" decreasing as the signal rose in frequency. These results, thus, agree with those obtained by Nelson & Johnson (1970), insofar as a signal apparently becomes less attractive as it rises in frequency.

There appear to be at least three good reasons why the lowest frequency band proved to be the most attractive, and at least two possible reasons why it should have been the least attractive. On the positive side, any decrease in wavelength is accompanied by increased scattering and absorption (i.e., attenuation), as well as greater channelization at, or near, the surface (i.e., decreased permeation with depth). Thus, at the depths used in the study, one would expect that low-frequency sounds would travel greater distances than those sounds of higher frequencies, produced with the same energy at the same time. Note that our bands obviously did not possess equal energy. Secondly, evidence from Banner (1967) and Nelson (1967) points to the most sensitive region in the hearing curve, *relative* to ambient noise, as being around 40 Hz for at least one large predatory shark, *Negaprion brevirostris*. This indicates that perhaps other predatory sharks also possess similar sensitivity within the limits of our lowest frequency band (greatest *absolute* sensitivity is, however, around 500 Hz for *Carcharhinus leucas* [Kritzler & Wood, 1961], while this same point stands around 320 Hz for *Negaprion brevirostris* [Nelson, 1967]). Thirdly, from the standpoint of biological significance, Banner (1972), Nelson & Gruber (1963), and Nelson & Johnson (1970) found a significant amount of low-frequency energy in those biological sounds which attract sharks. On the negative side, however, ambient-noise curves for ocean waters invariably have a negative slope; that is, the noise is greatest at lowest frequencies and decreases as one goes up the frequency scale. This would tend to obliterate low-frequency attractants. Secondly, low-frequency sound is less directional than higher-frequency sound, thus making it more difficult for an animal to locate its source.

Differential Attraction of Sharks to Various Types of Pulsed Noise

Materials and Methods.—The signals used in this study all consisted of the optimal frequency band determined from the previous study: 25 to 50 Hz. Each signal differed from another, however, as regards the nature of its pulse. The irregularly pulsed, 25- to 50-Hz signal of the previous study was again used. Four additional signals were constructed (using a pulse generator), with the following pulse characteristics: 20/sec (pulse duration—10 msec, continuous train); 10/sec (pulse duration—50 msec, continuous train); 5/sec (pulse duration—50 msec, continuous train); and 1/sec (pulse duration—50 msec, continuous train). These signals were then recorded for three minutes each with the Uher recorder and, as in the previous study, final recordings were inspected for freedom from artifact.

The field phase was carried out, using the R/V Observer, at the deep-moored buoy of AUTEC (24° 14′ N; 77° 11′ W) in the Tongue of the Ocean, Bahamas The continual presence of sharks in the immediate vicinity of that buoy, coupled with our desire to remain also reasonably near that object, forced us to use a technique of stationing our vessel so that we could obtain data similar to those used during our previous study in the Straits of Florida. Upon arrival at the site on the first day of testing, we tied a 3⁄16-in line to the buoy. As predicted, sharks were seen swimming about the buoy, and as we drifted away, holding the line attached to the buoy, a number of sharks followed. As we approached a distance of about

200 m from the buoy, sharks were no longer seen. At that point, a small buoy was attached to the line and then dropped over the side. On each day of testing, the OBSERVER slowly approached this small buoy, made fast to the line, all motors were cut and the vessel drifted, until the line became taut. This procedure thus allowed us to hold the same position during all tests; yet it was far enough from the moored buoy so that any sharks initially attracted to the vessel during its approach remained for no more than 30 to 45 min (such relatively long periods occurred only after the first few initial approaches; thereafter sharks generally remained for no more than a few minutes after completion of a test).

The first experiment carried out at the site was to determine whether sharks could be drawn away from one vessel by attracting them to another vessel that was transmitting an irregularly pulsed, low-frequency signal (25-50 Hz). A 4-m skiff was placed astern of the OBSERVER with a small floating cage drifting 4 m behind it (both connected by line). One person entered the skiff with a recorder, amplifier, and a J-9 projector, while another person entered the cage. Then, by "playing-out" a monofilament line (250-lb test = 113 kg), the skiff and cage were allowed to drift 250 m from the OBSERVER (distance between the moored buoy and skiff was more than 400 m). A J-11 was then lowered over the side of the OBSERVER, the recorder and amplifier were connected to it, and a diver entered the water and stationed himself between the two out-drives of the vessel. Communication was established between the two vessels (CB radios), and both observers reported no sharks in visual range.

The initial transmission was carried out by the skiff. Within 30 sec from the onset of transmission the diver astern the OBSERVER reported that sharks were moving from the direction of the deep-moored buoy, towards the skiff (OBSERVER was about 40 m from a "direct line" between buoy and skiff). In about 1 min, three sharks appeared in visual range of the diver stationed at the skiff. These sharks circled the skiff and cage from a distance of about 8 m. A fourth shark then appeared, but rapidly moved off. After about a minute, the sharks approached within 3 to 5 m of the cage and were identified as silkies, *Carcharhinus falciformis*, each about 1.5 m total length. The cage man waited until two sharks were moving away from the direction of the OBSERVER and then signalled for transmission to begin from that vessel (transmission ceasing at the skiff at that moment). Within a few seconds, the smaller of the two sharks suddenly turned around and began swimming in the direction of the OBSERVER. The second shark also reacted at the same time, but differently; it swam unhurriedly in a wide arc and then moved also in the direction of the OBSERVER. The remaining shark was also seen moving unhurriedly in the direction of the OBSERVER, but its initial movements, immediately subsequent to onset of transmission, were not observed.

No sharks were in the immediate vicinity of the skiff 30 sec after the cage man had signalled for transmission to begin at the other vessel. Within 1.5 min, the diver, astern of the OBSERVER, spotted sharks approaching from the direction of the skiff. These sharks were identified also as silkies. Three minutes later, the skiff was notified to begin transmission (transmission ceasing at the OBSERVER) and about a minute thereafter, the diver at the OBSERVER reported that sharks around him were moving in the direction of the skiff. These sharks did not, however, veer suddenly and swim rapidly in that direction; rather they moved unhurriedly and, in the case of those sharks moving in a direction other than toward the skiff, they moved in that direction only after making a rather wide arc. One shark that had moved initially in the correct direction, turned back before leaving the visual range of the diver astern of the OBSERVER. Five sharks appeared at the skiff between 1 min 30 sec and 1 min 50 sec after onset of transmission. These sharks remained always within 10 m of either the skiff or the cage during the entire 3-min transmission period. Again, the OBSERVER began transmitting signals at the moment when transmission ceased at the skiff. Within a minute all sharks at the skiff had moved again in the precise direction of the OBSERVER. Their movements were also unhurried, and smooth, rather large arcs were again noted in those sharks that had been moving in directions other than the correct one. As before, sharks arrived at the OBSERVER from the direction of the skiff within 2 min and there they remained. After a few minutes the skiff again began transmitting, with simultaneous cessation of transmission at the OBSERVER. This time, the majority of sharks around the OBSERVER did not move away. Although most turned slowly and began moving in the correct direction, some returned to the OBSERVER. Four sharks were, however, sighted by the cage man at the skiff coming from the direction of the OBSERVER about 2 min after onset of transmission. As before, all sharks around the skiff headed toward the OBSERVER when transmission ceased at the skiff and began from the other vessel. Sharks, in turn, were seen approaching the OBSERVER from the direction of the skiff, but an accurate count was not possible because of the presence of other sharks already in the close vicinity of the vessel. At that time, the skiff and cage were pulled to about 125 m of the OBSERVER and two additional tests were made. The first resulted in 8 sharks arriving at the skiff from the direction of the OBSERVER, all arriving between 2 min 20 sec and 2 min 35 sec after onset of transmission. At the end of that transmission (3 min), signals from the OBSERVER resulted in all but one of these sharks moving in an unhurried fashion toward that vessel. The next "call" brought only one shark (within 1 min) and tests then ceased.

It was clearly demonstrated by the above tests that silkies at our test site could be drawn successfully away from a small vessel by transmitting appropriate acoustic signals from another vessel, standing nearby. Sharks arrived at the latter vessel shortly after onset of transmission. It was obvious to the observers that the intervals between onset of transmission and arrival of sharks became longer as tests continued. Sharks also appeared more reluctant to leave the immediate area of the OBSERVER than the area surrounding the skiff. Reasons for this are unclear.

Finally, the clear orientation demonstrated by sharks during these tests was unequivocal. Although in most cases rapid turns and immediate "fixation" on the "true" course did not occur, those sharks that were observed closely demonstrated unhesitating and unhurried movement to that particular course and to no other. There can be no doubt that these animals did orient to a low-frequency signal from distances of 125 to over 400 m away. Orientation to the intermittent vibration caused by the fine monofilament line that extended between the two vessels could not possibly have occurred during the initial movement of sharks from the buoy to the skiff; and insurmountable acoustic problems are engendered when surmising that such a fine line could be used as a source of orientation in the presence of a much louder vibrating source. Sound levels at the source were not determined during these tests, since we were interested only in transmitting a sound at a level that would probably reach sharks within a few hundred meters. All signals were transmitted near maximum gain of the respective amplifiers.

The second phase of the work near the moored buoy commenced on the day following the "vessel-to-vessel" tests and continued throughout the remainder of our stay. This phase was concerned with testing differential attraction of sharks to five signals all having the same frequency spectrum (i.e., 25 to 50 Hz), but each possessing a different pulse rate (i.e., 1, 5, 10, and 20 per sec, and irregular).

Most experimental procedures used during this phase were those used previously in our study in the Straits of Florida. There were a few exceptions, however. One concerned the length of the rest periods. Such periods were inserted between a given test and control period so that sharks would have time to leave the area of surveillance before a control (silent) period began. Although these rests had been brief in our previous studies, many became lengthy during the present one. Sharks usually arrived within visual range of divers within 30 to 90 sec following the initial transmission on a given day. These animals subsequently remained within that range long after transmission had ceased (i.e., 3 min). Since we could not begin a control period until all sharks had left the area of surveillance, we simply waited. Rest periods, therefore, varied from about 35 min (e.g., after the first test on a given day) to less than 5 min (e.g., after tests during the second or third series of a given day). Although time consuming, this procedure resulted in greater objectivity than could have been obtained by any other means. The appropriate distance maintained by the OBSERVER from the moored buoy was also instrumental in the eventual disappearance of

TABLE 3

DIFFERENTIAL ATTRACTION OF SILKY SHARKS TO VARIOUS INSTRUMENTAL SIGNALS, EACH HAVING A DIFFERENT PULSE CHARACTER
(All signals had the frequency spectrum of 25–50 Hz)

	Pulse nature of signal	No. of 3-minute periods	No. of sightings of sharks*	Sightings per period ($\bar{x}$)
13 test sessions	Irregular	13	33	2.6
	20 pulses/sec	13	27	2.0
	10 pulses/sec	13	24	1.8
	5 pulses/sec	13	17	1.3
	1 pulse/sec	13	14	1.0
13 control sessions	No signal	65	34	0.5
	TOTAL		149	

* Distribution of sightings among the signals is significantly different from random distribution: -0.05 (Kolmogrov-Smirnoff, one sample test).

sharks from our immediate area. A rest period was not inserted between a given control period and the following test, since a shark had to arrive at the site during a test before it was counted.

Two or three test sessions were conducted during a given day. Each session consisted of five transmissions (each test signal, once, for a period of 3 min), and the appropriate rest and control periods. The order in which signals were transmitted during each session varied so that each signal held different positions in the playback sequence, at least once during a two-day period.

Based on our previous measurements of ambient noise and signal attenuation in the Straits of Florida as well as similar measurements by others taken over deep waters of the Tongue of the Ocean, we felt it unnecessary to determine once again propagation distance, etc. Rather, since the waters at our test site, no doubt, possessed a lower level of ambient noise than that recorded in the Straits (but, at most, by only 6 dBμb) for the same frequency band, i.e., 25 to 50 Hz (both regions being protected from open-ocean, shipping noise), we compensated for this difference by using the J-9 sound projector rather than the J-11 (the former having a corresponding 6 dB reduction over the latter in transmission response for the same voltage input for the frequencies of interest). Thus, reasonably comparable transmission-distances existed between the present study and that one carried out in the Straits (see Figs. 6 and 7: 25 to 50 Hz).

Results.—Table 3 summarizes the results obtained during this particular phase. A total of 115 sightings of sharks was made during all 65 test periods vs. 34 sightings during an equal number of control periods. This significant difference was expected; but important significance was also attained when the distribution of sightings among the various signals was checked against the possibility of random distribution. The Kolmogrov-Smirnoff, 1 sample, statistic provided the strongest test of our data and it clearly demonstrated that the distribution of our sightings among the respective signals was, in fact, significantly different from random distribution at the 0.05, alpha level. These findings, therefore, directed our attention to three important facts: (1) irregular pulsing of the previously demonstrated optimal signal clearly resulted in more sharks being attracted to it than to any regularly pulsed signal of the same frequency spectrum, (2) regularly pulsed signals, with a bandwidth of 25-50 Hz, definitely attracted sharks, and (3) as pulse rate increased among these regularly pulsed signals, so the number of sharks attracted increased.

The close approach of sharks to divers during test periods provided relative ease in identification—all were silkies, *Carcharhinus falciformis.*

General Notes on Behavior of Sharks in the Region of the Deep-Moored Buoy

Sharks were constantly noted in the immediate vicinity of the buoy. Its isolated location over extremely deep water (1900 m), and its relatively large size (approximately 4 m diameter), no doubt contributed to a prevalence of sharks because the object probably served as a source of orientation or security for possible prey of these animals. Although sharks would trail a slow-moving vessel, they eventually left its immediate area within 200 to 300 m from the buoy.

Sharks were generally smaller than those noted during tests in the Straits of Florida. Most individuals ranged from 1.5 to probably 2 m in total length (TL), although one tiny fellow was sighted that was about 0.5 m, TL.

Sharks usually arrived at the site within 30 to 90 sec after the onset of signal transmission. Most individuals entered the range of observation moving at a directed, but unhurried, pace to the general region of the underwater projector. They, in turn, either began slowly circling the area surrounding the vessel and the divers or swam deep and left the area. Some individuals, however, arrived with surprising speed. The latter entered the field of view generally on a "beeline" to the sound projector, which was suspended at a depth of from 5 to 10 m. Usually these rapidly moving sharks veered off when within 1 to 3 m of the projector; but at least twice the projector was grabbed by such an individual that did not hesitate, whatsoever, in continuing its rapid speed up to actual contact. The projector was immediately released after such a grab, with the shark moving off.

Underwater visibility, easily exceeding 40 m in the vertical axis, provided the chance for divers to observe various patterns of behavior, a number of which had been previously noted by us in a few other species.

A slow, exaggerated head-shake was rather frequently noted, especially preceding approach by the actor toward a diver. Oftentimes this motor pattern was initiated 10 to 12 m away, and at that time the head moved horizontally through an arc of about 90° (the tail moving to the side opposite from that to which the head was moving). As a shark approached a diver, shaking became faster until it ended with a rapid approach followed by veering off (either an apparent glide compensated by the pectoral fins or an active movement produced by a tail beat and compensated for by the pectorals). When individual silkies were moving slowly about 5 m from a diver, and at about the same depth, a slight suggestion of a motor pattern appeared which had previously been noted in the bonnethead (*Syphrna tiburo*) and the blacknose shark (*Carcharhinus acronotus*) (Myrberg & Gruber, 1972, and in manuscript). This pattern, the "hunch," consisted of a slight dropping of the tail and pectorals from the horizontal while the head was turned slightly upward, resulting in a slightly hunched appearance. A similar pattern was noted three times in nearby silkies, but in those cases the head went up only slightly, the tail dropped a corresponding amount, and the pectorals did not appear to drop at all.

Oftentimes, sharks in the area moved together in a rather loose aggregation. Occasionally, however, two or three individuals moved close together and carried out, simultaneously, sharp turns and other maneuvers. One pattern noted at these times (i.e., two sharks swimming parallel and 1.0 to 1.5 m apart) was a sudden tilting of the body sideways by one individual, with the dorsal aspect being directed at the side of the other individual. Tilting lasted about 3 to 5 sec followed by the actor's regaining vertical position and moving off with the other individual. Another pattern noted occasionally was rather unique in that an individual, swimming horizontally at a depth of about 5 to 10 m, suddenly oriented vertically (head up) and, in a twisting, accelerating movement, headed toward the surface. Within a meter of the surface, the shark glided to a horizontal position and then moved just below the surface for 2 or 3 m before moving down to a greater depth. No aggressive movement was apparent following the action.

The final two patterns noted were "yawning" and "gill-puffing." This latter pattern, often following yawning, was a noticeable expansion of the branchial region for about 1 or 2 sec. Occasionally 2 or 3 gill-puffs would occur in rapid succession.

Although no sharks came closer than 1 m to any diver, an occasional incident was worthy of note. Generally, sharks moved at a slow, steady pace while circling the sound projector or the vessel, itself. In fact, they continued this rather constant pattern even when a diver approached. One might, therefore, consider that these sharks were either not very perceptive or not attentive to what was going on about them. Nothing could apparently have been further from the truth. Near the end of testing, we wished to film certain facets of the underwater study. One of us (AAM) had moved to a depth of about 10 m by SCUBA and began filming a group of five sharks from a distance of about 8 m. One shark slowly turned and moved directly at the camera. When within 1 m of the camera, the diver pushed the camera at the "face" of the shark, and it suddenly veered to the left. Almost simultaneously, the diver looked over his shoulder and spotted the cage about 10 m distant. While turning, however, he began to lose his vertical attitude and to compensate for this, kicked rapidly and awkwardly about four times. Immediately upon the diver's kicking (which followed the veering of the shark by about 2 sec, at the most), the remaining four sharks suddenly turned and moved rapidly toward him. Fortunately, he immediately regained a vertical position with the camera again between the sharks and himself, and each individual veered away when no closer than 1 m. He then slowly swam to the underwater cage. We cite this incident not for melodramatic effect, but rather to indicate the rapid reaction that sharks can suddenly show when a disturbance occurs in their vicinity.

Discussion

Various conclusions, based on the data provided in this report, appear to have rather important connotations. We wish to dwell momentarily on each of these points and indicate their possible relevance to already existing knowledge.

Most, if not all, sharks appearing during tests were silky sharks, *Carcharhinus falciformis.* Thus, it is obvious that many members of at least one species of "blue-water" sharks can be attracted as easily or as rapidly to an underwater sound source as the members of various inshore species. The silky must, of course, be considered a potentially dangerous shark, because of its size, lack of shyness, and preference for the upper layers of the epipelagic region in both the Atlantic and Pacific.

It is also clear that all of the irregularly pulsed instrumental signals used in the first study attracted sharks, irrespective of whether the signal was 25 to 50 Hz or 500 to 1000 Hz. The data demonstrated, however, differential performance to the various spectra, i.e., the signal comprising frequencies from 25 to 50 Hz was clearly more attractive than the other test signals. It is noteworthy, however, that the data show clearly that the lower the frequency is, the more attractive the signal. It is important now to determine if a "more preferential" band exists below those frequencies tested. This next step will, however, require not only greater technical knowledge and more sophisticated instrumentation, but based on the present "state of the art" of sound projectors, our lower limit will most probably not extend below 10 Hz.

Our "vessel-to-vessel" study has shown that under the conditions existent at the time of testing, an attractive signal, transmitted from one vessel, can draw sharks rapidly from around another vessel stationed a few hundred meters distant. Results of later tests in the area emphasized the long periods of time that sharks often remained around a vessel, even though no signal was being transmitted. Therefore, the speed with which sharks were repeatedly drawn away from the small skiff and cage toward the OBSERVER, and vice versa, might well point to an unexplored practical consideration, i.e., the possibility of using such signals when sharks are endangering a small vessel or its occupants. Even though a diver was bobbing at the water's surface in the immediate vicinity of the skiff during tests, his presence did not deter sharks from moving toward the other vessel.

Finally, the distance over which sharks moved to a sound source (e.g., from the immediate vicinity of the moored buoy to the small skiff) and the clear correlation that existed between initial and correct orientation for the brief period following onset of signal indicated an obvious directional capability and sensitivity that members of the test species must possess in the acoustic modality.

The third and final study demonstrated that irregularly pulsed signals definitely attract more sharks to a sound source than continuously trained, regularly pulsed signals having the same frequency spectrum. Yet, it is also clear that regularly pulsed signals attract sharks. Finally, as pulse rate increased (from 1, to 5, to 10, to 20 per sec), so increased the effectiveness of the signal. Thus, it is apparent that any object transmitting a high-level, low-frequency signal in a regularly pulsed fashion will probably attract sharks when the latter are within audible range; and as the pulse rate increases (probably to some level untested), so increases the attractiveness of that signal.

Based on preliminary discussions with helicopter pilots, a practical consideration again appears evident. At hover, the main rotor of an HH52-A Sikorsky (used in air-sea rescue operations) has a shaft rotation of 221 pulses/min. Actual rotation based on the rotor's having three blades is, however, 663 pulses/min or approximately 11 pulses/sec (the confounding factor of tail rotor is not considered here). This regularly pulsed signal, emanating from the helicopter to the water surface, must contain low-, as well as high-frequency noise. Thus, it is possible that helicopters of this type, when hovering for periods of more than a minute or so above a given point, may well be attracting sharks to them. Although we realize fully that each model of helicopter (and other hover craft) no doubt possesses a different rotor rate during hover, evidence presented here implies that various of these craft may also be doing the same thing. Distance of propagation will, of course, be dependent on sound-source level, but apparently appropriate levels can certainly be attained by such craft.

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SUMARIO

EFECTIVIDAD DE SEÑALES ACÚSTICAS PARA ATRAER TIBURONES DE "AGUA AZUL" A UNA FUENTE DE SONIDO SUBMARINA

Se realizaron tres estudios experimentales en el ambiente natural para determinar la efectividad de varias señales acústicas para atraer tiburones *Carcharhinus falciformis* que nadan libremente, hacia la inmediata vecindad de una fuente de sonido submarina. Estos estudios se llevaron a cabo en aguas profundas de los Estrechos de la Florida a millas de distancia de tierra o en una boya anclada en la Lengua del Océano, Bahamas.

Todas las bandas de octavas de sonido usadas en las pruebas dieron por resultado atracción, con el nivel de atracción aumentando según disminuía el espectro de la frecuencia, respectivamente, de 500-1000 Hz, a 250-500 Hz, a 75-150 Hz y finalmente, a 25-50 Hz. Señales irregularmente pulsadas también tuvieron más atracción que señales regularmente pulsadas, con las últimas aumentando su atracción según el ritmo del pulso aumentaba de 1, a 5, a 10 y finalmente, a 20 pulsaciones/seg. Además, se estableció que al menos bajo ciertas condiciones, los tiburones pueden ser alejados de uno de los barcos transmitiendo señales de baja frequencia, irregularmente pulsadas, desde otro barco estacionado a unos cuantos cientos de metros de distancia.

Se describen varias acciones en el comportamiento de tiburones individuales, después de acercarse a la fuente de sonido. También se discuten varias consideraciones prácticas surgidas de los resultados de los experimentos.

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